

Article

Life Cycle Assessment of Thermoelectric Cooling Modules for Thermal Management: From Manufacturing to Lifetime Useful Cooling

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Abstract

The life cycle environmental impact of a thermoelectric cooling module operated under a reference condition is presented. Cradle-to-gate and cradle-to-grave system boundaries were considered to distinguish manufacturing from the use and end-of-life stages. A foreground life cycle inventory was developed for a commercial thermoelectric module, considering a functional unit of 1 kWh of useful cooling delivered on the cold side. Moreover, a sensitivity analysis addressing service life, electricity mix, bismuth economic allocation modelling, consideration of auxiliary electronics, and end-of-life scenarios was conducted. When expressed per functional unit, the results indicate that the environmental impacts of the thermoelectric cooling module are governed primarily by use-phase electricity demand, making lifetime and electricity mix decisive parameters in the cradle-to-grave approach. At the manufacturing level, the main cradle-to-gate burdens are related to semiconductor material production, alumina manufacturing, and auxiliary components. Overall, sustainable improvement of thermoelectric systems requires an integrated design strategy. Material substitution alone is insufficient unless it is combined with high thermoelectric efficiency, low-impact ceramic and metallisation processes, efficient auxiliary power conversion, robust thermal management, low-carbon electricity supply, and extended service life.

Keywords: activity browser; critical materials; ecoinvent; green engineering; LCA; resource sustainability; thermoelectric cooling



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1. Introduction

Thermoelectric cooling (TEC) modules are a solid-state cooling technology of growing interest for applications in electronics thermal management, particularly where compactness, precise temperature control and the absence of moving parts are mandatory or advantageous [1–3].

Thermoelectric modules operate through the coupled Seebeck, Peltier, and Thomson effects over p-type and n-type semiconductor couples, thereby enabling electrically driven heat pumping from the cold side to the hot side. This structure is a stable option for small-scale cooling applications and thermal control of power electronic systems [4–8]. Due

to maturity and practical modular architecture, thermoelectric devices have already been applied in compact cooling applications. However, their performance remains constrained by Joule heating, thermal back-conduction, and intrinsic material limitations [9–11].

A TEC module is built from repeated thermoelectric couples, each formed by one p-type and one n-type semiconductor leg connected electrically in series and thermally in parallel. Under direct current operation, charge carriers move through the p-type and n-type legs, producing heat absorption at the cold junction and heat rejection at the hot junction through the Peltier effect. The performance of the module therefore depends on the thermoelectric properties of both semiconductor legs, including the Seebeck coefficient, electrical resistivity and thermal conductivity, as well as on the geometry and number of couples and on losses associated with metallic interconnections and ceramic substrates. This is relevant for LCA because the p-type and n-type materials define part of the foreground inventory, while their thermoelectric performance influences the electricity required to deliver a given cooling service. More broadly, recent studies on semiconductor junctions and heterostructures have also shown that semiconductor type, interface quality and charge transport behaviour can strongly affect the performance of energy conversion systems [12,13].

The performance of thermoelectric devices is commonly discussed at both the material and device levels. Under the usual one-dimensional approximation, the material figure of merit, expressed as zT , is given by Equation (1).

$$zT = \frac{\alpha^2 T}{\rho \kappa} \quad (1)$$

In this equation, α is the Seebeck coefficient, ρ is the electrical resistivity, and κ is the thermal conductivity [9,10]. Although the figure of merit is a performance indicator, it does not capture the full environmental relevance of a TEC module. Device performance also depends on module architecture, ceramic substrates, metallic interconnections, soldering materials, and auxiliary power electronics. Therefore, a technology that is promising from a thermal management perspective may still have significant environmental burdens during raw material extraction, semiconductor production, assembly, use, and end-of-life.

Objectives

This article aims to evaluate the life cycle environmental impacts of a TEC module operated under a fixed reference condition according to the following specific objectives:

- To develop a transparent and comprehensive foreground life cycle inventory (LCI) for a TEC module, including semiconductor elements, ceramic substrates, metallic interconnections, auxiliary materials, assembly processes, and dedicated power electronics;
- To model the cradle-to-gate and cradle-to-grave system boundaries of the TEC system under a fixed reference operating condition;
- To quantify the midpoint life cycle environmental impacts of the TEC system, with explicit separation between manufacturing, use, and end-of-life burdens;
- To identify the dominant life cycle contributors, evaluate the robustness of the results, and assess the influence of critical modelling assumptions through sensitivity scenarios that address service life, electricity mix, bismuth economic allocation, and consideration of auxiliary power electronics.

The novelty of this work lies in connecting a transparent reconstructed foreground inventory for a commercial TEC module with a functional unit based on useful cooling and an operating condition derived from manufacturer data. The study explicitly separates manufacturing, use-phase and end-of-life contributions, while including the dedicated

power conversion stages required for operation. This provides a reproducible basis for interpreting how module materials, auxiliary electronics, electricity demand, lifetime and modelling assumptions jointly influence the environmental profile of the analysed TEC system.

2. Literature Review

A literature review following the PRISMA (Preferred Reporting Items for Systematic reviews and Meta-Analyses) 2020 statement reporting directives was conducted to identify previous studies addressing the life cycle or environmental assessment of TEC modules [14].

The screening was intended to support the methodological context of this research. The purpose was to identify how previous studies have selected and dealt with functional units, system boundaries, LCI modelling, manufacturing processes, use-phase electricity demand, service life assumptions, end-of-life treatment, and life cycle impact assessment (LCIA) methods for TEC technologies.

2.1. Information Sources

The literature search was performed in three bibliographic databases: Scopus, Web of Science Core Collection, and IEEE Xplore. The first two were selected for their broad coverage of the peer-reviewed literature in LCA, material science, energy systems, and environmental and production engineering. IEEE Xplore was included to broaden coverage of TEC, electronics' cooling and thermal management applications within the environmental engineering and electrical and electronics systems literature.

2.2. Search Strategy

The search was conducted on 15 March 2026. No limits were imposed on the publication date to capture early and recent studies involving TEC and life cycle or environmental assessment terminology. The search was limited to records available in English.

The search query combined three concept groups: (i) thermoelectric technology; (ii) cooling or thermal management; and (iii) life cycle or environmental assessment terminology. The resulting Boolean search structure is presented in Box 1.

