

## *Iaquis Conference Proceedings*

*Fostering organizational transformation for a  
sustainable future:  
Enhancing synergies between quality, innovation and  
sustainability*



**Iaquis International Conference**  
**11<sup>th</sup> – 13<sup>th</sup> September 2024**  
**Viterbo, Italy**

# **Iaquis Conference Proceedings**

**Iaquis Conference 2024**

**Fostering organizational transformation for a  
sustainable future:**

**Enhancing synergies between quality, innovation and  
sustainability**

# Editors

**Manuel Francisco Suarez Barraza**  
Universidad de las Americas Puebla

**Frederic Marimon**  
Universitat Internacional de Catalunya

**Bo Edvardsson**  
Karlstad University

**Maria Gianni**  
University of Macedonia

**Carmen Jaca**  
Universidad de Navarra

**Samuel Sebahtu**  
Karlstad University

**Evangelos Psomas**  
University of Patras

**Alessandro Ruggieri**  
University of Tuscia

**Maria Francesca Renzi**  
Roma Tre University

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# Foreward

The current economic, social, and environmental landscape is marked by a profound crisis, underscoring the urgent need for a paradigm shift in production and consumption patterns. The interconnectedness of these domains has become increasingly evident, with the effects of unsustainable practices rippling through economies, societies, and ecosystems.

Recent environmental and geopolitical events have further highlighted the fragility of the existing production system. Climate change, resource depletion, and geopolitical tensions have exposed the vulnerabilities of traditional economic models and the imperative for transformative action. Organizations must adapt to these challenges by embracing sustainable practices and innovating to create more resilient and equitable systems.

A synergistic contribution from academics, practitioners, and policymakers is essential to navigate this complex landscape. Academics can bring their research expertise to identify emerging trends, develop innovative solutions, and inform policy decisions. Practitioners can offer insights into the practical challenges and opportunities faced by organizations in their respective sectors. Policymakers can create enabling environments that support sustainable practices and incentivize innovation.

Academia, in particular, can play a pivotal role in driving the development of new ideas through research activities. The International Association of Quality, Innovation, and Sustainability (IAQUIS) can serve as a valuable platform for aggregating, coordinating, and mediating these efforts. By fostering collaboration among professors, researchers, doctoral students, and practitioners from around the world, IAQUIS can facilitate constructive discussions and knowledge sharing.

The choice of the main themes, "Quality, Innovation, and Sustainability," reflects the interconnected nature of these concepts and their critical importance for a sustainable future. Quality, as a cornerstone of excellence and customer satisfaction, is essential for long-term organizational success. Innovation, as the driving force behind progress and adaptation, is crucial for addressing emerging challenges and creating new opportunities. Sustainability, encompassing environmental, social, and economic dimensions, is a fundamental imperative for ensuring the well-being of future generations.

By adopting a cross-cutting and synergistic perspective, organizations can unlock the full potential of quality, innovation, and sustainability. This involves integrating these elements into all aspects of business operations, from product design and production to supply chain management and customer relationships.

The First IAQUIS Conference provides a unique opportunity to initiate a network of relationships and connections among key stakeholders from academia, industry, and policymaking. Through collaborative discussions and knowledge sharing, participants can explore innovative approaches, identify best practices, and develop strategies for fostering organizational transformation.

By focusing on quality, innovation, and sustainability, IAQUIS aims to contribute to a more equitable, resilient, and sustainable future for all.

Viterbo, Italy

Alessandro Ruggieri

# Preface

The first Iaquis Conference was held in Viterbo (Italy) from 11<sup>th</sup> to 13<sup>th</sup> September 2024. It was promoted by the International Association for Quality, Innovation and Sustainability and hosted by the Department of Department of Economics, Engineering, Society and Business Organisation of University of Tuscia in Viterbo, Italy.

The objective of the Conference was to stimulate and foster collaboration and knowledge exchange in the areas of Quality, Innovation and Sustainability among researchers, educators, practitioners, and doctoral students hailing from diverse countries and backgrounds.

Over the course of the three-day Conference, the participants had the opportunity to present their research in both plenary and parallel sessions.

The central theme that permeated all discussions revolved around the synergies between Quality, Innovation, and Sustainability, embracing an interdisciplinary perspective and a cross-cutting approach.

A pre-conference Doctoral Consortium was held. During the Doctoral Consortium the PhD Students presented their research program and findings, and received suggestions by the mentors. Moreover a seminar on how to develop an impactful paper was held to provide young scholars with in-depth feedback from experienced lecturers on their ongoing research.

The Conference collected a total of 83 Papers from 15 countries. Some of the authors asked not to be publish their paper in these proceedings, thus some contributions will not appear, besides being counted.

The great number of papers and the variety of the topics allowed us to organize numerous parallel sessions, by dividing the papers into 18 tracks, plus the Doctoral Consortium:

- 1) Circularity
- 2) Healthcare
- 3) Sustainability in Tourism
- 4) Sustainability in Agri-Food
- 5) Sustainability
- 6) Life Cycle Assessment
- 7) Quality and Innovation in Food Sector
- 8) Innovation Industry 4.0
- 9) Quality Management
- 10) TQM and Sustainability
- 11) TQM and Employees
- 12) Quality Management and Improvement
- 13) Management Systems
- 14) Life Cycle Assessment
- 15) Sustainability and Service Innovation
- 16) Sustainability
- 17) Sustainability in Energy Sector
- 18) Innovation.

