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Assessment of Scarcity, Toxicity, and Circularity Risks in the European Thermoelectric Market: A Focus on Tellurium, Antimony, Bismuth, and Lead

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Abstract: This study assesses supply risks for critical raw materials (CRMs) essential to Europe's thermoelectric (TE) technology, which transforms heat into electricity. Given the EU's heavy reliance on imports for key materials like tellurium, antimony, bismuth, and lead, the analysis incorporates market forecasting, scarcity quantification, and Monte Carlo simulations to model demand and supply risks. This study reveals that tellurium poses high risks due to scarcity and potential geopolitical impacts, with antimony and bismuth at moderate risk, and lead presenting notable health hazards. The findings suggest the necessity of circular supply chains and material alternatives to mitigate resource, environmental, and geopolitical challenges for sustainable TE development in Europe. Moreover, there is a pressing need to update and expand data availability for materials like tellurium to enable more robust risk assessments in the immediate future.

Keywords: thermoelectric technology; critical raw materials; supply risk; resource scarcity; circular economy; geopolitical risk; material alternatives; environmental impact; recycling practices; sustainable development

Academic Editors: Thomas Olofsson and Alírio E. Rodrigues

Received: 6 November 2024
Revised: 9 December 2024
Accepted: 27 December 2024
Published: 9 January 2025

Citation: Jamil, U.; Holden, N.M. Assessment of Scarcity, Toxicity, and Circularity Risks in the European Thermoelectric Market: A Focus on Tellurium, Antimony, Bismuth, and Lead. *Clean Technol.* **2025**, *7*, 5. https://doi.org/10.3390/cleantechnol7010005

1. Introduction

Thermoelectric (TE) materials are used to convert thermal energy into electricity (thermoelectric generators or TEGs), or electricity into thermal energy (cooling or heating systems) [1]. TE materials use a combination of thermal, electrical, and semiconducting properties [2], typically as semiconductors that are highly doped to increase electrical conductivity so transport properties approximate those of metals [3]. These multi-component alloys are used to make TEGs, which have the remarkable ability to directly convert heat into electricity, or electricity into heat [4]. TEGs are also used for electrical enclosure cooling, as an alternative to fluid-based systems for air conditioning and heat pumping [5,6]. Moreover, they are invaluable for a range of applications where reliability is a priority over efficiency, such as self-powered wireless devices, health monitoring, engine control, and industrial electronics [4].

The Seebeck effect is fundamental to thermoelectric power generation [7]. It occurs when a thermoelectric material is subjected to a temperature gradient. The mobile charge carriers at the hot end diffuse to the cold end, creating a charge accumulation heading toward equilibrium between the chemical potential for diffusion and electrostatic repulsion, which results in a net charge with an electrostatic potential (voltage) [8,9]. A thermocouple is the most basic TE device harnessing the Seebeck effect for generating electricity in a structure known as a thermoelectric uni-couple. It consists of two thermoelectric elements, an n-type semiconductor (containing free electrons e-) and a p-type semiconductor (containing free holes h+), wired electrically in series and thermally in parallel (Figure 1); hence, they share the same heat source and heat sink [10]. The efficiency of thermoelectric material is evaluated using the dimensionless figure of merit zT ((α2σ/κ) T), where α is the Seebeck coefficient, σ is the specific electrical conductivity (S/m), κ is the thermal conductivity (W/m·K), and T is the absolute temperature (K). A minimum zT of 1.5 is typically required for efficiency and commercial viability in most technological applications [2,11].

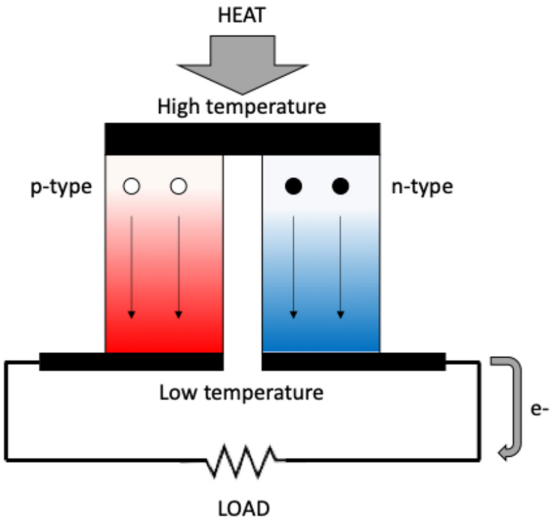

Figure 1. Working principle of a thermocouple (redrawn from Swarnkar et al., 2019 [12]).

TE materials are made using a range of raw materials but are largely reliant on metalloid elements such as antimony (Sb), bismuth (Bi), and tellurium (Te), which are relatively rare and expensive [13]. Moreover, TE devices are typically non-moving systems with zero direct emissions in operation, so they offer an enticing decarbonization pathway. TE technology offers the opportunity to harvest waste heat (e.g., from combustion engines, microprocessors, and industrial processes) [14] and turn it directly into electricity, thus helping to decarbonize the energy system [15,16].