Box 1. Search query used in the systematic literature search.

```
((thermoelectric OR "thermo-electric" OR peltier) AND (cool* OR refrigerat* OR "thermal management")) AND ("life cycle assessment" OR "life-cycle assessment" OR "life cycle analysis" OR "life-cycle analysis" OR LCA OR LCIA OR "life cycle inventory" OR LCI OR "carbon footprint" OR "environmental impact"))
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The search query was adapted to the syntax of each database. The search strings for each database are reported in Appendix A.

2.3. Eligibility Criteria

Eligibility criteria were defined before title and abstract screening to ensure a consistent and reproducible selection process. Studies were considered eligible when addressing thermoelectric materials, TEC modules or closely related thermoelectric systems, and reporting LCA, LCI, LCIA, carbon footprint or environmental assessment results. Studies were also retained when providing transferable inventory or relevant methodological information.

Only records written in English were considered. Eligible publication types included peer-reviewed journal articles and conference papers, provided that sufficient methodological information was available for data extraction. Minimum extractable information included at least one of the following elements: functional unit, system boundary, inventory data, background database, LCIA method, impact categories, and end-of-life management.

Records were excluded when they focused exclusively on thermal, electrical or thermodynamic performance without environmental assessment. Studies limited to coefficient of performance, heat transfer, numerical simulation, optimisation, control strategy or device design were therefore excluded unless they also included LCA or environmental impact indicators. Studies were also excluded if inventory data, impact assessment results or sufficient methodological information were not provided.

Records from which the full text could not be retrieved were excluded at the eligibility stage. Studies focused exclusively on thermoelectric generators were excluded unless they contained transferable inventory data for thermoelectric materials or module manufacturing processes.

2.4. Screening and Reporting

All records retrieved from database searches were imported using reference management software (Zotero 9.0) and duplicates were manually removed [15]. The remaining records were exported to Rayyan for title and abstract screening [16]. The screening process followed a two-stage procedure. Records were initially assessed by title and abstract against the predefined eligibility criteria and classified as included, excluded or uncertain. Records classified as uncertain were retained for full-text assessment when the title or abstract suggested possible relevance.

A total of 544 records were identified: 420 from Scopus, 100 from Web of Science Core Collection, and 24 from IEEE Xplore. After removing 90 duplicate records, 454 records were retained for title and abstract screening. During this stage, 446 records were excluded for failing to meet the eligibility criteria. The remaining eight documents (reports, according to PRISMA 2020 nomenclature) were retrieved and assessed in full text. One report was finally excluded, as it included life cycle-related terminology in the title and abstract but did not actually report an LCA, LCI, LCIA, carbon footprint or environmental assessment. Consequently, seven studies were included in the qualitative synthesis. The selection process was documented using the PRISMA 2020 reporting flow diagram, as represented in Figure 1.

The screening process focused on extracting methodological information relevant to this research. For each included study, the following elements were considered when available: technology, materials, function, functional unit, system boundaries, software, database, LCIA method, impact categories, use phase, end-of-life, and sensitivity analysis. The objective was to identify methodological gaps in previous environmental assessments of thermoelectric systems and to support the definition of the foreground inventory model in the present study.

2.5. Data Extraction

Data extraction was organised into two complementary levels of methodological information. Table 1 reports the goal and scope of the retained studies, including the thermoelectric technology or material system assessed, its function, and the functional unit and system boundaries selected. Table 2 complements the information by summarising the modelling approach.

Table 2 summarises information on the software and databases used, the LCIA methods and impact categories selected, the inclusion of use phase and end-of-life, and whether sensitivity or scenario analysis was reported. The extracted studies show marked methodological heterogeneity. First, the object under assessment is not uniform in the literature. Some studies assess only the product system, whereas others evaluate complete cooling, heating or refrigeration devices that include auxiliary components such as heat exchangers, fans, photovoltaic panels, batteries, water circuits, control devices, or phase change materi-

als. As a result, the environmental impacts reported in each study do not always refer to the same technical level. In some cases, the results primarily represent the thermoelectric module production, whereas in others, they represent the operation of a complete device or building service system.

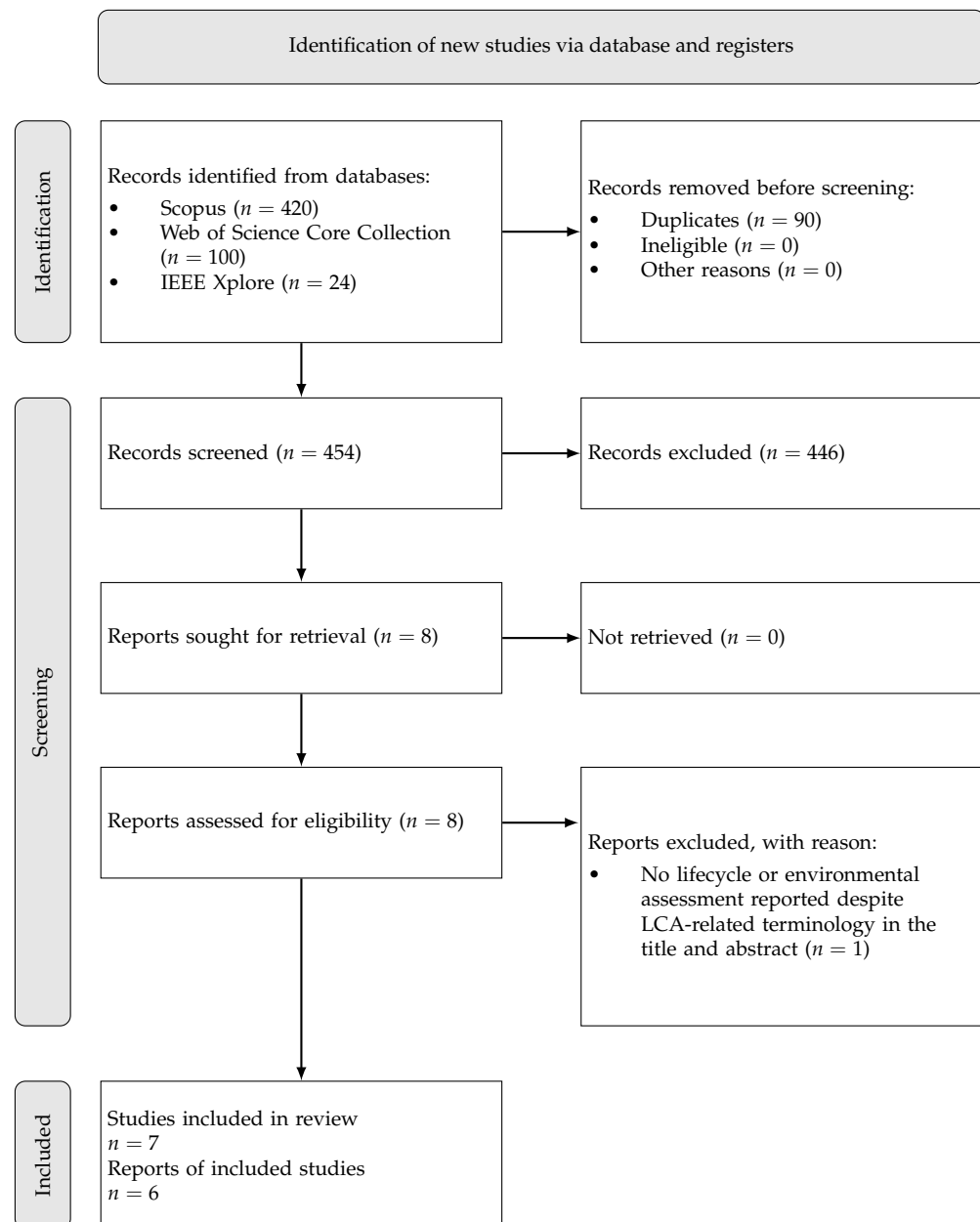


Figure 1. PRISMA 2020 flow diagram for the literature screening and study selection process [14].

Second, the declared functions and functional units differ considerably. The reviewed studies use energy-related units, such as emissions per Wh of cooling or heating, single-product units such as a single thermoelectric cooler or refrigerator, or the performance of an entire building system over 10 or 25 years. In addition, some studies report results without formally defining a functional unit. This is particularly relevant because the functional unit determines the reference flow, the scaling of the inventory, and the interpretation of the electricity demand in the use phase. Therefore, results expressed per unit of delivered cooling energy cannot be directly compared with results expressed per device, per building or per lifetime without additional harmonisation.

Table 1. Goal and scope of LCA studies on thermoelectric cooling devices and materials.

Ref.	Technology/Material	Function	Functional Unit	System Boundary
[17]	Thermoelectric cooling system exemplified by an electric water cooler	Solid-state cooling and resource	Solid-state cooling system: TEC module/water heating system and material input per service unit (MIPS)	Production and assembly of the TEC module, water cooler fabrication, use, maintenance and recycling
[18]	TEC cooling and heating system with a cold-side finned heat sink/fan and hot-side water heat exchanger	Cooling of a chamber and heat recovery from hot-water preparation	Reported as g CO ₂ -eq/Wh; effectively 1 W h of useful cooling/heating energy, although FU is not directly defined	Conceptual LCA according to ISO 14040; production and operation over 10 years; two electricity sources: EU-voltage grid and small-scale PV
[19]	PV-powered TEC module system with heat recovery; TEC module, PV, panel, charge controller, battery and alternative grid/lab supply scenarios	Air cooling with heat recovery for water heating	1 W h of cooling or heating	Production, predicted servicing energy performance/use and final disposal; six 10-year scenarios with 3 or 4 h/day operation and direct PV, mixed PV/battery, or grid supply; packaging and transport excluded
[20]	Thermoelectric refrigerator with phase change material	Food refrigeration/cooling storage maintains food below 5 °C and can operate without electricity during PCM discharge	Single PCM-based thermoelectric cooler with 6.84 L internal volume	Cradle-to-grave including material extraction/production, manufacturing, distribution, use and end-of-life; transport between stages included
[21] *	TEC module manufacturing; module assumed for refrigeration use	Manufacturing-stage environmental assessment of TECs; module assumed to be mounted in a refrigerator for food/pharmaceutical storage	1 MW h of cooling amount from a 47.68 g module set during a lifetime of 100,000 h; assumed $\dot{Q}_{c,max} \approx 50$ W and $P_{in} \approx 170$ W	Manufacturing process from raw /market materials to finished components: p/n-legs, alumina plates, copper tabs; Regions: France, USA, Australia, China, South Korea; manufacturing, use and transport
[22]	Solar thermoelectric HVAC system with Peltier module, two aluminium heat exchangers, two fans and PV module	Space heating and cooling of a residential house	Not stated as a conventional FU; results are reported for a typical family house and 25-year service life separated into heating and cooling modules	Cradle-to-grave: production, transport, installation, use, disposal/recycling; includes TEC module, heat sinks, fans and PV module

* Manufacturing foreground inventory is based on the BT-2/KELK module inventory developed by Iyer and Pilla [23], rather than on primary industrial data. Therefore, the results inherit assumptions from the original inventory, including process-level estimates for p/n-leg, alumina-plate and copper-tab manufacturing.

Table 2. Scope and interpretation of the LCA studies on thermoelectric cooling devices and materials.

Ref.	Software/Database	LCIA Method	Impact Categories	Use Phase?	EoL	Sensitivity Analysis?
[17]	LCA Light Tools/MIT coefficients from Wuppertal Institute	Not reported	Abiotic, biotic and water resource depletion; air and soil-related material flows; GWP; POCP; eutrophication; acidification; toxic waste creation	Conceptual yes; quantitative emphasis in production	Conceptually yes: recycling/utilisation after end-of-life appears in boundary	Yes, sensitivity to initial-data variation was analysed and GWP, PoCP and MIPS were reported as generally insensitive
[18]	LCA software not specified/ecoinvent 3.0 for electricity generation processes	Not reported	Greenhouse-gas emissions only (kg and g CO ₂ -eq)	Yes; operation dominates both scenarios	Not reported as included	No formal sensitivity analysis; comparison is mainly PV vs. grid electricity source
[19]	SimaPro v8.1/ecoinvent database	IPCC	Greenhouse-gas emissions/GWP100	Yes	Yes; final disposal included for TEC module	Yes, scenario analysis and lifetime extension analysis; extending expected lifetime to 20 years reduces GWP mode in PV/battery scenarios than in grid scenarios
[20]	SimaPro/No database specified	TRACI 2.1 v1.02	Ozone depletion, global warming, smog, acidification, eutrophication, carcinogenic and non-carcinogenic effects, respiratory effects, ecotoxicity, fossil fuel depletion	Yes; electricity use over 15 years included	Yes; PCM is not recycled/reused, while other components are assumed recycled	No formal LCA sensitivity analysis found; appendix reports relative uncertainty for experimental sensors, not LCA parameters
[21]	openLCA v2.0.3/ecoinvent v3.8	ReCiPe 2016 Midpoint	GHG emissions, HTC, terrestrial ecotoxicity, fresh water ecotoxicity, mineral resource scarcity, fossil resource scarcity	Article: no, manufacturing focus; supplementary material: includes a use process comparison, where use emissions exceed 99% across categories/regions	No, in the manufacturing boundary	Scenario/prospective analysis of South Korean 2030 grid mix; not a conventional parameter sensitivity analysis
[22]	Not reported; appears to use literature-based carbon footprint factors and building energy calculations	Carbon footprint accounts; no LCIA method beyond CO ₂ -eq reporting and ISO 14040 reference	CO ₂ /carbon footprint only	Yes; operation phase calculates from annual/monthly heating and cooling needs	Yes; EoL is included as literature-estimated contribution of 200–500 kg CO ₂ -eq	No formal sensitivity analysis reported; comparative scenarios include electricity from grid, PV and heat-pump systems