Due to the conspicuous number of the papers which fell under the topics of “Sustainability” and “Life Cycle Assessment”, each of these parallel sessions were split in two sessions, allowing all the authors to present their contribution.

# Conference Scientific Committee

**Manuel Francisco Suarez Barraza**  
Universidad de las Americas Puebla

**Frederic Marimon**  
Universitat Internacional de Catalunya

**Bo Edvardsson**  
Karlstad University

**Maria Gianni**  
University of Macedonia

**Carmen Jaca**  
Universidad de Navarra

**Samuel Sebahtu**  
Karlstad University

**Evangelos Psomas**  
University of Patras

**Alessandro Ruggieri**  
University of Tuscia

**Maria Francesca Renzi**  
Roma Tre University

# Conference Organising Committee

**Alessandro Ruggieri**

Department of Economics, Engineering, Society  
and Business Organisation  
University of Tuscia  
Viterbo, Italy

**Stefano Poponi**

Department of Economics, Engineering, Society  
and Business Organisation  
University of Tuscia  
Viterbo, Italy

**Mariagrazia Provenzano**

Department of Economics, Engineering, Society  
and Business Organisation  
University of Tuscia  
Viterbo, Italy

**Gioia Capati**

Department of Economics, Engineering, Society  
and Business Organisation  
University of Tuscia  
Viterbo, Italy

**Federico Stendardi**

Department of Economics, Engineering, Society  
and Business Organisation  
University of Tuscia  
Viterbo, Italy

**Cecilia Silvestri**

Department of Economics, Engineering, Society  
and Business Organisation  
University of Tuscia  
Viterbo, Italy

**Francesco Pacchera**

Department of Economics, Engineering, Society  
and Business Organisation  
University of Tuscia  
Viterbo, Italy

**Alessandro Lanfranco Bruno**

Department of Economics, Engineering, Society  
and Business Organisation  
University of Tuscia  
Viterbo, Italy

**Stefania delle Monache**

Department of Economics, Engineering, Society  
and Business Organisation  
University of Tuscia  
Viterbo, Italy

**Isabella Spolverini**

Department of Economics, Engineering, Society  
and Business Organisation  
University of Tuscia  
Viterbo, Italy

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*Mariagrazia Provenzano<sup>1\*</sup>, Francesco Pacchera<sup>2</sup>, Cecilia Silvestri<sup>3</sup>, Michela Piccarozzi<sup>4</sup>, Alessandro Ruggieri<sup>4</sup>*

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*Panagiotis Kafetzopoulos<sup>1</sup>, Evangelos Psomas<sup>2</sup> and Angelos Pantouvakis<sup>3</sup>*

# A preliminary Life Cycle Assessment of electromagnetic energy harvesting devices. A focus on Magnetic Tunnel Junctions

*Teresa Maria Gulotta<sup>1</sup>, Roberta Salomone<sup>2</sup>, Patrizia Primerano<sup>3</sup>, Giuseppe Saija<sup>4</sup>*

<sup>1</sup>Department of Engineering, University of Messina. [teresamaria.gulotta@unime.it](mailto:teresamaria.gulotta@unime.it)

<sup>2</sup>Department of Economics, University of Messina. [roberta.salomone@unime.it](mailto:roberta.salomone@unime.it)

<sup>3</sup>Department of Engineering, University of Messina. [patrizia.primerano@unime.it](mailto:patrizia.primerano@unime.it)

<sup>4</sup>Department of Economics, University of Messina. [giuseppe.saija@unime.it](mailto:giuseppe.saija@unime.it)

## Abstract

The Internet of Things (IoT) encompasses a vast network of diverse interconnected smart devices, and their number is expected to rise rapidly. In this context, a critical challenge to face is finding solutions for the supply of adequate quantity of electricity necessary to power these devices. In particular, this means the development of miniature energy-efficient power supplies to ensure sustained autonomous operation. Charging these devices with energy from the environment could offer a valid alternative to reduce environmental concerns. Electromagnetic waves in the microwave spectrum, typically used for wireless data transmission, offer a valuable yet underutilised resource. Emerging electromagnetic energy harvesting technologies, like spin-torque devices, show promise in converting unused electromagnetic energy into electricity for IoT devices. However, their reliance on materials categorised as critical and rare could pose potential environmental challenges. This paper aims to preliminarily assess the environmental impacts of Magnetic Tunnel Junctions (MTJs), which are pivotal components in spintronic devices. Through a systematic literature review, key materials used in MTJs are identified, facilitating hotspot mapping. Then, the Life Cycle Assessment (LCA) method is used to evaluate the potential environmental impacts associated with different sizes and efficiency parameters. The results are useful for identifying critical materials within devices and suggesting solutions for reduction or substitution without compromising energy efficiency. This preliminary analysis also aims to guide LCA application to electromagnetic energy harvesters, identifying gaps, limitations, and methodological considerations. Funded by the EU Next Generation initiative through the MUR-PNRR project, this research contributes to the "Innovation Ecosystem - Sicilian MicronanoTech Research and Innovation Center" (SAMOTHRACE - ECS00000022) project.