Reliance on costly and uncommon materials has hindered the widespread adoption of TE technology [17], and if the full potential of TE materials is to be realized as part of an energy transition away from fossil resources, a greater understanding of their availability and supply will be required. Furthermore, some of the elements and the TE materials themselves are hazardous or toxic, such as Pb and Te, which pose additional challenges due to safety and environmental concerns [18]. While the environmental impact of TE materials has been the subject of some research, the fundamental starting point for any assessment of their contribution to sustainable energy transition [19,20] is the supply and impact of the raw materials used. Understanding the supply limitations will be important for evaluating the overall contribution of TE devices to sustainable energy supply and utilization [21]. Competition for limited resources will have serious implications for the expanding EU market for TE technologies.

The global market for thermoelectric generators was estimated to be USD 0.47 billion in 2022 and was anticipated to rise to USD 1.46 billion by 2033, with a compound annual growth rate (CAGR) of almost 12% between 2023 and 2033 [22]. Some of the important elements for TE materials are considered to be critical raw materials (CRMs) [23], meaning they are economically important but are associated with significant supply risks, such as limited reserves or sourced from politically unstable regions [24]. At the EU regional level, the Raw Materials Initiative [25] and resource efficiency policy [26] both mention managing the implications of resource insecurity as a policy goal. Several studies and approaches for evaluating CRMs have focused on supply risk [27] and system susceptibility to disruption [28]. From an economic perspective, supply security is a fundamental requirement for guaranteeing a steady flow of raw materials and market growth (Mancini et al., 2018). The EU is highly dependent on imports of many CRMs, which makes it vulnerable to supply chain disruptions and price fluctuations [29]. For example, recent data indicate that China supplies 98% of the EU demand for rare earth elements and Turkey supplies 98% of the EU demand for borate [30].

In this context, it is necessary to consider several supply risks, including potential economic, environmental, or social hazards and consequences, referred to as vulnerability to supply restrictions [31]. Understanding geopolitical factors is also crucial for companies, countries, or regions as these represent non-technical limitations that may affect the supply chain in the short and medium term [32]. The rapid advancements in technologies and the increasing demand have led to a substantial rise in global raw material consumption, estimated to double between 2010 and 2030 [33]. If the CRM demand significantly exceeds the secure supply, "green" energy technologies thought to be sustainable will not find a place in the market either due to cost or supply restrictions.

TE technologies, although potentially environmentally friendly during operation, present the challenge of "fossilization" because of the reliance on CRMs during manufacture [34] and potential toxicity during disposal. These challenges underscore a knowledge gap about the availability and development of sustainable materials for advanced energy technologies, so research is needed to understand TE dependency on CRMs, addressed in this work, to identify new materials that improve eco-effectiveness [35] and to design for circularity [36]. Circular TE supply chains offer a route to decoupling CRM depletion (and other impacts) from consumption [37].

The purpose of this study was to assess the CRM supply available for thermoelectric market growth in Europe to provide a basis for (i) planning to design reduced use of CRMs and (ii) quantifying the need for circularity in the supply chain due to associated risks. The specific objectives were to (i) assess the current status of CRM supply risk to the EU, (ii) identify knowledge gaps associated with lack of available data, (iii) analyze the future scarcity of materials important for the developing the European TE market, and (iv) identify the need for new material development and supply chain system circularity.

2. Materials and Methods

Four steps were used to quantify the current and future demand for CRMs and other mineral resources by the TE market: (1) analysis of market reports to define the current and future demand for TE materials; (2) estimation of the current and future demand for raw materials; (3) definition and analysis of several future scenarios and stochastic evaluation of the uncertainty inherent in the assumptions and scenarios; and (4) quantification of the mineral scarcity. The data were also placed in both chemical and political contexts considering (a) toxicity, (b) chemical hazard, and (c) geopolitical risk so potential circularity in the context of the future of TE market growth could be explored.

2.1. Demand and Resource Scarcity

Step 1: Monte Carlo simulations were used to forecast the magnitude and uncertainty of the TE market in Europe using a combination of global thermoelectric market growth projections and regional projects for Europe, as summarized in Table 1. These data were used to estimate the size of the market in 2020 using a range of CAGR values to predict market growth by 2030.

Step 2: The material demand was estimated bottom-up from [38] and top-down from bulk material cost [39], and the share for each material was calculated from the total cost [40]. The mineral demand was forecast using the European TE market growth from Step 1.

Step 3: Three scenarios were evaluated, Baseline, Pessimistic, and Optimistic, defined based on forecast mid-point growth (9.10% of CAGR [41]), low growth (~6% of CAGR [42]), and high growth (12.64% CAGR [38]). To account for the uncertainty of the input data, a stochastic simulation approach was used to compare the scenarios. Monte Carlo simulations were conducted using @Risk software assuming a uniform distribution. The simulation ran for 10,000 iterations to quantify uncertainty in trends for the European technology and electronics market and raw material demand from 2020 to 2029.