Third, the system boundaries differ in both breadth and detail. The studies range from manufacturing-focused assessments, in which the analysis is limited to the production of thermoelectric legs, alumina plates and copper tabs, to cradle-to-grave studies that include material extraction, manufacturing, distribution, use phase and end-of-life. The inclusion of the use phase is especially relevant as thermoelectric cooling devices typically require electricity during operation and several studies identify this stage as a major contributor to climate-related impacts. Conversely, when the assessment is restricted to manufacturing, the results primarily highlight process electricity demand, material production and component manufacturing. The inclusion of end-of-life is also inconsistent: some studies model recycling or disposal, while others exclude this stage or include it only as a simplified estimate.

Fourth, the LCIA scope is uneven. Several studies are limited to Global Warming Potential (GWP) or carbon footprint, while others include a broader set of midpoint categories such as toxicity, ecotoxicity, mineral resource scarcity and fossil resource scarcity. This difference affects the interpretation phase. A single climate indicator can capture the importance of electricity consumption, but it does not represent the potential burdens associated with scarce elements used in thermoelectric legs, nor the impacts linked to ceramic plate production, soldering materials or auxiliary components. Multi-category LCIA studies therefore provide a broader environmental diagnosis, although they are still affected by data availability and modelling assumptions.

Overall, Tables 1 and 2 indicate that the retained studies should not be interpreted as directly comparable numerical results. Instead, they provide complementary methodological insights into how thermoelectric cooling devices and materials have been modelled in LCA. The comparison is most useful for identifying recurring modelling approaches, the influence of system boundaries, the role of electricity supply and the main environmental burden drivers reported across different thermoelectric applications. This methodological heterogeneity also justifies the need for clearly defined functional units, transparent system boundaries and explicit sensitivity analysis in future LCA studies of thermoelectric cooling modules.

2.6. Synthesis of Gaps

Data presented in Tables 1 and 2 show that the LCA literature on TEC devices remains methodologically fragmented. Although studies provide relevant evidence on thermoelectric modules, cooling systems, refrigeration devices and hybrid configurations, results are not directly comparable as they differ in functional unit definition, system boundary coverage, modelling approach, impact assessment scope and treatment of operational assumptions. This is consistent with the systematic review of Ref. [24], who reported that published LCAs of thermoelectric materials and devices are affected by inconsistent functional units, incomplete reporting, limited adherence to ISO 14040/14044 and insufficient methodological transparency [25,26]. These issues are particularly relevant because the standards define LCA as an assessment structured around the functional unit, with inventory and impact assessment results referred to that unit.

Therefore, the following research gaps are identified:

- Limited comparability of functional units: the reviewed studies adopt heterogeneous reference bases, including individual devices, transferred heat rates, internal storage volume, service life, vehicle operation and power output per unit area. This diversity prevents direct extrinsic comparison, as the functional unit determines the reference flow and the scaling of material and energy flows. Jamil and Holden [24] specifically identified functional unit inconsistency as a major barrier to establishing a

coherent knowledge baseline for thermoelectric LCA. This gap motivates the use of a measurable, service-based functional unit under a clearly defined operating condition.

- Insufficient harmonisation of system boundaries: the extracted studies range from manufacturing-centred assessments to complete cradle-to-grave evaluations. Some models focus only on photovoltaic panels, batteries or refrigeration enclosures. Different approaches modify the relative importance of manufacturing burdens, operational electricity demand and end-of-life processes. This gap motivates a clear distinction between manufacturing-related burdens and full life cycle burdens including use and end-of-life stages. This structure enables a clearer interpretation of whether the dominant contribution arises from material production, module assembly, auxiliary components, operational electricity consumption or end-of-life scenario.
- Incomplete representation of auxiliary electronics: in several studies, the TEC module is treated as the core technological element, while the auxiliary power electronics conversion components required for the operation are not considered, are simplified or are not disaggregated. This is a relevant limitation for low-capacity TEC systems, where power conversion components, wiring, connectors and other support elements may become non-negligible in the foreground inventory. This gap indicates the need to assess the TEC module together with the auxiliary power electronics required for operation.
- Limited parameter sensitivity analysis for critical raw materials and foreground assumptions: TEC modules use materials associated with resource scarcity, including bismuth, tellurium, antimony and copper. However, the reviewed literature often emphasises electricity mix, operational lifetime or scenario configuration, while material composition and foreground mass assumptions are examined in less detail. This is relevant as impact categories such as mineral resource scarcity can be strongly influenced by thermoelectric leg composition and the modelling of critical raw materials. This study addresses this gap by developing a transparent and comprehensive foreground LCI for the TEC module at a defined cooling operating point, with explicit reference flows, allocation options and database activities.

The identified research gaps define the methodological contribution of this work. Using a functional unit related to the system's purpose, a fixed operating condition, explicit separation of the cradle-to-gate and cradle-to-grave approaches, inclusion of auxiliary power electronics and sensitivity analysis, this study provides a robust and transparent basis for assessing the environmental impacts of thermoelectric cooling modules. The objective is to establish a reproducible and technically explicit LCA model that enables future system boundary harmonisation and comparative assessments within this application domain, rather than generalising the performance of all TEC technologies.

2.7. Research Gap and Scientific Contribution

The literature review shows that previous environmental assessments of thermoelectric cooling technologies remain heterogeneous in terms of functional units, system boundaries, foreground inventory detail, inclusion of the use phase, treatment of auxiliary components, and sensitivity analysis. Several studies address thermoelectric materials or system-level applications, but fewer provide a transparent connection between a defined cooling service, the physical inventory of a commercial TEC module, the operating point, and the resulting cradle-to-gate and cradle-to-grave environmental burdens.

The contribution of the present study is therefore not limited to applying LCA to a selected TEC module. The study develops an explicit foreground inventory for a commercial thermoelectric cooling module, including semiconductor legs, alumina substrates, copper interconnections, assembly-related materials and dedicated auxiliary power electronics. This

inventory is linked to a service-based functional unit, defined as 1 kW h of useful cooling delivered on the cold side under a specified reference operating condition. The assessment then separates manufacturing-related burdens from use-phase and end-of-life contributions, allowing the relative importance of material production, component manufacturing, electricity demand and lifetime to be interpreted consistently. The sensitivity analysis further evaluates how key modelling assumptions affect the environmental interpretation.

In this context, 1 kW h of useful cooling delivered on the cold side was selected as the functional unit because it expresses the function of the TEC system in terms of delivered cooling service, rather than device count, module mass or electrical input. This basis allows manufacturing, use-phase and end-of-life burdens to be normalised to a common useful cooling output, while preserving the link between the physical inventory, the operating point and the reference flow. It also improves comparability with previous LCA studies of thermoelectric cooling and heating systems that report impacts per unit of delivered thermal energy.

3. Materials and Methods

This section presents the goal and scope, functional unit and reference flow of the system under study, describes the production processes modelled in Activity Browser/Brightway 2.0, the background database used and the impact assessment methods selected.

3.1. Goal and Scope

The LCA study was conducted in accordance with the ISO 14040/14044 guidelines [25,26]. The main goal of the study is to quantify the environmental impacts of the production and operation of a commercial thermoelectric module under a fixed reference cooling condition. The assessment also identifies the main environmental hotspots across material production, module and auxiliary electronics manufacture, module assembly, use phase and end-of-life treatment.

The intended application of the study is the environmental assessment of TEC modules as solid-state cooling devices, with an emphasis on the contribution of materials, manufacturing processes, auxiliary electronics, operating efficiency and service life.

3.2. Functional Unit

The functional unit was defined as 1 kW h of useful cooling delivered on the cold side of the thermoelectric module. The reference operating condition was set at a cooling capacity of 0.74 W and a temperature lift of 11.94 K, derived from the manufacturer's performance data. This operating condition was selected as a reproducible reference point located near a high coefficient of performance (COP) operating region of the assessed module, rather than as a representative condition for all possible thermoelectric cooling applications.

3.3. Reference Flow

According to ISO 14040/14044, the functional unit quantifies the performance delivered by the product system and the reference flow defines the amount of product system required to fulfil the function expressed by the functional unit [25,26]. The operating time required to deliver the functional unit was calculated using the module's useful cooling capacity (Equation (2)).

$$t_{\text{FU}} = \frac{E_{\text{c,FU}}}{\dot{Q}_{\text{c}}} = \frac{1.000 \text{ kW h}}{0.7400 \text{ W}} = 1351 \text{ h} \quad (2)$$

Therefore, the functional unit corresponds to 1351 h of continuous module operation at the defined cooling capacity and temperature lift. This operating period serves as the

basis for scaling both the manufacturing burden and the electricity consumption associated with providing useful cooling.

For the manufacturing and end-of-life stages, the reference flow of the TEC module was calculated as the fraction of the module's lifetime required to provide the functional unit as represented in Equation (3), where $N_{\text{TEC,FU}}$ is the number of thermoelectric modules assigned to the functional unit and L_{TEC} is the assumed operational lifetime of one module, expressed in hours.

$$N_{\text{TEC,FU}} = \frac{t_{\text{FU}}}{L_{\text{TEC}}} \quad (3)$$

A baseline operational lifetime of $L_{\text{TEC}} = 200,000$ h was assumed for the thermoelectric module. This value is consistent with reliability information reported for commercial TEC modules [27,28]. The same lifetime was assigned to the dedicated auxiliary power electronics as AC-DC and DC-DC converter modules are modelled as integrated support components required for the operation of the system. This assumption is considered appropriate for the baseline scenario because commercial power supply modules are commonly characterised by Mean Time Between Failures (MTBF) in the range of 100,000 h to 400,000 h, depending on operation temperature, load and application environment [29]. Nevertheless, because MTBF is not equivalent to service life, the influence of auxiliary power electronics was evaluated separately in the sensitivity analysis.