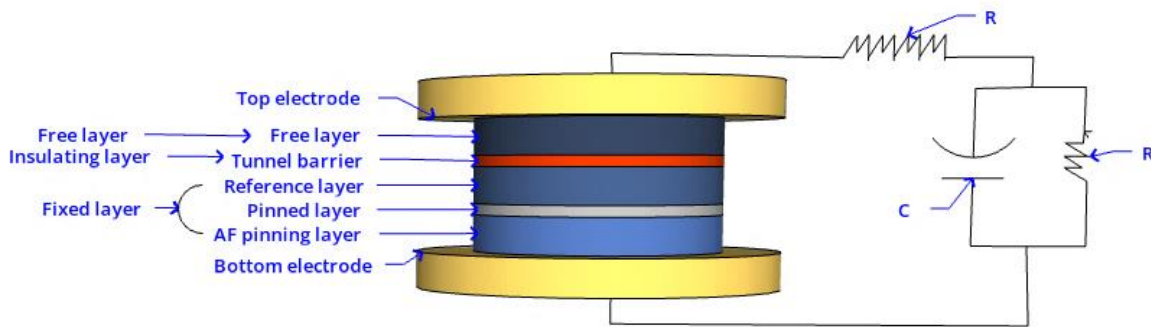
**Keywords:** Spin-torque; MTJ; Life Cycle Assessment (LCA); Electromagnetic energy harvester; microwaves detector

## Introduction

The Internet of Things (IoT) comprises billions of interconnected smart devices that require much energy to be powered. However, in this context, a critical challenge is the development of miniature, energy-efficient power chargers to ensure sustained autonomous operation (Demin et al., 2020). This challenge underscores the crucial need for energy harvesters, especially at the level of nanodevices.

Electromagnetic energy harvesting technologies, such as spintronic devices, offer promising solutions for harvesting and converting unused electromagnetic energy into electricity for IoT devices (Cutugno et al., 2023; Tu et al., 2020). Within spintronic devices, Magnetic Tunnel Junctions (MTJs) play a pivotal role in radiofrequency and microwave detection, serving as core components.

An MTJ primarily comprises three main layers: the free layer, the insulating layer (or tunnel barrier), and the fixed layer (or pinned layer), along with two electrodes (top and bottom), as schematically represented in Figure 1. Generally, MTJs are produced through the consecutive deposition of materials via sputtering processes on a base layer, followed by annealing (Gupta et al., 2023; Tomasello et al., 2013; Zhang et al., 2020). The literature also indicates that the fabrication method of MTJs can influence the device's efficiency (Gribelyuk et al., 2024).



**Figure 10.** Example of a Magnetic Tunnel Junction and a schematic representation of a matching circuit.

This technology has gained attention due to its high efficiency, scalability, and integrability in electronic circuits for various applications, ranging from memory storage to energy harvesting (Ikeda et al., 2007). However, some materials used in these devices are classified as critical (Palomino et al., 2020), necessitating a thorough examination of their environmental sustainability that could affect the benefits reached.

To the authors' knowledge, no environmental impact assessment has been conducted on spintronic energy harvesting technologies. This study aims to preliminarily evaluate the potential environmental impacts of key components in spintronic devices, with a specific focus on MTJs. The study excludes additional components such as receiving antennas and impedance-matching networks (circuits). A systematic approach is used to identify the main components and material compositions in spintronic devices for energy harvesting. The materials are then evaluated using the Life Cycle Assessment (LCA) method to assess the potential environmental impacts associated with different sizes and efficiencies of MTJs, normalised to 1V/W of sensitivity. The results help to identify critical materials within devices and suggest solutions for reduction or

substitution without compromising energy efficiency. In addition, the approach implemented following in part a prospective LCA allows for identifying the critical aspects in modelling nano energy harvesters and identifying the potential uncertainty in data analysis.

This study is part of the "Innovation Ecosystem - Sicilian MicronanoTech Research And Innovation Center" (SAMOTHRACE) project (ECS00000022), funded by the EU Next Generation initiative, which aims to develop sustainable micro and nano technologies and systems for various applications, including energy, environment, smart agriculture, smart mobility, health, and cultural heritage.

## **Methods**

To achieve the objective of this paper, a preliminary LCA study is conducted following the guidelines outlined for the preliminary phase of prospective LCA as detailed in the articles from Sander-Titgemeyer et al. (2023) and Arvidsson et al. (2018), as well as the ISO 14040-44 standards (ISO, 2006a, 2006b, 2020a, 2020b). The methodological approach of a prospective LCA differs from traditional attributional LCAs by emphasising additional considerations for uncertainty and variability in results. A systematic literature review is typically conducted to map the device's materials, components, and production processes (Arvidsson et al., 2015). The same steps have been followed in this study to gather data. Subsequently, the LCA method is applied from the initial goal and scope definition to the interpretation of results, identifying critical aspects and hotspots of selected components and materials as well as uncertainty in the characterisation results generated by data variability.

### **Preliminary goal and scope of study**

The study aims to assess the cradle-to-grave life cycle impacts of MTJs used in spintronic devices for harvesting energy, including data from raw material extraction to the production of MTJs and one potential end-of-life scenario. It is important to note that transport and infrastructure and the installation, maintenance and use phases are excluded in this preliminary study.