Table 1. Summary of market reports used to estimate current and future market demand for thermoelectric devices in Europe.

Data	Sources
CAGR Projection	Market Report [38,42]
Thermoelectric Market Share	Market Report [41]
European Thermoelectric Market Share	Market Report [41]
Dominant Thermoelectric Materials in Europe	Market Report [38]
Bulk Material Share	[39]

Step 4: The demand for mineral resources was normalized using the mineral scarcity index from the ReCiPe life cycle impact method [43] to calculate net resource depletion driven by primary consumption required for the European TE market from 2020 to 2029. The midpoint characterization factor utilized for assessing mineral resource scarcity was the Surplus Ore Potential (SOP). The SOP quantifies the average additional quantity of ore that needs to be mined in the future because of extracting 1 kg of a specific mineral resource. This calculation considers all future production of the mineral resource, and it is expressed relative to the average extra amount of ore that would be produced in the future due to the extraction of 1 kg of copper (Cu), considering all future copper production. A higher SOP value suggests that to meet the same demand or obtain the same functional unit, additional ore will need to be extracted in the future. This can be indicative of greater resource scarcity associated with the extraction of a particular mineral. In contrast, a lower SOP value implies a lower environmental burden in terms of future ore extraction.

2.2. Chemical and Political Context

Toxicity: The toxicity and abundance of product constituent raw materials influence environmental impact [44]. Toxicity has an impact on human health and ecosystems [45], whereas abundance affects resource extraction and transportation implications [46]. Understanding these aspects can guide decisions on sustainable product design and material sourcing, promoting environmental responsibility and resource efficiency [47]. The US EPA CompTox Chemicals Dashboard v2.3.0 [48] was used to determine the toxicity of the elements involved in the most important TE materials in the European market. It provides information about the toxicity levels of specific raw materials, taking into account ecological persistence, chemical composition, and possible risks to human health or ecosystems, to improve their comprehension of how material choices and product design affect environmental outcomes utilizing these techniques and theories [49].

Block list Scan. The safety and health considerations of a product extend beyond its ingredients to include the substances and chemicals utilized in its manufacturing process. Hence, a thorough "block list" examination was conducted to highlight substances used in production that pose significant risks to both human health and the environment [50]. The block list scan was performed for the relevant elements in Regulation (EC) No. 1272/2008 Annex VI (CLP) (EU-OSHA, 2008) [51]; Safety, Health and Welfare at Work (Chemical Agents) Regulations 2001 to 2021 [52]; Candidate List of substances of very high concern by Article 59(10) of the REACH Regulation [53]; Canadian Domestic Substances List 2019 [54]; European Inventory of Existing Commercial chemical Substances [55]; WATER | NORMAN: French Monitoring List [56]; and NORMAN: REACH Chemicals List Provided to NORMAN Network [57].

Geopolitical risk. The GeoPolRisk method was initially designed as a midpoint characterization factor for Life Cycle Sustainability Assessment (LCSA), but for this work, it was applied independently as a comparative supply risk assessment for resources used in thermoelectric materials in the EU for the period 2020 to 2029 [58]. The GeoPolRisk method quantifies supply risk by considering the global production concentration of the raw material and the import shares of trade partners, weighted by their political instability. The production concentration is evaluated using the normalized Herfindahl–Hirschman Index (HHI) on a scale of 0 to 1 for raw material extraction or processing, while political instability is estimated using the Political Stability and Absence of Violence dimension of the Worldwide Governance Indicators (WGI-PV). Domestic production is incorporated into the GeoPolRisk calculation. The GeoPolRisk index is calculated using Equation (1) [59]:

$$GeoPolRisk = HHI_A \times \sum i \frac{g_i \times f_{AIC}}{p_{AC} + F_{AC}} \quad (1)$$

where

HHI_A = Herfindahl–Hirschman Index for commodity A;
g_i = Geopolitical (in)stability of country i;
f_{AIC} = Imports of commodity A from country i to country C (t);
F_{AC} = Total imports of commodity A to country C (t);
p_{AC} = Domestic production of commodity A in country C (t).

The dimension of Political Stability and Absence of Violence from the Worldwide Governance Indicators (WGI-PV) [60] was utilized to estimate political instability (g_i), which varies by country and year. The data on major importers and suppliers (used to calculate F_{AIC} and F_{AC}) for the years 2014 [23], 2017 [61], and 2020 [62] were obtained from an EU critical raw material study for the respective years alongside total imports and domestic production [62]. In 2014, China, Vietnam, Kyrgyzstan, and Russia had 99% share for the total imports [23]. In 2017, 94% of the total imports were from China and Vietnam [61]. In 2020, the list of importers expanded to China, Korean Rep, Bolivia, UK, Vietnam, Turkey, Guatemala, Switzerland, and Kosovo [62]. There was no domestic production of antimony in the EU (i.e., p_{AC} = 0). The data were used to calculate HHI_A for refined antimony import to the EU for 2014, 2017, and 2020.