For the baseline lifetime assumption of $L_{\text{TEC}} = 200,000$ h, the manufacturing reference flow is given by Equation (4):

$$N_{\text{TEC,FU}} = \frac{1351 \text{ h}}{200000 \text{ h}} = 6.757 \times 10^{-3} \text{ module FU}^{-1} \quad (4)$$

The same reference flow was applied to the dedicated auxiliary power electronics, because the AC-DC and DC-DC converter modules are assumed to have the same operational lifetime as the TEC module. Consequently, the cradle-to-gate hardware input is the complete cooling hardware assembly, including the thermoelectric module and the associated power conversion components.

In the cradle-to-grave approach, the electricity consumed during operation was calculated independently from the manufacturing reference flow. The electrical power required by the TEC module was obtained from the voltage and current at the selected operating point, corresponding to the useful cooling power of 0.74 W at the defined temperature lift (Equation (5)).

$$P_{\text{TEC}} = V_{\text{TEC}} \cdot I_{\text{TEC}} = 1.432 \text{ V} \cdot 0.1682 \text{ A} = 0.2408 \text{ W} \quad (5)$$

At this operational point, the COP of the thermoelectric module is given by Equation (6).

$$\text{COP}_{\text{TEC}} = \frac{\dot{Q}_c}{P_{el}} = \frac{0.7400 \text{ W}}{0.2409 \text{ W}} = 3.073 \quad (6)$$

Since the module is supplied through dedicated AC-DC and DC-DC power conversion stages, the AC input power is therefore determined by accounting for the conversion efficiencies of the two auxiliary power electronic components (Equation (7)).

$$P_{\text{el,in}} = \frac{P_{\text{TEC}}}{\eta_{\text{AC-DC}} \cdot \eta_{\text{DC-DC}}} \quad (7)$$

The efficiencies of the RECOM AC-DC and Murata DC-DC converter modules are $\eta_{\text{AC-DC}} = 0.74$ and $\eta_{\text{DC-DC}} = 0.93$, respectively. Accordingly, the total power consumed is given by Equation (8).

$$P_{\text{el, in}} = \frac{0.2408}{0.7400 \cdot 0.9300} = 0.3500 \text{ W} \quad (8)$$

The operational electricity demand associated with the functional unit is given as a function of the input electrical power and the operating time to deliver 1 kW h of useful cooling (Equation (9)):

$$E_{\text{el, FU}} = P_{\text{el, in}} \cdot t_{\text{FU}} = 0.3500 \text{ W} \cdot 1351 \text{ h} = 0.4729 \text{ kW h FU}^{-1} \quad (9)$$

Therefore, the process delivering the functional unit was modelled with an operational electricity input of 0.4729 kW h of low-voltage electricity per kW h of useful cooling. This input of electricity already accounts for the conversion losses of the dedicated auxiliary power electronics.

The auxiliary power electronics were modelled as representative dedicated conversion stages required to supply the TEC module, rather than as a manufacturer-validated power supply design for the selected device. The RECOM AC-DC and Murata DC-DC modules were selected as commercially available low-power converter modules compatible with the voltage and power range of the reference operating point. Their nominal conversion efficiencies were used to estimate the AC input electricity demand. No-load consumption, standby losses, control circuitry overhead, converter oversizing and load-dependent efficiency variation were not modelled explicitly. This simplification is relevant for low-power TEC operation, where such losses may become non-negligible. Therefore, the operational electricity demand should be interpreted as a nominal-efficiency estimate for the selected reference point.

3.4. System Boundaries

Two system boundaries were defined according to the goal and scope of the study: (i) cradle-to-gate and (ii) cradle-to-grave. Cradle-to-gate includes raw material acquisition, production of thermoelectric materials and components, module assembly, lead wires and insulation, and production of dedicated power supply hardware. Cradle-to-grave extends the cradle-to-gate model by including the use phase, transport and the end-of-life treatment of the module and associated power supply components.

Cradle-to-Gate

The foreground processes included in the cradle-to-gate assessment of the TEC module are shown in Figure 2. The cradle-to-gate boundary was defined to quantify the manufacturing burden of the amount of hardware considered for the functional unit.

3.5. Cradle-to-Grave

The cradle-to-grave boundary extends the cradle-to-gate model by including the distribution, use and end-of-life stages of the TEC system. Therefore, it includes all foreground and background processes considered in the cradle-to-gate boundary, together with transport from the assumed manufacturing location to the European use context, operational electricity consumption, transport to end-of-life treatment, and waste electrical and electronic equipment (WEEE) material recovery.

Distribution was modelled as a combined freight transport route, including a transoceanic container ship route and road transport by lorry. The usage was represented by the electricity required to supply the TEC module and the dedicated auxiliary power electronics needed to deliver 1 kW h of useful cooling. In the baseline model, this electricity input was supplied by the European low voltage electricity mix. At the end-of-life, the

TEC module and its associated power electronics are assumed to be transported to a WEEE treatment facility for subsequent processing.

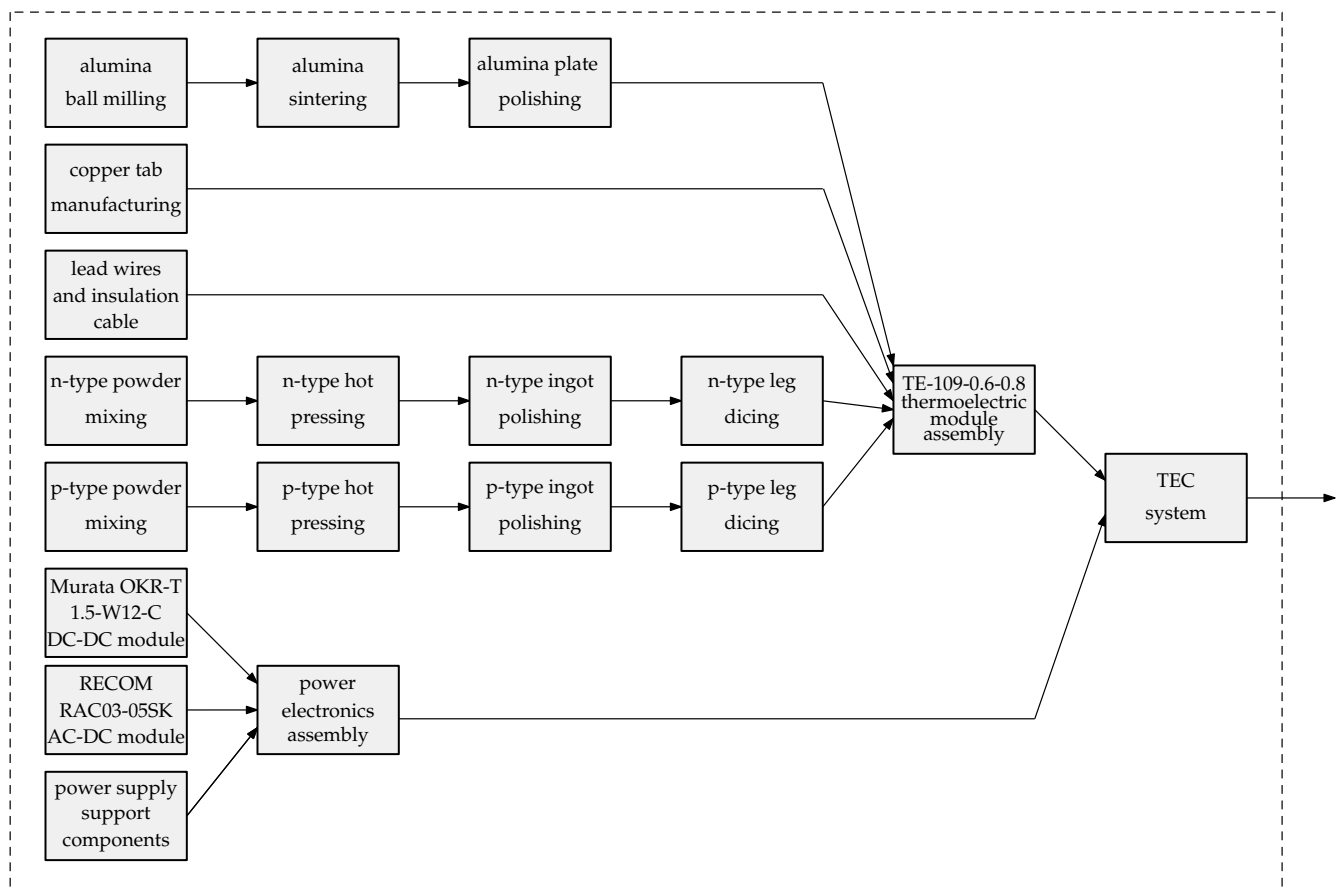


Figure 2. Foreground processes in the cradle-to-gate assessment of the TEC system.

This boundary represents the complete life cycle impacts of the TEC hardware system and distinguishes the relative contributions of manufacturing, transport, use-phase electricity and end-of-life treatment.

3.6. Foreground Inventory and Transport Considerations

A foreground inventory was developed for the thermoelectric module TE Technology, model TE-109-0.6-0.8 [30]. The assembled model comprises p-type and n-type thermoelectric legs, alumina plates and copper tabs, soft solder, lead wires and electrical insulation [23]. These components represent the material structure required to convert the electrical input into the useful cooling service defined by the functional unit. Module assembly links component manufacturing processes with the final thermoelectric module output.

The foreground inventory should be interpreted as a transparent reconstructed inventory rather than as a directly validated manufacturer bill of materials. No primary manufacturer bill of materials or teardown dataset was available for the selected commercial module. The inventory was therefore constructed from manufacturer-reported module information, published thermoelectric module inventory data and proxy datasets for materials, component manufacturing and auxiliary electronics where direct datasets were unavailable. Where component-specific yield or scrap data were not available, this was explicitly treated as a modelling limitation. The cradle-to-gate contribution analysis should therefore be interpreted as a source-traceable engineering reconstruction of the selected TEC system, rather than as an independently validated manufacturer inventory.

Transport was included as the foreground model assumes manufacturing of the TEC module and auxiliary electronics in China, use in the European context, and end-of-life treatment through a WEEE treatment process.

The manufacturing stage considers regional transportation. The supply chain transportation followed the Product Environmental Footprint Category Rules (PEFCRs) assumption for supply chains outside Europe, considering 1000 km by heavy-duty road freight and 18,000 km by transoceanic container ship [31].

End-of-life transport to WEEE treatment was included in the study. A European road transport distance of 150 km was assumed for transport facilities, following the default end-of-life transport distance recommended in LCA guidance for products sent to recycle [32–34]. This assumption follows the fact that transport distances can materially influence the environmental indicators of waste management and recycling systems [34].

3.7. Implementation of Foreground and Background Processes

The foreground LCI was implemented in Activity Browser (version 2.11.2), using the Brightway 2 framework (version 2.4.6) for the LCA modelling and calculation [35,36].

Activity Browser was used to structure foreground unit processes, link intermediate flows between module manufacturing stages and connect foreground exchanges to background datasets. The foreground systems included the thermoelectric module assembly, p-type and n-type leg manufacturing, copper tab production, external electrical connections and auxiliary power supply electronics.

The background processes were obtained from the Ecoinvent 3.9 database using allocation and cut-off by classification system model [37]. This database was used for upstream material supply, energy carriers, industrial gases, chemicals, and market processes. The cut-off system model was selected because it is consistent with an attributional modelling approach and with the recycled-content logic used in the selected database system model. Under this approach, recyclable secondary materials enter subsequent product systems without the full burden of primary production, while waste treatment remains assigned to the product system generating the waste, unless otherwise specified by the database structure.

The selection of background datasets followed technological, geographical, and temporal representativeness criteria where possible. Global and Rest-of-the-World market datasets were used when the foreground process was not assigned to a specific production region or when no more specific dataset was available and the chosen one is representative of the processes.

For the foreground processes that consume electricity, the electricity market was selected according to the geographical modelling assumption defined in the goal and scope of the study. Economic allocation was used only when a direct process was unavailable. These choices were documented in the foreground inventory to maintain transparency regarding data limitations and modelling assumptions.

Data quality was considered in terms of geographical, technological and temporal representativeness. Geographically, foreground manufacturing was modelled according to the assumed production location in China, while use-phase electricity and end-of-life processes were represented in the European context. Technologically, datasets were selected to match the closest available material, energy, transport and waste treatment processes. Proxy datasets were used only when direct datasets for specific TEC components or auxiliary electronics were unavailable. The model used ecoinvent 3.9 for background processes, together with the most recent available manufacturer and literature information for the foreground inventory. These choices provide a consistent inventory basis for the analysed case study, although the absence of primary manufacturer data for some components remains a source of uncertainty.

3.8. Life Cycle Impact Assessment Methods

Life cycle impact assessment was performed using the ReCiPe 2016 midpoint method [38]. The midpoint level was selected since it provides impact category indicators closer to the underlying inventory flows than endpoint aggregation, reducing the additional value choices associated with damage-level modelling. The selected method was applied consistently to all foreground and background processes, allowing the contributions of semiconductor materials, ceramic substrates, metallic interconnections, auxiliary electronics, electricity demand and manufacturing waste to be evaluated on a common impact assessment basis.

The LCIA results were calculated as characterised midpoint indicators. Normalisation, grouping, and weighting were not applied in the main results because the objective was to compare contribution patterns across life cycle stages and inventory components without aggregating results into a single environmental score. This is consistent with the ISO 14040 and ISO 14044 requirement to document impact assessment choices and avoid unsupported aggregation where value choices may affect interpretation [25,26]. The characterised results were subsequently used for contribution analysis and sensitivity analysis of the main foreground assumptions.