The functional unit is 1 V of potential voltage produced for 1 W of microwaves harvested. This information is collected using the sensitivity parameter, which quantifies the device's ability to detect radiofrequency and microwave signals and convert them into voltage (Vdc) (Fang et al., 2016; Li et al., 2016; Wang et al., 2009). This, along with the Tunnel Magnetic Resistance (TMR), represents the main parameters for evaluating the efficiency of MTJs as energy harvesters.

### **Preliminary inventory analysis**

To evaluate the life cycle of MTJ devices, two steps are conducted: first, the collection of data on material compositions and assumption on metalworking, and second, the estimation of the recycling rate of different materials to close the loop partially, quantifying the reduction of impacts due to the reemployment of materials into the same system.

To identify the materials used in MTJ devices (employed as energy harvesters or microwave detectors), a literature search is conducted on Scopus using keywords related to "magnetic tunnel junctions" and "energy harvesting" or "microwave detectors"<sup>2</sup>. This search is limited to English peer-reviewed articles, resulting in the identification of 45 articles.

During the screening process, 37 articles are excluded for not focusing on using MTJ devices as energy harvesters or for not providing a comprehensive description of layer composition. Additionally, two articles are excluded due to the unavailability of the full text. Finally, 12 articles are considered eligible for the study, as they effectively reported the sensitivity value and the geometric size of the device's layers. Two articles (Sidi et al., 2022; Zhang et al., 2020) also propose two variants of MTJs that are included in the sample, resulting in 14 prototypes.

However, not all the analysed papers specify the materials used for the top and bottom electrodes, and even fewer for the base layer (excluded from the analysis). Therefore, only the prototypes in which both top and bottom electrode materials are reported, in addition to the core layers, are included in this study, reducing the sample to 9. Additional details about the characteristics of the selected devices are reported in Table 1.

**Table 9.** Main technical characteristics of selected prototypes.

ID	References	Sensitivity	Volume [ $\mu\text{m}^3$ ]	Weight [ng]
1	Goto et al. (2021)	106 V/W	1.48E-03	1.26E-05
2	Gupta et al. (2023)	5 mV/mW	3.73E-02	2.74E-04
3	Hemour et al. (2014)	128 $\mu\text{V}/\mu\text{W}$	7.51E-03	7.43E-05
4	Li et al. (2016)	151 mV/mW	1.44E-03	1.08E-05
5	Sidi El Valli et al. (2022)	300 mV/mW	7.43E-05	5.01E-07
6		7 mV/mW	4.91E-04	3.31E-06
7	Wang et al. (2009)	16.67 mV/mW	5.58E-04	4.52E-06
8	Zhang et al. (2020)	10.5 mV/mW	7.09E-03	5.60E-05
9		42.5 mV/mW	3.99E-03	3.15E-05

As shown in Table 1, the prototypes exhibit significant variability in sensitivity parameters and geometric dimensions. To harmonise the results, the data collected from the studies are first broken down into individual materials, with composite materials considered using an average density among the weight percentage generally indicated for composite materials (e.g.  $\text{Co}_{20}\text{Fe}_{60}\text{B}_{20}$ ,  $\text{Pt}_{38}\text{Mn}_{62}$ ). Thus, the geometric size is then converted into weight. Next, the weight is normalised to 1V/W of sensitivity by dividing the weight of each material by the sensitivity reported in the literature case studies (see Table 1). A benchmark prototype is then developed for the study, and average arithmetic values for each material in each layer are calculated independently from the original material composition. Then, a descriptive analysis is conducted to identify the data variability along the sample.

<sup>2</sup> TITLE-ABS-KEY (( "magnetic tunnel junction\*" OR MTJ\* ) AND ( "energy harvest\*" OR "microwave detect\*" )) AND ( LIMIT-TO ( DOCTYPE , "ar" )) AND ( LIMIT-TO ( LANGUAGE , "English" )) (Accessed by 25/04/2023)

The production phase includes consideration of the use of metalworking processes accounting for all the mass of nanodevice core layers and top and bottom electrodes.

For the quantification of the recycling rate of different materials, similar to the study proposed by Abokersh et al. (2021), the End-of-life Recycling Input Rate (EOL-RIR) proposed by the European Commission (2023) is used to estimate the potential benefits derived from the recycling of different materials. Instead, the other parts of materials that are not reused are accounted as waste in landfills, while the treatment process is assumed to be equal to the electric and electronic waste treatment (FitzGerald and Sonderegger, 2022).

For all the life cycle phases, the background processes associated with the extraction, production and final treatment of materials are estimated using the Ecoinvent v3.8 database (FitzGerald and Sonderegger, 2022). In addition, another assumption related to Platinum Group Metals (PGM) is made for which representative datasets are identified, such as iridium and ruthenium. In this case, the extraction processes are assumed equal to that of Platinum (Gulotta et al., 2022) assumed to be equal to metals that are generally mined with them as part of the PGMs group (Snowden-Swan et al., 2016). All the results of this phase are discussed in section 3.1.

### **Impact assessment**

Considering that no other LCA studies have been found on this kind of device, the CML-IA baseline method has been selected, consistent with other LCA studies on energy technology (Masoni and Zamagni, 2011). This method includes characterisation factors for various categories such as Abiotic depletion (elements) (ADE), Abiotic depletion (fossil fuels) (ADF), Global warming potential (GWP), Ozone layer depletion (ODP), Human toxicity (HT), Freshwater aquatic ecotoxicity (FAE), Marine aquatic ecotoxicity (MAE), Terrestrial ecotoxicity (TE), Photochemical oxidation (PCO), Acidification (AC), Eutrophication (NP).