2.3. Circularity

An economy needs to balance its material inputs and outputs to be fully circular. Investments in the TEG market are set to rise significantly, highlighting the importance of developing end-of-life (EoL)-TE recycling modules to enable the mass application of TEG products. However, the conventional manufacture and synthesis of TE materials will persist until the full development of novel ideas for the ecologically benign degradation of EoL-TE modules and purposeful and optimized element recovery, making waste recycling one of the outliers in the TE industry [63]. Ideally, materials and products would be fully circular, where both the quantity and quality of materials are fully retained through recycling processes [64]. The current available methods for circulation face significant challenges, particularly concerning the degradation of material quality during the recycling processes [65]. This degradation leads to downcycling, where recycled materials are of lower quality and less suitable for high-value applications compared to virgin materials [66]. It has been estimated that only 28% of recoverable end-of-life (EOL) waste is recycled, while the remaining material is either disposed, lost as dissipation, or left as "hibernating" stocks [67]. As specific product level data were not available to the calculate the material circularity index [68], the simple circularity index proposed by Cullen (2017) was used. This was selected because it considers the amount of recovered material as a proportion of material demand (Equation (2)) and the energy required for recovery as a proportion of energy required for primary production (Equation (3)).

$$\alpha = \text{recovered EOL material (t)/total material demand (t)} \quad (2)$$

$$\beta = 1 - \text{energy to recover material (MJ)/energy for primary production (MJ)} \quad (3)$$

When $\alpha = 1$, the mass circulation is perfect, and when $\beta = 1$, the energy required for circulation is negligible. Since most materials cannot be recycled without deteriorating the quality of the material, and in using energy, α and β are unlikely to ever equal 1. The product of α and β is the circularity index (Equation (4)), which accounts for material losses during reprocessing, both in terms of quantity and quality.

$$\text{Circularity Index, CI} = \alpha\beta \quad (4)$$

3. Results

In combining the data for demand, scarcity, health risk, and GeoPolRisk (Table 2) tellurium poses a high risk to the market; antimony and bismuth, a low to medium risk; and lead, a low risk. From a health perspective, lead poses the highest risk, and attention should be placed on determining the geopolitical risk associated with tellurium. The details behind this result are presented below.

Table 2. Overall risk for supply for key materials for TE materials.

Category	Antimony	Bismuth	Lead	Tellurium
Demand (high/med/low)	Low	Med	Low	High
Resource scarcity (high/med/low)	Low	Med	Low	High
Safety risk (high/med/low)	Med	Low	High	Med
GeoPol risk (high/med/low)	Med	Low	Low	unknown
Overall risk to market	Low-Med	Low-Med	Low	High

3.1. Demand and Resource Scarcity

The size of the European TE market was predicted to range from USD 199M by 2029 for the pessimistic scenario to USD 258M for the baseline to USD 343M for the optimistic scenario. The CARG will be important in understanding the pressure on raw materials for the TE market, as the optimistic scenario resulted in a market 72% larger than the pessimistic scenario. The data show a consistent forecast growth in the European thermoelectric sector that will drive a continuously increasing demand for raw materials and TE devices. The forecast share of specific thermoelectric materials (BiTe, PbTe, BiSb, SbTe) assumed that the proportion of each material will remain consistent over time. It was estimated that the baseline market (with pessimistic–optimistic range in parenthesis) would demand USD

39M (USD 30M–USD 51M) BiTe, USD 19M (USD 15M–USD 26M) PbTe, USD 10M (USD 7M–USD 13M) BiSb, and USD 10M (USD 7M–USD 13M) SbTe by 2029.

The calculated mineral resource scarcity for the base year 2020 ranged from 38 kg Cu-eq/kg for Pb and 39 kg Cu-eq/kg for Sb. These are low values that imply scarcity is unlikely to be a problem for these two mineral resources. Much greater scarcity or 1123 kg Cu-eq/kg for Bi to 7579 kg Cu-eq/kg for Te suggests these minerals could become limiting for the TE market over the coming decade.

3.2. Chemical and Political Context

The GeoPolRisk scores for the importation of antimony, bismuth, and lead into the EU for 2020 were calculated as 0.227, 0.055, and 0.067, respectively, while tellurium was 0 [69]. These scores indicate that antimony had the highest risk of supply disruption due to political issues. Tellurium appears to have minimal politically related supply risk; however, this may be due to a lack of comprehensive data. The limited availability of geopolitical risk data, especially for materials like tellurium, highlights a critical gap and underscores the need to address and resolve it for more robust supply chain assessments.