Although the ReCiPe 2016 midpoint method includes a wider set of impact categories, three categories were prioritised for detailed reporting and discussion: climate change, fossil resource scarcity and mineral resource scarcity. These categories were selected because they are directly aligned with the main mechanisms expected to govern the environmental profile of the assessed TEC system. Climate change and fossil resource scarcity capture the influence of electricity consumption, manufacturing and background electricity supply, while mineral resource scarcity reflects the relevance of thermoelectric materials, metallic interconnections and auxiliary electronic components. The selection of these categories was therefore intended to focus the interpretation on the most relevant mechanisms on energy and resources for the analysed case study. This prioritisation does not imply that other ReCiPe midpoint categories are irrelevant, but rather that they were not the focus of the main contribution analysis.

4. Results and Discussion

This section presents the environmental performance of the TEC system, followed by a component-level analysis of the cradle-to-gate impacts. The robustness of the results is examined through sensitivity analysis addressing the system lifetime, electricity mix, bismuth economic allocation and auxiliary electronics. The main contribution patterns are subsequently interpreted and compared with previous LCA studies, considering their implications and methodological limitations.

4.1. Cradle-to-Grave Life Cycle Impacts

Tables 3 and 4 report the cradle-to-grave LCIA impacts of the TEC system for the selected ReCiPe 2016 midpoint categories. Table 3 presents the absolute results per functional unit, including the scaled manufacturing contribution, transport contribution, use-phase electricity consumption, end-of-life contribution, and total cradle-to-grave result.

Table 4 reports the corresponding relative contribution of manufacturing, transport, use-phase electricity and end-of-life treatment to each impact category. The end-of-life stage was modelled as transport to WEEE material recovery. Therefore, negative end-of-life contributions represent recovery credits associated with the selected treatment dataset.

Table 3. Cradle-to-grave life cycle impact assessment results for the TEC system, reported per functional unit of 1 kW h of useful cooling.

Impact Category	Unit	Manufacturing	Transport	Use Phase	End-of-Life	Total
Climate change	kg CO ₂ -eq	2.680×10^{-2}	7.368×10^{-5}	1.925×10^{-1}	-7.563×10^{-6}	2.194×10^{-1}
Fossil resource scarcity	kg oil-eq	6.079×10^{-3}	2.174×10^{-5}	4.657×10^{-2}	-1.329×10^{-6}	5.267×10^{-2}
Mineral resource scarcity	kg Cu-eq	9.417×10^{-4}	1.116×10^{-6}	1.527×10^{-3}	-1.010×10^{-8}	2.470×10^{-3}

Note: Transport includes freight from manufacturing in China to the European use context. The end-of-life stage includes transport of the complete discarded TEC hardware system over 150 km to WEEE treatment and subsequent WEEE material recovery.

Table 4. Relative contribution of manufacturing, transport, use-phase and end-of-life treatment to the total cradle-to-grave impact of the TEC system per kW h of useful cooling.

Impact Category	Unit	Manufacturing (%)	Transport (%)	Use Phase (%)	End-of-Life (%)
Climate Change	kg CO ₂ -eq	12.21	3.358×10^{-2}	87.75	-3.447×10^{-3}
Fossil resource scarcity	kg oil-eq	11.54	4.127×10^{-2}	88.42	-2.523×10^{-3}
Mineral resource scarcity	kg Cu-eq	38.12	4.516×10^{-2}	61.83	-4.090×10^{-3}

Note: Percentages were calculated relative to the total cradle-to-grave result for each ReCiPe 2016 midpoint category. Negative end-of-life shares indicate credits associated with WEEE recovery. Transport refers to freight from China (manufacturing) to Europe (use phase).

The relative contribution impacts confirms that use-phase electricity is the dominant contributor to the cradle-to-grave results for the selected ReCiPe 2016 midpoint categories considered [38]. Its contribution ranged from 61.83% for mineral resource scarcity to 88.42% for fossil resource scarcity. Climate change was also strongly dominated by operation, with the use phase representing 87.8% of the total result, whereas manufacturing represented 12.21%. Transport had a negligible contribution in all three categories, remaining below 0.05% of the total cradle-to-grave impact. The end-of-life contribution was also very small and negative, reflecting recovery-related credits associated with the selected WEEE material recovery treatment process.

This contribution pattern is consistent with the functional unit adopted in the study: operational electricity scales directly with the delivered cooling service, while the manufacturing burden is distributed over the assumed hardware lifetime. The relatively higher manufacturing share observed for mineral resource scarcity indicates that material production and hardware components remain relevant for impacts related to the resources, when the operation dominates the overall cradle-to-grave impacts.

Similar use-phase relevance has been reported in LCA studies and reviews of electrical and electronic products, where operational electricity demand can govern the total environmental impacts when devices consume electricity throughout their service life [39]. The use of ReCiPe 2016 midpoint indicators also requires category-specific interpretation, because each percentage refers to a different environmental mechanism and should not be compared across categories as a single aggregate score [38].

4.2. Cradle-to-Gate Contribution by Component

The cradle-to-gate results were disaggregated by component group to identify the main physical contributors to the manufacturing burden of the TEC hardware system. This contribution analysis complements the life cycle stage results by resolving the foreground hardware inventory into thermoelectric legs, alumina ceramic plates, copper tabs, solder and nickel metallisation, lead wires and insulation, power supply support components, the RECOM AC-DC module and the Murata DC-DC converter. The results in Figure 3 are reported as relative contributions to the total cradle-to-gate impact of one hardware system

for the selected ReCiPe 2016 midpoint categories: climate change, fossil resource scarcity and mineral resource scarcity.

The contribution impacts show that the alumina ceramic plates are the main contributor to climate change and fossil resource scarcity, representing approximately 46.6% and 41.3% of cradle-to-gate impact, respectively. The RECOM AC-DC module is the second-largest contributor in these two categories, accounting for approximately 25.5% of climate change and 28.6% of fossil resource scarcity, followed by the Murata DC-DC converter and the power supply support components. In contrast, mineral resource scarcity is dominated by the auxiliary power electronics, particularly the RECOM AC-DC module, which contributes approximately 53.5%, followed by the power supply support components with 22.3% and the Murata DC-DC converter with 19.5%. This result indicates that the environmental relevance of the auxiliary electronics is especially pronounced for the impacts related to the resources. The thermoelectric legs, copper tabs, solder and nickel metallisation, lead wires and insulation make comparatively small contributions in the selected categories. This does not imply that these components are environmentally irrelevant in absolute terms, but rather that, within the present foreground models and selected midpoint indicators, their contribution is reduced compared to that of the alumina substrates and the dedicated power conversion components. Overall, the results at the component level show that cradle-to-gate impacts are not governed only by the thermoelectric semiconductor materials, but also by ceramic substrates and auxiliary power electronics.

The applicability of these contribution patterns to other TEC modules should be interpreted cautiously. For modules with similar architecture, based on ceramic substrates, metallic interconnections and dedicated power conversion components, alumina substrates and auxiliary electronics may remain relevant contributors to the cradle-to-gate boundary environmental impacts. However, their relative importance may change with module capacity, substrate area and thickness, thermoelectric leg composition, metallisation route, manufacturing technology and the degree of integration of the power electronics. Modules with larger cooling capacity or alternative converter architectures may reduce the relative contribution of auxiliary electronics, whereas different ceramic materials or semiconductor compositions may shift the dominant manufacturing hotspots. Therefore, the component-level contribution pattern identified here should be interpreted as specific to the assessed commercial module and as indicative of relevant mechanisms, rather than as directly transferable to all TEC technologies.

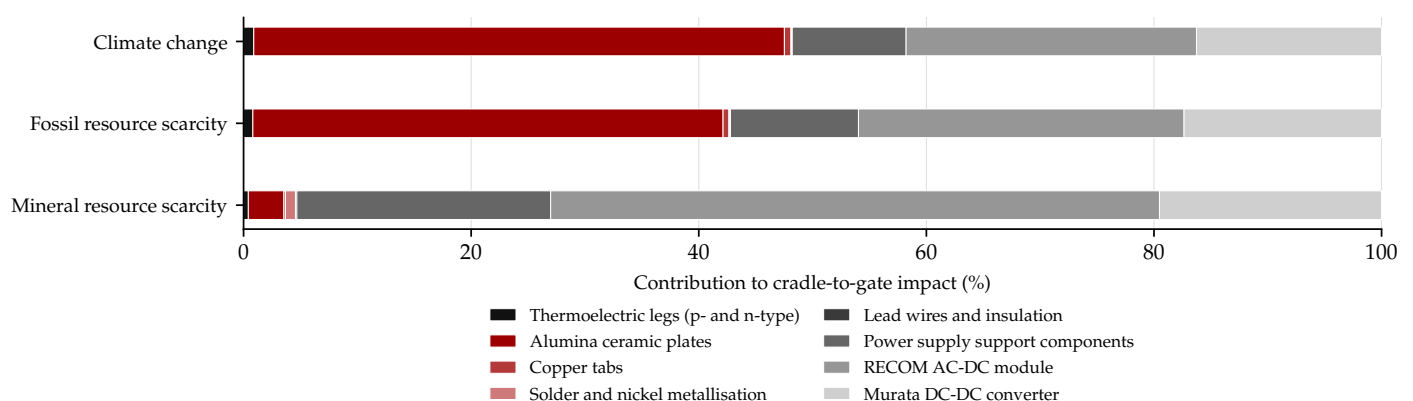


Figure 3. Cradle-to-gate contribution by component group for the TEC hardware system, reported for the selected ReCiPe 2016 midpoint categories.

For mineral resource scarcity, Figure 3 supports an interpretation at the component and material group level rather than a validated ranking by individual metal. The mineral resource scarcity contribution is dominated by the auxiliary power electronics, namely the

power supply support components, the RECOM AC-DC module and the Murata DC-DC converter. In contrast, the thermoelectric legs, copper tabs, solder and nickel metallisation make smaller contributions in the selected model. This indicates that, for the assessed TEC hardware system, mineral resource scarcity is driven mainly by the material requirements embedded in the electronic conversion hardware and support components, rather than by the thermoelectric semiconductor inventory alone. A more detailed attribution to individual metals would require a manufacturer bill of materials or more disaggregated datasets for the converter modules and printed circuit components. Therefore, the mineral resource scarcity result is interpreted here at component and material group level, and not as a validated ranking of individual metals.

4.3. Sensitivity Analysis

A sensitivity analysis was performed to evaluate the robustness of the baseline results with respect to the main modelling assumptions affecting reference flow, background electricity supply, critical-material proxy modelling, and auxiliary power electronics. The reference operating condition was kept fixed in all scenarios, with the useful cooling demand and temperature lift unchanged. Therefore, the electrical input during operation was not varied independently, because such a variation would imply a different operating point and would no longer represent the same functional performance. Sensitivity analysis was instead defined to test modelling choices and parameter assumptions while preserving the operating conditions and the same functional unit (Table 5).

Table 5. Selected parameters for sensitivity analysis.

Parameter	Alternatives Considered
Lifetime	Lifetime of 200,000 h, corresponding to the baseline hardware reference flow (reference) Lifetime of 100,000 h, affecting the hardware reference flow per kW h of useful cooling Lifetime of 50,000 h, affecting the hardware reference flow per kW h of useful cooling
Electricity mix	Europe low-voltage electricity supply for the use phase (reference) Global low-voltage electricity supply for the use phase
Bismuth proxy	0.02 kg lead per kg Bi as the economic allocation proxy used for bismuth production (reference) 0.01 kg lead per kg Bi as the economic allocation proxy used for bismuth production 0.03 kg lead per kg Bi as the economic allocation proxy used for bismuth production
Auxiliary power electronics	Auxiliary power electronics included (reference) Auxiliary power electronics excluded

The following subsections analyse the influence of each sensitivity scenario on the LCIA results and compare the corresponding variations with the baseline scenario.

4.3.1. Lifetime