### **Interpretation**

The data are first interpreted by presenting the absolute inventory values and LCA characterisation results. Then, a contribution analysis is performed to identify the main hotspots throughout the life cycle. However, since MTJ is a yet commercialised device, the technical system used for energy harvesting is still under development and in the early assessment and design stage, presenting changes in materials employed to reach the highest efficiency possible in converting harvested energy. Therefore, the challenges in assessing emerging products include data unavailability, scale-up effects, choosing a relevant functional unit, and comparing existing products. As for a prospective LCA (Thonemann et al., 2020), this study would like to address the uncertainties of applying LCA methods to this emerging device. This is evaluated by applying a Monte Carlo analysis using the Simapro software and comparing two different uncertainty modelling approaches: i) uniform distribution of data between maximum and minimum values and ii) normal distribution using the calculated standard deviation. This allows for identifying which layer has the highest uncertainty and what effects this might have on the final characterisation results.

## Results and Discussion

### Inventory data description

In Table 2 the mean data for the benchmark prototype, along with the statistical variation for each material in each layer of the prototypes, are reported.

The analysis reveals that copper and ruthenium are the prevalent materials in the nanodevice, accounting for 51% and 18% of the composition, respectively. These are followed by aluminium and tellurium, constituting 13% and 7%, respectively. All other materials, including platinum, are less than 5% of the total weight.

As highlighted by the Coefficient of Variation (CV) in Table 2, the materials used in MTJ devices can exhibit significant variability, sometimes exceeding 200%. This high variability is strongly influenced by the different design choices researchers make, because, as mentioned earlier, this technology is still in the experimental and design stages. Thus, identifying a benchmark prototype could be difficult. Therefore, accounting for the effects generated by the statistical variability on results is essential, especially in the preliminary stages, as yet identified by different LCA studies on emerging technologies at low Technology Readiness Levels (TRLs) (Arvidsson et al., 2018; Sander-Titgemeyer et al., 2023).

**Table 10** Inventory data and statistical variability of main materials included in the benchmark prototype functional unit and EOL-RIR

Layer	Material	Mean [ng]	Min [ng]	Max [ng]	Std [ng]	CV	EOL-RIR*
Bottom layer	Aluminum	8.53E-07	-	7.68E-06	2.41E-06	283%	32%
	Cobalt	1.39E-08	-	1.24E-07	3.91E-08	282%	22%
	Copper	5.89E-07	-	3.52E-06	1.13E-06	191%	55%
	Platinum	1.57E-08	-	1.40E-07	4.41E-08	282%	12%
	Ruthenium	4.97E-08	-	3.73E-07	1.15E-07	232%	12%
	Tantalum	4.03E-07	-	2.57E-06	8.02E-07	199%	1%
Free layer	Boron	2.89E-09	1.20E-11	1.33E-08	4.31E-09	149%	1%
	Cobalt	1.68E-08	-	5.32E-08	2.11E-08	126%	22%
	Iron	2.20E-08	3.84E-11	1.27E-07	3.98E-08	181%	31%
	Tungsten	2.34E-09	-	2.10E-08	6.60E-09	282%	42%
Insulating layer	Magnesium	1.49E-09	-	1.04E-08	3.29E-09	221%	13%
	Magnesium oxide	6.51E-09	-	3.35E-08	1.16E-08	178%	13%
Fixed layer	Boron	6.72E-09	6.31E-12	4.92E-08	1.52E-08	226%	1%
	Cobalt	9.18E-08	1.51E-10	5.95E-07	1.83E-07	200%	22%
	Iron	5.72E-08	2.02E-11	4.06E-07	1.26E-07	220%	31%
	Iridium	7.10E-08	-	5.42E-07	1.68E-07	237%	12%
	Manganese	1.95E-07	-	1.51E-06	4.67E-07	239%	9%
	Platinum	3.04E-07	-	2.67E-06	8.35E-07	275%	12%
	Ruthenium	3.56E-08	-	2.04E-07	6.28E-08	177%	12%
	Tantalum	1.35E-09	-	1.21E-08	3.81E-09	282%	1%
	Tungsten	1.95E-09	-	1.75E-08	5.50E-09	282%	42%
Top layer	Aluminum	3.41E-08	-	3.07E-07	9.65E-08	283%	32%
	Copper	2.93E-06	-	2.57E-05	8.07E-06	276%	55%
	Magnesium	1.09E-09	-	9.76E-09	3.07E-09	282%	13%
	Ruthenium	1.14E-06	-	9.58E-06	2.99E-06	263%	12%
	Tantalum	8.59E-08	-	4.99E-07	1.54E-07	179%	1%
Metalworking for all mass device		6.93E-06	1.67E-09	5.47E-05	1.70E-05	245%	

\*Data from European Commission et al. (2023)

## Environmental impacts and contribution analysis

Table 3 reports the potential environmental impacts calculated for the prototype.