From a health perspective, Antimony can induce respiratory, cardiovascular, and gastrointestinal problems in people [70]. It may also have negative consequences for aquatic creatures and land environments [71]. Bismuth is usually thought to be low in toxicity for humans and the environment [72]. It is widely utilized in medications and cosmetics. Humans who are exposed to lead may experience neurological, developmental, and reproductive consequences [73]. It is harmful to aquatic life and can contaminate soil and water sources [74]. Tellurium compounds can be harmful when consumed or inhaled in significant quantities, and they may irritate the respiratory system [75]. There is scant information on their environmental consequences. Antimony was ranked 104 out of 490 chemicals reported in the TRI (toxic release inventory), and lead ranked 35 out of 490 in 2019, while bismuth and tellurium were not ranked. Moreover, for antimony, the ecotoxicity hazard exposure route is listed as aqueous, while for bismuth and lead, it is oral [76]. The "block list" scan for the elements of concern is summarized in Table 3, which confirms their presence in several international lists for chemical and toxicity-related concerns. Lead was universally regarded as hazardous, followed by antimony, then tellurium and bismuth. Bismuth telluride was the least hazardous compound.

Table 3. Summary of the block list scan (+: listed; -: not listed).

Substance	EC NO.	CAS NO.	CLP (a)	SHW (b)	REACH (c)	DSL (d)	ECCS (e)	FML (f)	NN (g)
Antimony	231-146-5	7440-36-0	+	+	-	+	+	+	+
Bismuth	231-177-4	7440-69-9	+	-	-	+	+	-	+
Bismuth telluride	215-135-2	1304-82-1	-	+	-	-	+	-	-
Lead	231-100-4	7439-92-1	+	+	+	+	+	-	+
Tellurium	236-813-4	13494-80-9	+	+	-	+	+	-	+

Source: (a) Regulation (EC) No. 1272/2008 Annex VI (CLP) (EU-OSHA, 2008) [51]; (b) Safety, Health and Welfare at Work (Chemical Agents) Regulations 2001 to 2021 [52]; (c) Candidate List of substances of very high concern in accordance with Article 59(10) of the REACH Regulation [53]; (d) Canadian Domestic Substances List 2019 [54]; (e) European Inventory of Existing Commercial chemical Substances [55]; (f) WATER | NORMAN: French Monitoring List [56]; (g) NORMAN: REACH Chemicals List Provided to NORMAN Network [57].

3.3. Circularity

All of the materials used for conventional TE materials have a circularity index less than 1 (Table 4), indicating a gap between current practice and the ideal of circularity [64,67]. The α values ranged from 0.7 to 0.94, which is somewhat contradictory to the reports that suggest TE devices and materials are largely not recovered [63], and only 72% of materials are not recovered [67]. The degradation of recovered materials might not allow for circulation, but the recovery rate estimated from bulk data seems to be greater than that reported for TE materials and devices. The β values are all close to 1, indicating that very little energy is used for recovery and reuse. The data suggest that bismuth circulation is well advanced and should be routinely achieved by the industry. There is room for improvement for the other materials used.

Table 4. Estimates for α, β, and CI.

Required Data	Materials			
	Antimony	**Bismuth**	**Lead**	**Tellurium**
Recovered EOL material (Mt)	0.48	3.30	0.54	2.84
Total material demand (Mt)	0.69	3.51	0.77	4.05
α	0.7	0.94	0.7	0.7
Energy required to recover material (MJ/kg)	0.54	0.54	0.54	0.54
Energy required for primary production (MJ/kg) from virgin ore	55	55	30	55
β	0.99	0.99	0.98	0.99
Circularity index (CI)	0.69	0.93	0.69	0.69

4. Discussion

4.1. Mineral Demand and Resource Scarcity

Bi_2Te_3 and Sb_2Te_3 are probably the most common thermoelectric materials in Peltier devices, with high zT values, which determine maximum efficiency of TE materials [77,78] from ~18 °C to ~200 °C and a well-established history of design, development, and optimization of devices. These materials are suitable for IoT devices and medical applications, where they can efficiently harvest low-grade waste heat and body heat. Bi_2Te_3 is also used for TE generators working temperatures around 300 °C, where it can generate 20 to 30 mW of power making it suitable for powering embedded sensors. The demand for Bi_2Te_3 will grow for the foreseeable future in the absence of materials that can rival its performance in diverse thermoelectric applications [79]. In an optimistic scenario with a CAGR of 12.64%, the EU TE market is projected to see substantial expansion. The EU market may exert significant pressure on global resources, raising concern about the long-term resilience of supply.

The ca. 30,000 Mt terrestrial reserves of tellurium pose challenges for the widespread use of telluride-based thermoelectric technology [80]. The demand for tellurium is also driven by photovoltaics, which has not been factored into the analysis presented here. While the demand and resource scarcity of bismuth are lower than for tellurium, there are many competing uses of bismuth, including medicine, low-melting point alloys, and fire detection/extinguishing systems [81]. The estimated demand, combined with mineral resource scarcity indicates that tellurium and possibly bismuth could be bottlenecks due to physical limitations to supply. This risk will be important for the market and the development of new devices, indicating the urgency that should accompany the development of novel TE materials and devices.