The lifetime sensitivity analysis shown in Figure 4 indicates that reducing the assumed TEC service life increases all selected ReCiPe 2016 midpoint results relative to the 200,000 h baseline.

The 100,000 h scenario increases the results by approximately 11.6 % for fossil resource scarcity, 12.2 % for climate change and 38.2 % for mineral resource scarcity. The 50,000 h scenario produces larger increases, corresponding to approximately 34.7 % for fossil resource scarcity, 36.7 % for climate change and 114.5 % for mineral resource scarcity. This trend reflects the higher allocation of module manufacture, auxiliary electronics and end-of-life burdens to the same functional unit when the service life is shortened [25,26]. The largest variation occurs for mineral scarcity, indicating that the lifetime assumption particularly affects the contribution pathways related to material and electronics, whereas categories

more strongly governed by use-phase electricity show a lower relative sensitivity to the service life.

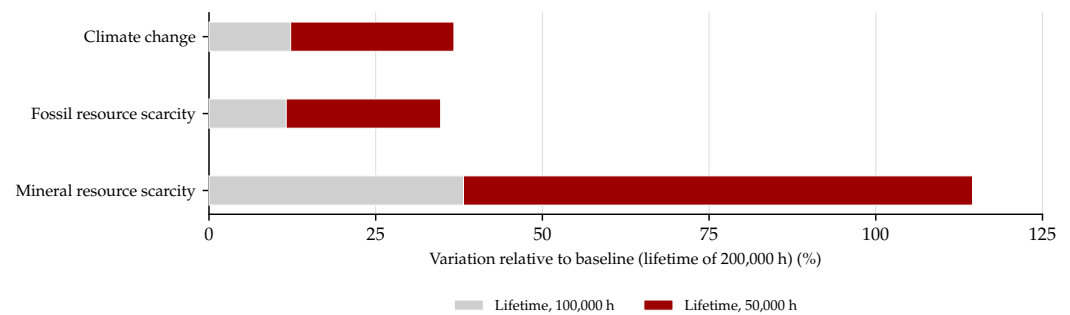


Figure 4. Comparison of the ReCiPe 2016 midpoint results for the TEC lifetime sensitivity scenarios of 50,000 h and 100,000 h relative to the 200,000 h baseline.

4.3.2. Electricity Mix

The electricity mix sensitivity results shown in Figure 5 indicate that replacing the baseline European electricity mix with a global electricity mix increases all selected ReCiPe 2016 midpoint indicators. The increase is particularly pronounced for climate change and fossil resource scarcity, whereas mineral resource scarcity is only marginally affected.

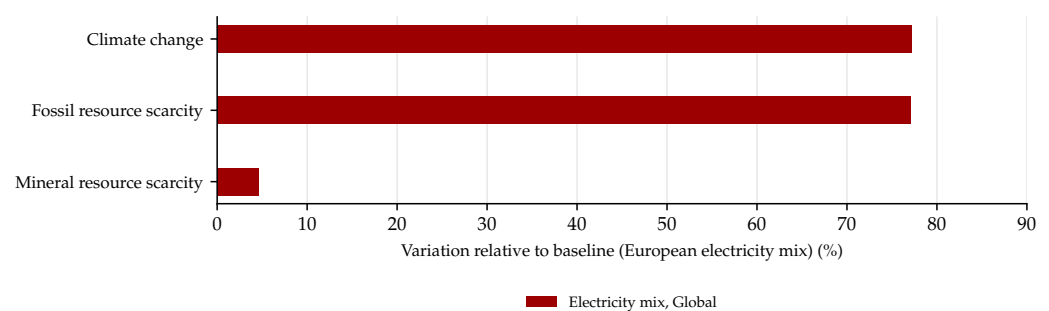


Figure 5. Variation in the selected ReCiPe 2016 midpoint results for the TEC electricity mix sensitivity scenario using a global (GLO) electricity mix relative to the European (RER) electricity baseline.

The magnitude of the sensitivity response differs among impact categories as the electricity mix affects only the use-phase, while the remaining LCI remains unchanged. Consequently, the stronger variations observed for climate change and fossil resource scarcity indicate greater sensitivity to the electricity mix, whereas the limited variation in mineral resource scarcity suggests that this indicator is governed by other life cycle stages. The selection of geographical electricity market is therefore an influential modelling parameter, although its relevance depends on the impact category considered.

4.3.3. Bismuth Economic Allocation

The bismuth proxy sensitivity results shown in Figure 6 indicate that varying the proxy from 0.01 to 0.03 kg lead per kg Bi has a negligible effect on overall LCA profile relative to the 0.02 kg baseline.

The response was approximately symmetrical as the economic allocation proxy was varied by the same amount below and above the baseline. Mineral resource scarcity exhibits the greatest relative sensitivity, although its variation remains below 0.001%, while the changes in climate change and fossil resource scarcity are substantially lower. Therefore, within the tested range and for the three selected ReCiPe 2016 midpoint categories, the economic allocation proxy for bismuth production did not materially influence the reported LCIA results. This result should not be interpreted as a validation of the proxy itself, but

only as an indication that the selected indicators are relatively insensitive to this modelling assumption under the conditions assessed.

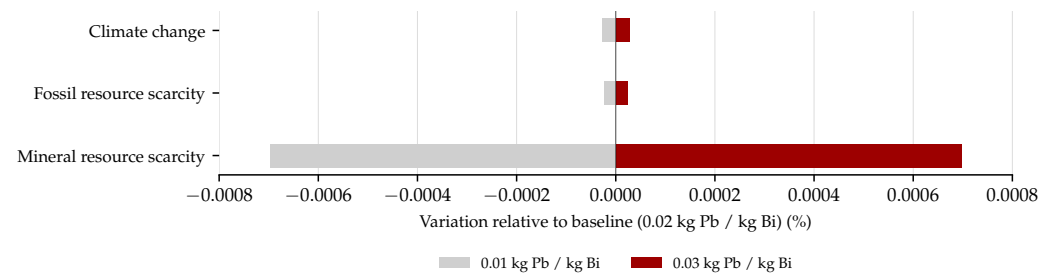


Figure 6. Comparison of the ReCiPe 2016 midpoint results for the TEC bismuth economic allocation sensitivity scenarios.

4.3.4. Auxiliary Electronics

The auxiliary electronics sensitivity results represented in Figure 7 indicate that excluding the auxiliary power electronics reduces all three selected ReCiPe 2016 midpoint results relative to the baseline. Climate change and fossil resource scarcity decreased by 6.4% and 6.6%, respectively. Mineral resource scarcity decreases by 36.4%. The substantially greater response of mineral resource scarcity demonstrates the importance of auxiliary electronics in the environmental impacts of the system.

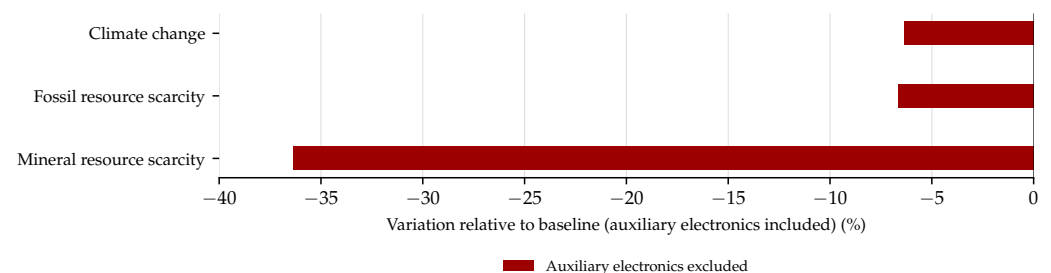


Figure 7. Variation of the selected ReCiPe 2016 midpoint results after excluding the auxiliary power electronics, relative to the baseline system in which these components are included.

The pronounced reduction in mineral resource scarcity is consistent with the material requirements and upstream supply chains associated with the AC-DC and DC-DC converter components, including copper and other metallic materials. By contrast, the similar and more limited reductions in climate change and fossil resource scarcity indicate that the auxiliary electronics are secondary contributors to these indicators. The results support the inclusion of auxiliary electronics in the foreground inventory, particularly when evaluating the environmental impacts related to material resources.

4.4. Interpretation of Dominant Contributions

The overall results demonstrated that no single process governs the environmental impacts across all system boundaries and impact categories. In the cradle-to-grave boundary, use-phase electricity is the dominant contributor, accounting for 87.8% of climate change, 88.4% of fossil resource scarcity and 61.8% of mineral resource scarcity. Manufacturing is therefore a secondary contributor to climate change and fossil resource scarcity, but remains relevant to mineral resource scarcity, representing 38.1% of the total result. Under the assumptions adopted, transport contributes less than 0.05% in all three categories, while end-of-life stage produces credits.

The cradle-to-gate boundary has a different contribution pattern. Alumina ceramic plate production is the principal contributor to climate change and fossil resource scarcity, representing approximately 46.6% of respective manufacturing impacts. The RECOM AC-DC module is the second-largest contributor in these categories, accounting for approximately 25.5% of climate change and 28.6% of fossil resource scarcity. Mineral resource scarcity is instead dominated by the auxiliary power electronics, accounting for 95.3% of the cradle-to-gate results in this category. This contribution pattern is consistent with the 38.4% reduction in the cradle-to-grave mineral resource scarcity when these components are excluded.

The sensitivity analysis reinforces this interpretation. Reducing the assumed service life increases the hardware reference flow required per functional unit and consequently increases the relative importance of manufacturing, particularly for mineral resource scarcity.

Conversely, varying the electricity mix had the most pronounced influence on climate change and fossil resource scarcity because these indicators are predominantly associated with the use phase. The negligible response to the bismuth economic allocation proxy indicates that this foreground modelling assumption is not influential within the tested range, whereas the auxiliary electronics and service life materially affect the environmental impacts related to material resources.

Overall, the dominant contributions depend on both the system boundary and the environmental mechanism represented by each midpoint indicator. Use phase electricity and its geographical mix are the principal modelling parameters for climate change and fossil resource scarcity, whereas service life and auxiliary power electronics are particularly influential for mineral resource scarcity. However, the comparatively small contribution of the thermoelectric legs in selected categories should not be interpreted as evidence that their critical raw materials are intrinsically insignificant.

The identified hotspots can be interpreted as the result of the coupling between material selection, component manufacturing and operating performance. Within the cradle-to-gate system boundary, the environmental burden is not concentrated in a single element of the TEC module. The thermoelectric legs are relevant because they rely on semiconductor compounds whose supply chains include critical elements and energy-intensive material production. Alumina substrates also contribute because they provide electrical insulation and mechanical support, while requiring ceramic manufacturing routes. Copper interconnections and metallic contact elements add burdens associated with conductive material production and component processing. In addition, the dedicated auxiliary power electronics introduce impacts related to electronic components, printed circuit materials and power conversion hardware.

This interpretation is consistent with life cycle studies of electronic products, printed wiring boards and power electronic converters, where manufacturing energy, laminate materials, electronic components and power conversion hardware are reported as relevant contributors to the embodied environmental burden [40–42]. Therefore, the cradle-to-gate hotspots reflect the material and manufacturing complexity required to obtain a functional thermoelectric cooling device, rather than the thermoelectric semiconductor alone.

In the cradle-to-grave system boundary, the dominant mechanism is the conversion of electrical input into useful cooling. Since the functional unit is defined as 1 kW h of useful cooling delivered on the cold side, the operating COP directly controls the electricity required per functional unit. The reference condition corresponds to a relatively efficient operating region for the selected module. However, any shift towards higher temperature lift or operation closer to maximum cooling capacity would reduce the COP and increase the electricity demand per unit of useful cooling. The use-phase contribution is therefore a consequence of the thermoelectric performance itself, the conversion losses of the auxiliary

power electronics and the background electricity mix. This mechanism is consistent with life cycle evidence from power electronic systems, where both manufacturing and operational performance can materially influence the final life cycle result [42].

These mechanisms also explain why material substitution alone is insufficient as an improvement strategy. Reducing the burden of semiconductor materials or ceramic substrates may improve the cradle-to-gate results, but the cradle-to-grave performance remains strongly dependent on whether the module operates in an efficient regime over a sufficiently long service life and is supplied by a low-impact electricity mix. Conversely, improving COP or reducing auxiliary conversion losses can reduce the use-phase burden, but does not eliminate the manufacturing contributions associated with thermoelectric materials, ceramic substrates, conductive interconnections and electronic support components [40,42].

4.5. Implications for Sustainable Materials and Green Engineering

The results show that the environmental performance and sustainability of cooling technologies cannot be inferred solely from their absence of refrigerants, moving parts and mechanical compressors. Under the reference operating conditions, use-phase electricity is the dominant contributor to climate change and fossil resource scarcity. The manufacturing remains particularly relevant to mineral resource scarcity. Environmental improvement strategies should therefore address both requirements of the complete functional system.

From a sustainability perspective, the contribution analysis does not support focusing exclusively on the thermoelectric semiconductor. Alumina ceramic plate production is the primary cradle-to-gate contributor to climate change and fossil resource scarcity, whereas the auxiliary power electronics dominate mineral resource scarcity. Resource-related improvement strategies should consequently evaluate lower-impact alumina supply and processing, and reduction in the resource requirements of power converters and their support components. The substitution of conventional thermoelectric materials may remain relevant due to critical raw material considerations, but its potential benefits should be assessed relative to the comparatively limited contribution of this component in the selected impact categories.