The results show that the highest impacts in all categories are linked to the raw materials used in the devices, with the production phase contributing less than 0.05% of the impacts. During the disposal phase, using current EOL-RIR parameters for each material, a reduction of about 12% is observed in each impact category. This indicates that improving recycling processes, particularly for electronic and electrical equipment, could enhance the potential environmental benefits of these devices.

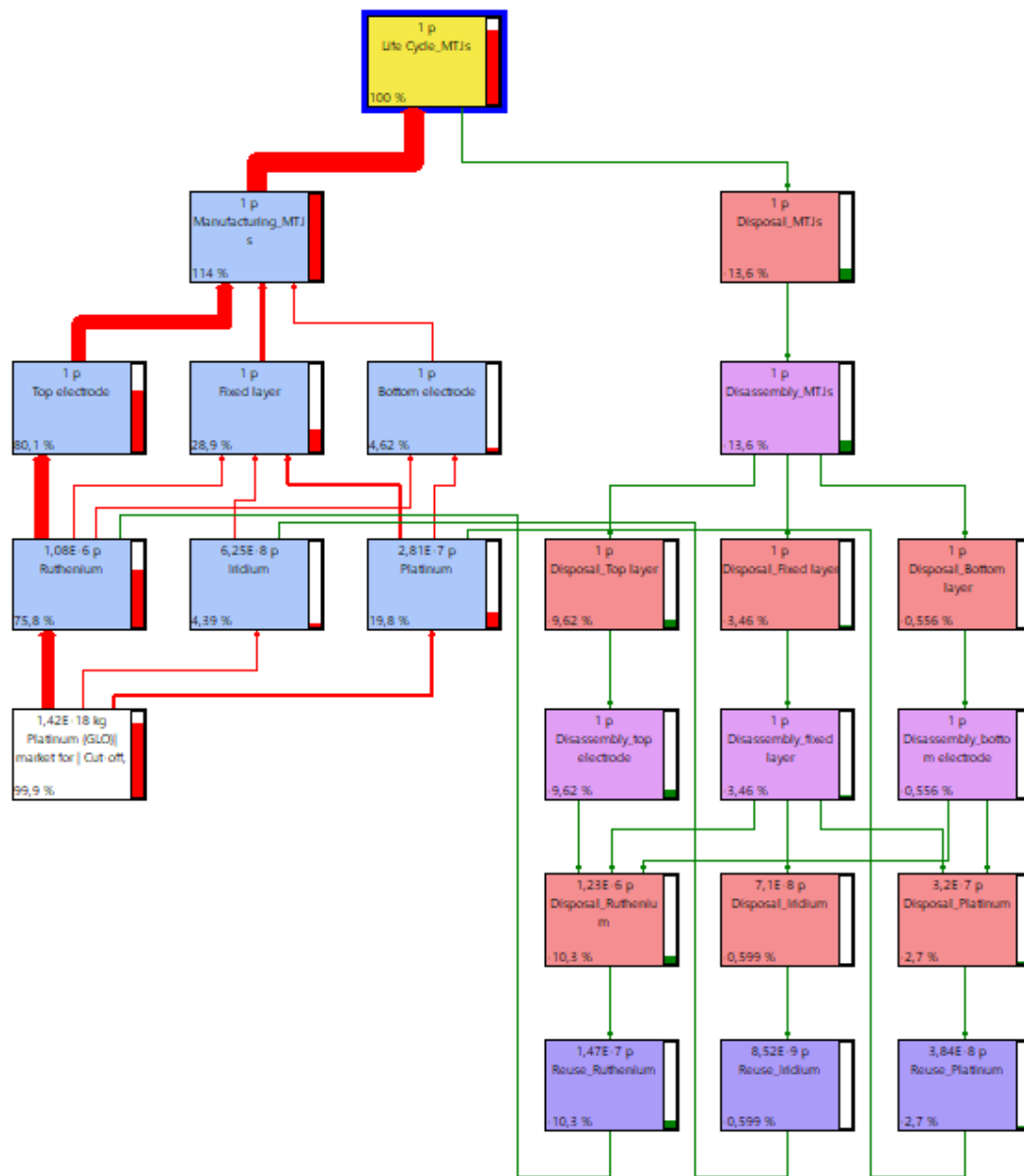
**Table 11** *Potential environmental impacts of the benchmark prototype functional unit ( $\varepsilon = IV/W$ )(characterization results)*

Categories	Units	Phases			Total
		Raw materials	Production	Disposal	
Abiotic depletion	kg Sb eq	5.54E-18	2.60E-21	-6.97E-19	4.85E-18
Abiotic depletion (fossil fuels)	MJ	1.56E-12	1.41E-16	-1.87E-13	1.37E-12
Global warming (GWP100a)	kg CO <sub>2</sub> eq	1.07E-13	1.34E-17	-1.28E-14	9.40E-14
Ozone layer depletion (ODP)	kg CFC-11 eq	4.81E-21	9.65E-25	-5.78E-22	4.23E-21
Human toxicity	kg 1,4-DB eq	3.55E-13	1.10E-16	-4.33E-14	3.12E-13
Fresh water aquatic ecotox.	kg 1,4-DB eq	4.39E-13	1.08E-16	-5.31E-14	3.86E-13
Marine aquatic ecotoxicity	kg 1,4-DB eq	6.15E-10	3.25E-13	-7.42E-11	5.41E-10
Terrestrial ecotoxicity	kg 1,4-DB eq	3.23E-16	7.74E-20	-3.93E-17	2.83E-16
Photochemical oxidation	kg C <sub>2</sub> H <sub>4</sub> eq	2.32E-16	6.20E-21	-2.79E-17	2.04E-16
Acidification	kg SO <sub>2</sub> eq	6.64E-15	1.30E-19	-7.98E-16	5.84E-15
Eutrophication	kg PO <sub>4</sub> <sup>3-</sup> eq	7.10E-16	5.37E-20	-8.54E-17	6.24E-16