Advancing the fundamental understanding of novel material solutions with reduced or eliminated critical raw material content is essential for sustaining or enhancing the performance of materials, components, and devices. Additionally the design of alternatives is imperative for the development of next-generation CRM-free or CRM-lean technologies [82]. Recent research has started to focus on TE materials that are both efficient and sustainable, using alternatives or nontoxic elements, thus creating a safer and more accessible future of TE technology [20]. Thermoelectric materials can be broadly categorized into three groups: inorganic, organic, and hybrid (inorganic/organic). Over the past decade, there has been a significant effort to replace traditional inorganic thermoelectric materials with organic or hybrid alternatives. The adoption of organic and hybrid thermoelectric materials offers promising solutions due to their potential for improved environmental sustainability and more abundant sources [83]. These alternative materials present opportunities to develop thermoelectric devices with reduced environmental impacts, thus contributing to a greener and more sustainable energy landscape. However, the environmental impact of a product goes beyond the toxicity and abundance of its raw materials, encompassing various factors like carbon emissions, primary energy demand, and so on. Organic thermoelectric materials typically include carbon nanotubes, graphene, and conductive polymers [84]. The main focus of research has been on improving the energy conversion efficiency of organic thermoelectric materials; however, their intrinsic low electrical conductivity poses a challenge compared to inorganic materials. To leverage the advantages of both types, hybrid thermoelectric materials have been developed, combining inorganic additives with organic matrices [85]. These hybrids have shown improved conversion efficiency compared to pure organic or inorganic materials. However, hybrid materials still face concerns regarding toxicity and resource scarcity due to the presence of inorganic elements [86]. The assessment of the life cycle impact of inorganic, organic, and hybrid thermoelectric materials at their production stage, shedding light on their environmental impacts, is crucial for advancing thermoelectric technology toward more sustainable alternatives for waste heat recovery and electricity generation [19].

4.2. Supply Risk

Despite the growth projections for the TE market, the supply chain faces challenges other than resource scarcity, perhaps the most important being geopolitical risk. Resource accessibility is influenced by regional and government trade policies. Importing from politically unstable nations heightens supply risk. The data indicate that bismuth (0.055) and lead (0.067) have a very low supply chain risk, but antimony (0.227) could be problematic. The reported value could reflect a lack of data as opposed to a low risk. China provides a significant portion of the EU’s antimony imports (averaging around 52% from 2016 to 2020). While trade between the EU and China is ongoing and necessary for both regions, it remains fraught with political tension, e.g., as summarized in [87]. The European Commission on Raw Materials Risk (ECRMR) seeks to reduce reliance on single-supply partners [88], but alternatives such as Tajikistan (contributing 15% to EU imports) pose a potential risk to the supply chain because of political tension in the area [89]. The discovery of antimony deposits in Bolivia introduces a potential new player in the EU’s critical raw material (CRM) supply chain [90], and at present, there are no explicit risks for developing economies in the antimony market [88]. While the bismuth supply chain risk is low, the EU is very dependent on a single supplier, China, which currently supplies ~63% of the EU demand, so diversification, with Laos and Vietnam being obvious suppliers [88], will also be desirable. Bismuth deposits in Bolivia will also influence the EU market in the coming years [88]. The social contexts of emerging geopolitical tensions and evolving trade dynamics will be important moderators of the growing EU market for TE materials and devices. Both antimony and bismuth are included on the critical raw material (CRM) list [91], which factors in all demands, while this study focused on change in demand due to the market for TE materials and devices. The most important question that needs to be answered in the short term is whether the tellurium supply risk is very small or not. At present, from a demand and scarcity perspective, tellurium is a high-risk material, and from a supply chain perspective, both antimony and bismuth are associated with potentially important risks.

4.3. Chemical Safety

The substances used for TE materials, and the materials themselves, have implications for human health. The human toxicity data, and associated block lists, provide an indication of which materials need careful consideration. Lead and antimony are classified as hazardous substances in the block list scan, indicating possible dangers to human health and the environment. Lead is high in the Toxic Release Inventory (TRI) [92], and its detrimental impact on health is well known [93]. Bismuth and tellurium do not appear in block list scans, but require careful thought because of their possible effects on the environment and human health [72]. Moreover, antimony is extensively used in many electronic and medical applications, but it is reported as toxic in aquatic environments [94]. An interesting research question is whether novel TE materials could be developed to reduce reliance on the toxic components currently used.