From a green engineering perspective, reducing the electricity required per unit of useful cooling offers the greatest potential to influence the cradle-to-grave climate change and fossil resource scarcity results. Relevant design directions include improving the COP, thermal contact design and heat rejection, while selecting a lower-impact electricity supply where possible. However, these alternatives were not modelled explicitly in the present sensitivity analysis and should therefore be regarded as an improvement direction. Service life is also a decisive design parameter, as premature replacement increases the manufacturing reference flow required per functional unit, particularly affecting mineral resource scarcity. Reliability, component durability and compatibility between the TEC module and its power conversion electronics should be considered alongside operational efficiency. Moreover, the substantial contribution of auxiliary electronics should be considered alongside operational efficiency. Moreover, the substantial contribution of the auxiliary electronics confirms that the environmental assessment and design decisions should consider the complete operating system rather than the bare TEC module alone.

4.6. Comparison with Previous LCA Studies

The cradle-to-gate results are qualitatively consistent with previous cradle-to gate studies of thermoelectric materials and modules, which report that inorganic thermoelectric materials are environmentally intensive because they combine critical-element supply with energy-demanding processing routes [21]. The present study extends that interpretation

by resolving the foreground manufacturing chain into p-type and n-type leg production, alumina substrate manufacturing, copper tabs, wiring, module assembly and auxiliary power electronics. This provides a more explicit basis for identifying whether impacts arise from semiconductor material, ceramic processing, conductive metals or electronic support components.

Compared with cradle-to-grave studies of thermoelectric cooling systems, the present results support the general conclusion that the use phase can dominate when the TEC system is assessed over its service life and supplied by grid electricity [18–20,22]. For example, previous system-level studies have shown that use phase electricity and mix selection strongly influence the life cycle carbon footprint of TE cooling and heating systems, while PCM or PV integration can reduce the use-stage electricity demand or shift the burden profile [18,20,22].

However, the comparison with previous studies should be interpreted primarily at the methodological level rather than as a direct numerical measure. The reviewed studies differ in functional unit definition, system boundary, inclusion of auxiliary components, treatment of the use phase, electricity supply, service life assumptions and LCIA scope. These differences affect the scaling of material flows, the allocation of manufacturing burdens and the relative importance of operational electricity. Therefore, differences between the present results and previous studies should not be interpreted as direct performance comparisons between TEC systems. Instead, the comparison highlights consistent modelling issues, including the importance of service-based functional units, transparent system boundaries, explicit treatment of use-phase electricity and inclusion of auxiliary power electronics where they are required for operation.

4.7. Limitations

The results should be interpreted within the constraint of the foreground inventory and modelling assumptions. The scope of applicability is also conditioned by the foreground modelling assumptions. The selected commercial TEC module was treated as the reference hardware system, but the results are specific to its geometry, material composition, auxiliary power electronics and reference operating condition. The assumed manufacture in China, distribution to a European use context and transport distances for supply chain and end-of-life stages were scenario assumptions rather than primary manufacturer logistics data. Similarly, background processes from ecoinvent 3.9 and proxy datasets were selected according to technological and geographical representativeness where direct datasets were unavailable. The main foreground and background data limitations are detailed below.

First, no primary manufacturer bill of materials or component-level inventory was available for the RECOM AC-DC and Murata DC-DC auxiliary power modules. These modules were represented using proxy foreground modelling, which introduces uncertainty regarding the electronic components, metallic materials and printed circuit assemblies embedded in the power conversion chain. The assumption that the auxiliary electronics have the same operational lifetime as the TEC module was adopted to avoid introducing an additional replacement schedule unsupported by product-specific reliability data. This assumption was considered plausible in view of generic reliability information for commercial AC-DC and DC-DC power supplies, which reports MTBF values in the same order of magnitude as the baseline lifetime considered in this study [29]. However, MTBF is not equivalent to service life, and this assumption does not imply that the TEC module and power conversion electronics have identical degradation mechanisms or failure behaviour. If the auxiliary electronics require earlier replacement, the hardware reference flow and end-of-life burdens associated with these components will increase. The sensitivity analysis excluding auxiliary electronics therefore quantifies the relevance of including

these components in the system boundary, but it does not represent a full reliability or replacement-frequency sensitivity analysis for the power supply chain.

Second, bismuth production was represented using an economic allocation proxy. This is a methodological simplification adopted for the bismuth production inventory. Although the sensitivity analysis indicates that this proxy has a negligible influence on the three selected ReCiPe 2016 midpoint categories, this does not validate the proxy as a robust representation of bismuth production. The proxy may be more influential for other impact categories.

Third, copper sheet was represented using a copper cathode proxy, which does not fully capture rolling, surface finish or component-specific processing. Fourth, some process wastes were documented in the foreground manufacturing chain but were not fully treated in the base case, meaning that waste treatment burdens may be underestimated for specific manufacturing steps. Fifth, part of the foreground manufacturing inventory was reconstructed from the literature sources rather than obtained directly from TEC manufacturers. This affects the technological representativeness of specific process routes, component masses and manufacturing assumptions, and should therefore be considered when interpreting the cradle-to-gate contribution results.

Sixth, the assessment was conducted at the fixed reference operating condition defined in Section 3.2. The conclusions therefore apply to this reference condition and should not be generalised to other current, voltage, temperature lift or cooling capacity configurations. To assess the robustness of this assumption, a *post hoc* verification of the response surface was performed using the operating region reported by the manufacturer. This verification indicated that, for nearby operating conditions with comparable COP values, the percentage contribution of the main life cycle stages to the selected ReCiPe 2016 midpoint indicators changed only slightly. This supports using the selected point as a local reference condition for interpreting contribution patterns within the high-COP region. However, this does not remove the broader limitation of using a single operating point. Operating conditions involving higher temperature lifts or operation closer to the maximum cooling capacity would generally reduce the COP and increase the electricity demand required to deliver 1 kWh of useful cooling, thereby increasing the contribution of the use phase. Broader generalisation would require coupling this response surface approach directly with the LCA model, so that the complete environmental profile can be evaluated across different cooling capacities, temperature lifts and cooling capacity conditions.

The environmental interpretation is also limited by the selected LCIA categories. The main analysis addresses climate change, fossil resource scarcity and mineral resource scarcity, and therefore emphasises mechanisms associated with energy use and material resources. Other ReCiPe 2016 midpoint categories were not analysed in the main contribution results. These categories may also be relevant for a complete assessment of electronic components, metals, ceramic production and end-of-life treatment, and should be considered in future broader environmental assessments of TEC systems.

Taken together, these limitations indicate that future work should prioritise primary manufacturer or teardown data for the TEC module and auxiliary electronics, including component masses, process routes, yield and scrap information, and more disaggregated datasets for converter modules and bismuth production.

5. Conclusions

For the analysed commercial TEC module and reference operating condition, the results show that the combined effects of material production, auxiliary power electronics, operating efficiency, electricity supply and service life govern environmental performance. The cradle-to-gate results indicate that semiconductor legs, alumina substrates, copper

interconnections and electronic support components are relevant foreground contributors, whose importance depends on the impact category. The cradle-to-grave results show that operational electricity is a decisive parameter when impacts are allocated to 1 kW h of useful cooling, and the electricity mix sensitivity confirms that changing the background supply shifts the impact profile across categories rather than producing a uniform improvement.

The sensitivity analysis demonstrates that service life and auxiliary power electronics are among the most influential modelling choices. Reducing the assumed lifetime increases all midpoint results because manufacturing and end-of-life burdens are distributed over a smaller amount of useful cooling, whereas excluding auxiliary electronics substantially reduces resource scarcity categories. In contrast, the bismuth economic allocation proxy and the selected end-of-life route have comparatively limited influence on the overall profile under the present assumptions. These findings reinforce the need to include the complete operating system, rather than the TEC module, when assessing the environmental performance of thermoelectric cooling.

Beyond the specific case study, the results suggest that environmental improvement strategies for TEC systems should be evaluated at the level of the complete operating system rather than just at the level of the thermoelectric module alone. Material substitution may reduce cradle-to-gate burdens, but the overall relevance depends also on the operating efficiency, auxiliary power conversion, thermal management, electricity supply and service life. These broader recommendations should therefore be interpreted as design implications derived from the analysed module and operating condition, rather than as universal conclusions for all TEC technologies. Future work should improve the foreground inventory with manufacturer-specific component data, refine waste treatment modelling, test alternative semiconductor and substrate materials, and expand the operating map beyond the fixed reference condition used in this study. This would improve the comparability, transparency and engineering relevance of LCA results for thermoelectric cooling technologies.

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Abbreviations

The following abbreviations are used in this manuscript:

COP	Coefficient of Performance
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MIPS	Material Input Per Service Unit
MTBF	Mean Time Between Failures

PCM	Phase Change Material
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
TEC	Thermoelectric Cooling
WEEE	Waste from Electrical and Electronic Equipment
PEFCRs	Product Environmental Footprint Category Rules

Appendix A. Database Specific Search Queries

Appendix A.1. Scopus