Although each nanodevice uses only small amounts of materials, their future widespread use in IoT devices could significantly impact supply risk<sup>3</sup>. Almost all materials used in this device have been identified as critical raw materials by the European Commission (2023), except for cobalt, boron, manganese, magnesium, and tungsten, which are considered strategic for different industrial sectors. Copper is also accounted as a strategic material, although it did not meet the CRM criteria, but it is employed in various technologies and industrial processes.

The effects of the recycling option can be better understood through the network graphical representation developed using Simapro. Figure 2 shows an example of the GWP impact category. The top electrode, followed by the fixed layer, achieves the highest benefits from the reuse of recycled materials.

<sup>3</sup> Supply risk indicates that the supply is associated with a high risk of not being adequate to meet EU industry demand and depends on the recyclability rate, taking into consideration the implementation of circular economy actions during the end-of-life of technologies (European Commission et al., 2023).



**Figure 11.** GWP network contribution of the life cycle of MTJ device (cut-off 0.5%) (characterization results)

Their environmental performance is strongly influenced by the significant, although small, amounts of PGMs, as shown in Figure 2. Even though they represent less than 5% of the nanodevice's weight and their recycling rate is only 12%, they impact both the manufacturing and disposal phases in terms of impacts and benefits. Instead, copper, which represents about 51% of the weight of MTJ and is characterised by a recycling rate of 55%, does not influence the environmental performance of the device. A similar distribution of environmental hotspots has been obtained across all impact categories.

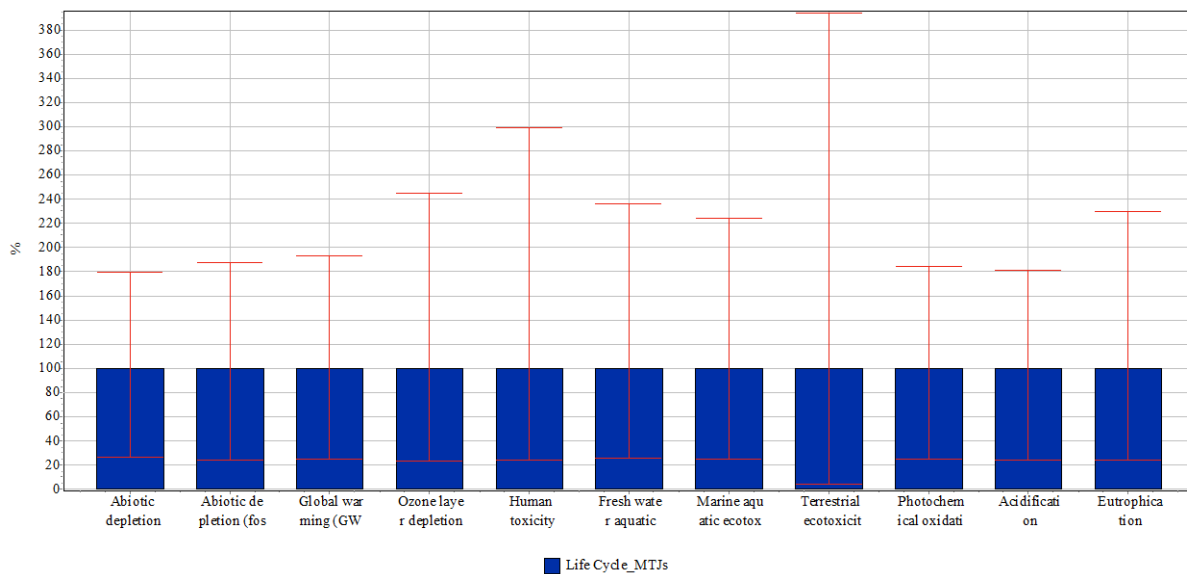
This result highlights the need to identify alternative design solutions that, while maintaining the highest possible energy performance, reduce the presence of PGM materials, confirming what was identified by Palomino et al. (2021) for memory spintronic devices. It is also true that missing reliable data on ruthenium

and iridium, assumed as platinum in this model, could generate the highest uncertainty in environmental impacts. Considering that these kinds of materials have the highest impacts in all impact categories, a consistent distribution is recorded among the different categories for each layer. Different datasets will be chosen in future studies to determine how the selection of different datasets in case of missing data could be reflected in results, such as conducting a sensitivity analysis.