There are European and globally recognized frameworks and guidelines to assess chemical hazards and their potential impacts on human health and the environment. Registration, Evaluation, Authorization, and Restriction of Chemicals (REACH) is a European Union regulation that came into effect on 1 June 2007. It aims to enhance the protection of human health and the environment from chemical risks while boosting the competitiveness of the EU chemicals industry. Additionally, REACH encourages alternative methods for hazard assessment to minimize animal testing. The regulation outlines processes for gathering and evaluating data on the properties and hazards of substances. Companies are required to register their substances and collaborate with others registering the same substance [95,96]. Under REACH, accurate study summaries are crucial for chemical risk assessments, as they detail objectives, methods, results, and conclusions. REACH data must be transparent, accessible, and open to independent scrutiny [97]. The regulations reflect the challenges in quantifying environmental benefits, highlighting tensions between ambitious environmental goals and regulatory feasibility [98]. Similarly, the Globally Harmonized System of Classification and Labelling of Chemicals (GHS) standardizes hazard classification and communication to protect human health and the environment during the handling, transport, and use of chemicals. Established in 2002 and published in 2003, the GHS facilitates global trade and harmonizes chemical regulations worldwide through labels and safety data sheets. It provides guidance for governments, organizations, and industries, with updates every two years to address evolving needs. The latest edition, GHS Rev.10, was published in 2023, and with the next update expected in 2025, the GHS ensures clear hazard communication, enabling informed decisions on sustainable material sourcing and product design [99]. Together, these frameworks and tools guide industries toward reducing ecological persistence, mitigating human and environmental risks and advancing resource-efficient, eco-conscious practices.

4.4. Potential for Novel TE Materials

The market demand will be moderated by factors such as environmental concerns, including climate and efficiency considerations [100]. Leveraging breakthroughs in TE materials into tangible, system-level demonstrations of integration with existing technology will be an essential step in mitigating the identified resource, supply chain and safety risks. Organic, carbon-based polymer compounds offer exciting opportunities for novel materials [101]. Compared to conventional TE materials, many organic materials are more affordable, widely available, and flexible, have lower thermal conductivity [102], and can attain zT values up to 0.75 [103]. Achieving high TE efficiency is a work in progress because of low electrical conductivity and the Seebeck coefficient [104]. The next generation of TE materials should leverage the synergies between experimental and computational expertise and innovative device architectures, along with novel manufacturing and material preparation techniques, all integrated seamlessly into systems [100].

4.5. Circularity and Sustainable Design

The Ellen MacArthur Foundation defines the circular economy (CE) as a strategy for decoupling global economic progress from finite resource usage, transitioning from linear economic systems to restorative and regenerative paradigms [105]. The goal is to reduce the environmental implications of resource consumption while promoting economic growth without the negative consequences of resource depletion. Considering the European thermoelectric market and methods of successful recycling of these materials as followed in several pieces of research [63,65,66], it is estimated, via calculating the circularity index [64], that the results are very potential. However, these processes must be in practice for large-scale recycling and recovery to give the practical outcome of a calculated circularity index, which is still a work in progress, since their life span is already 10 years, and their recycling practices are industrially not that common yet as an emerging technology.

The EU Safe and Sustainable by Design (SSbD) policy [106] provides a framework for managing the health risk associated with the growing market. SSbD emphasizes the significance of taking into account health and environmental factors throughout the product lifecycle: initial design, use, and end of life [106]. This includes decreasing the usage of dangerous substances, lowering the environmental impact, and ensuring product safety. To ensure compliance with SSbD, the TE market will need to priorities the development of safer alternatives to materials that are hazardous (lead, antimony, tellurium) or those that have a negative environmental impact (tellurium, bismuth). The development of new materials or enhancing existing ones to reduce or eliminate harmful pollutants are the obvious routes available to researchers [17,107]. While a small number of life cycle assessments of TE materials have been published [19], few studies have considered the whole life cycle, including use and end-of-life stages (one exception being [108]). An estimated 50% to 80% of LCA studies on thermoelectric generation systems (TEGs) have focused primarily on TE materials. There is an urgent need for more research in this area to facilitate the implementation of SSbD for the TE industry in the EU.

Developing low-cost, high-efficiency materials will be essential for achieving commercial viability in TE systems [66,109]. As the demand for sustainable technologies grows, incorporating circularity in materials and processes offers significant potential for TE technology to contribute as a primary, supporting, or complementary solution, given its high adaptability. The EU lacks detailed recycling schemes for thermoelectric (TE) materials, hindered by high costs, technical complexity, and limited infrastructure. Opportunities include implementing recycling targets, advancing cost-effective technologies, and promoting modular designs for easier material recovery [66]. Circular economy challenges include inefficient recycling and weak economic incentives. Actionable steps include adopting life-cycle assessments, researching sustainable TE materials, enforcing producer responsibility, and learning from successful recycling models like lithium-ion batteries. Public–private partnerships offer and opportunity to drive innovation with scalability [110].

4.6. Implications

The EU faces high supply risk for raw materials used for TE materials and devices due to reliance on imported resources, particularly rare earth elements sourced from China. Relying on a small number of countries for these materials increases vulnerability to disruptions in geopolitics and economics, amplifying supply risks. There are significant areas of knowledge gaps that need further research regarding the availability and advancement of sustainable materials for advanced energy technologies. These include accurately determining the reserves of critical raw materials (CRMs), creating alternative materials to decrease reliance on CRMs, and enhancing our understanding of the lifecycle effects of CRMs. Furthermore, there is a need for improved data on the geopolitical and environmental risks linked to CRM extraction and supply to develop more effective risk mitigation strategies.