```
TITLE-ABS-KEY (
  ( thermoelectric OR ‘‘thermo-electric’’ OR peltier )
  AND
  ( cool* OR refrigerat* OR ‘‘thermal management’’ )
  AND
  ( ‘‘life cycle assessment’’ OR ‘‘life-cycle assessment’’
    OR ‘‘life cycle analysis’’ OR ‘‘life-cycle analysis’’
    OR lca OR lcia
    OR ‘‘life cycle inventory’’ OR lci
    OR ‘‘carbon footprint’’
    OR ‘‘environmental impact’’ )
)
```

Appendix A.2. Web of Science Core Collection

```
TS=(
  ( thermoelectric OR ‘‘thermo-electric’’ OR peltier )
  AND
  ( cool* OR refrigerat* OR ‘‘thermal management’’ )
  AND
  ( ‘‘life cycle assessment’’ OR ‘‘life-cycle assessment’’
    OR ‘‘life cycle analysis’’ OR ‘‘life-cycle analysis’’
    OR LCA OR LCIA
    OR ‘‘life cycle inventory’’ OR LCI
    OR ‘‘carbon footprint’’
    OR ‘‘environmental impact’’ )
)
```

Appendix A.3. IEEE Xplore

```
(‘‘thermoelectric’’ OR ‘‘thermo-electric’’ OR peltier)
AND
(cooling OR cooler OR refrigeration OR ‘‘thermal management’’)
AND
(‘‘life cycle assessment’’ OR ‘‘life cycle analysis’’ OR LCA OR LCIA
  OR ‘‘life cycle inventory’’ OR LCI OR ‘‘carbon footprint’’
  OR ‘‘environmental impact’’)
```

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