### Uncertainty analysis

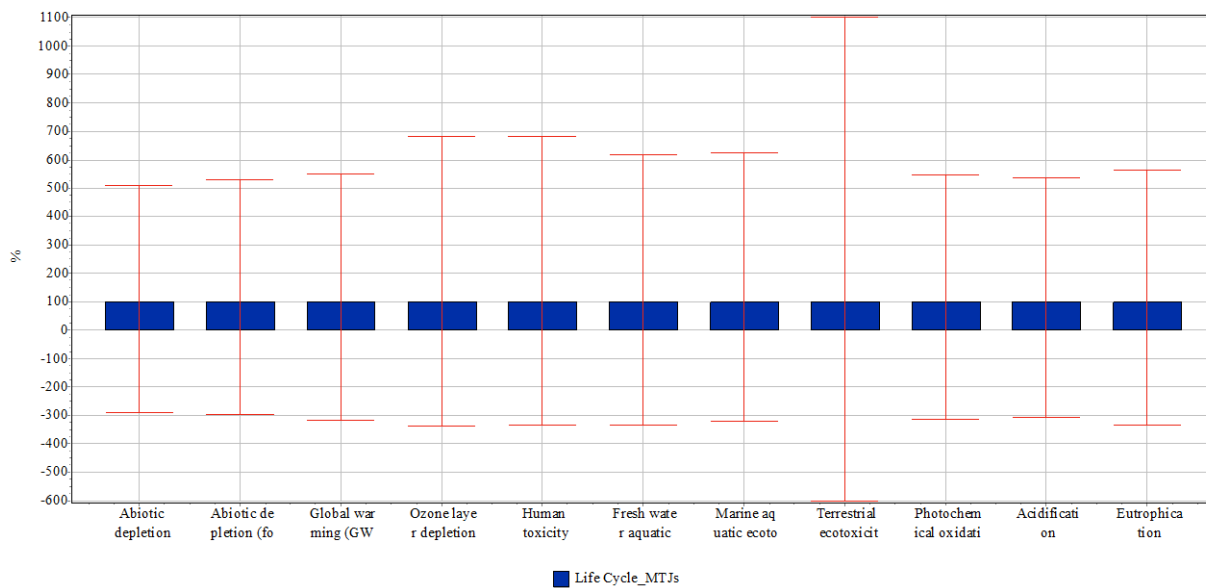
As mentioned above, the study refers to a benchmark prototype, where the highest variability is identified along with the different materials employed (see Table 2). Therefore, conducting an uncertainty analysis is essential in LCA studies, especially for low TRLs technologies and prospective LCA studies. Thus, this study presents the results of the Monte Carlo simulation using two approaches: first accounting for a uniform distribution of data from minimum to maximum values (Figure 3) and then using a normal distribution with standard deviation values (Figure 4).

The first approach (Figure 3) shows that the CV of uncertainty on characterisation results could range from 43% (ADE) to 86% (TE). In some impact categories, from the characterisation results reported in Table 3, average values could also differ by an order of magnitude with a variation of about 300% among them.



**Figure 12** Monte Carlo simulation using the minimum and maximum values with uniform distribution

The second approach (Figure 4) shows that the CV of uncertainty on characterisation results could range from 198% (ADE) to 251% (TE). These results are notably higher than those reported by the first approach, indicating a higher uncertainty in characterisation results. However, calculating the differences between the results reported in Table 3 and the average calculated from the Monte Carlo simulation, only a variability between  $\pm 2\%$  (FAE, ODP, TE) and 8% (NP) is noticeable among impact categories.



**Figure 13** Monte Carlo simulation using the standard deviation values with normal distribution

Although the second approach reports average values closer to those calculated for the benchmark prototype, it estimates negative values for some inventory data, altering the scope of the analysis conducted. Therefore, these results indicate the need to identify and select more appropriate methodological approaches in uncertainty calculation to select the most appropriate case-by-case. Although conducting an uncertainty analysis is widely suggested in the preliminary stage of prospective LCA studies, this information is generally omitted in the literature, representing a challenge in the transparency and reproducibility of studies, especially for emerging technologies (Moni et al., 2020).

## Conclusions

This study conducted a preliminary LCA of MTJ benchmark prototypes using a systematic approach to identify the average quantity of materials employed in the different layers. This study identified improvement options, uncertainties in characterisation results, and critical issues for conducting this kind of study.

The resulting inventory data shows high variability in the materials employed for the functional unit, resulting in a coefficient of variation close to 300%. Focusing on potential environmental impacts, the study shows that the highest impacts are linked to the raw materials phase, particularly using PGMs in almost all layers from the bottom to the top electrodes. Accounting for EOL-RIR, the impacts could be reduced by about 12% in all impact categories. This means that implementing circular practices to reuse materials could strongly reduce impacts and increase the benefits associated with energy technologies. However, different end-of-life scenarios must be implemented to account for the effective efficiency of the recycling process on nanodevices.

Given the emerging nature of this device, no other LCA studies have been identified to validate the results. However, following the initial steps proposed for conducting prospective LCA, an uncertainty analysis using Monte Carlo simulations was conducted. The analysis identified several magnitudes of variability in results,

obtaining different interpretations based on the chosen method. This indicates the need for more guidelines for developing LCA studies on emerging technology, suggesting the most relevant approach to calculate uncertainty in characterisation results. Indeed, communicating uncertainty interpretation represents one of the critical issues associated with emerging technologies and the implementation of prospective LCA.

Future studies will be conducted to identify the best practices in modelling nanodevices, accounting for selecting representative datasets for background processes. In the case of nanodevices, this could strongly affect the characterisation results and the uncertainty estimation.

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