The European thermoelectric (TE) market is expected to face significant challenges due to the potential scarcity of key materials in the future. The rising demand for materials like bismuth telluride and lead telluride, coupled with the EU's dependence on external suppliers, may result in difficulties in securing a stable supply. This could lead to shortages and higher costs in the face of growing global demand. Moreover, this situation could hinder the advancement of the promising thermoelectric market, which has the potential to make significant contributions to a future with zero emissions. These raw materials are not only crucial for this technology but also for various other industries that cater to everyday consumer needs. As a result, any disruptions in the supply of these materials would have widespread effects across multiple sectors.

Developing new materials and implementing a circular supply chain system cannot be overstated. It is crucial to create alternative materials that are less reliant on CRMs to minimize supply risks. Furthermore, incorporating principles of the circular economy, including material recycling and reusability, can greatly alleviate environmental impact and resource scarcity. This urgency is emphasized by the necessity to sustainably expand the TE market while tackling the geopolitical and environmental issues linked to CRM supply. Furthermore, the costs associated with extraction, processing, manufacturing, and recycling are key considerations in establishing a sustainable circular supply chain system for thermoelectric materials.

To ensure the long-term sustainability of the thermoelectric (TE) market and other industries reliant on these materials, it is essential to plan to reduce the use of critical raw materials (CRMs) by incorporating the safe and sustainable design approach. This involves exploring and adopting alternative materials, enhancing recycling and reuse processes, and improving material usage efficiency through advanced manufacturing techniques. These steps are crucial for reducing dependency on finite resources and mitigating the associated supply risks.

Recognizing the importance of circularity in the supply chain is crucial to tackling the challenges linked to raw material dependency. To address this, it is essential to focus on enhancing circularity by improving resource efficiency, encouraging material recycling and reusability, and establishing closed-loop systems to minimize waste. Achieving these goals will require advancements in recycling technologies, economic incentives for circular practices, and the implementation of strong policies to promote sustainable resource management. By adopting these strategies, we can effectively mitigate supply risks, minimize environmental impacts, and build a more resilient and sustainable market for thermoelectric technologies.

5. Conclusions

There are six important conclusions that can be drawn from this research:

i. *Data availability and accessibility for critical raw materials must be enhanced.* Address this critical knowledge gap by prioritizing the collection of accurate data on material reserves, particularly for high-risk elements like tellurium, which will be essential for better forecasting, risk assessment, and strategic planning for resource management.

ii. *Accelerated development of alternative materials is necessary*. Investment in research to develop and scale sustainable alternatives to TE materials reliant on CRMs will be essential to secure supply chains and mitigate geopolitical vulnerabilities.
iii. *Circular supply chain systems need to be implemented*. Establish robust closed-loop systems for material recycling and reuse to reduce environmental impact and alleviate resource scarcity for the TE market is essential. Advancing recycling technologies and incentivizing circular practices will be key to sustainable TE market growth.
iv. *Advance safe and sustainable material design.* The incorporation of efficient manufacturing techniques and life cycle design principles to optimize material usage is required.
v. *Mitigate geopolitical and environmental risks.* Developing strategies to diversify supply chains and reduce reliance on single-country sources should be prioritized. Enhancing resilience to geopolitical and economic disruptions will safeguard access to critical materials, the demand for which could be reduced through the introduction of novel materials, but is unlikely to be eliminated.
vi. *Promote policy and economic incentives.* Policies that prioritize sustainable resource management and provide economic incentives for adopting circular practices in the TE industry need promoting and perhaps strengthening. These measures should encourage industry-wide alignment with long-term sustainability goals.

Author Contributions: Conceptualization, U.J. and N.M.H.; Methodology, U.J.; Software, U.J.; Validation, N.M.H.; Formal analysis, U.J.; Investigation, U.J.; Data curation, U.J.; Writing—original draft, U.J.; Writing—review & editing, U.J. and N.M.H.; Visualization, N.M.H.; Supervision, N.M.H.; Project administration, N.M.H. All authors have read and agreed to the published version of the manuscript.

Funding: This work was funded by the (1) Science Foundation Ireland (SFI) under Grant Number 16/RC/3889 for BiOrbic Bioeconomy, SFI Research Centre, which is co-funded under the European Regional Development Fund and by BiOrbic industry partners; and (2) Atoms-2-Products, Centre for Doctoral Training (CDT) Program, which is a partnership between BiOrbic (Ireland) and University of Nottingham (UK).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data were derived from public domain resources.

Acknowledgments: The authors gratefully acknowledge the expert advice of Michael Weir and support of research colleagues Alexander Sterling and Zichen Zhang at the University of Nottingham.

Conflicts of Interest: The authors declare no conflicts of interest.

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