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# Exploring sustainability in emerging technologies: a reference framework utilising multicase studies

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**Abstract:** Recent technological advancements are positioned as a remedy to contemporary challenges in sustainable development. However, existing methods for evaluating the sustainability impact of these technologies are insufficient, lacking comprehensive coverage of a technology's entire lifespan and proving less effective in initial developmental phases. This paper presents three case studies evaluating the sustainability of technological R&D projects in the metal sector, contributing to the advancement of sustainable technological propositions. As a result of the analysis, the paper proposes a robust framework for assessing emerging sustainable technologies. The relevant novelty of this framework is that it can be easily applied to assess technological projects from their conception, including the sustainable assessment of the development itself.

**Keywords:** emerging technologies; technology assessment; sustainable technology; case studies.

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## 1 Introduction

The integration of sustainable technologies has become indispensable in the modern era. These technologies harness sustainable resources, diminish natural resource consumption, exhibit inherent efficiency, or empower consumers to embrace sustainability through active intervention via metering technologies (Neves et al., 2022).

Presently, technologies associated with Industry 4.0 are touted as exemplars of sustainability (Machado et al., 2020). Nevertheless, the overall impact of these technologies on sustainability remains shrouded in uncertainty (Cole et al., 2019; Hickel and Kallis, 2020; Nižetić et al., 2020). For instance, certain studies estimate that artificial intelligence, exemplified by models like chat GPT-3, requires approximately half a litre of water to cool its systems during each 30–50 question conversation. In its training and development phase, it demanded a staggering 700,000 litres of water and consumed 1,287 MWh of electricity, resulting in an environmental footprint of 552 tons of $CO_2$ equivalent (Patterson et al., 2022). Another recent study underscores the environmental footprint of AI as it stands today (Wu et al., 2021). Furthermore, concerns about the social sustainability of artificial intelligence have been raised, particularly regarding the potential displacement of jobs (Bessen, 2019).

All this apparent contradiction in terms of sustainability may be due to the fact that sustainable technology is not merely defined by its nature but also by the manner in which it is conceived, employed, and managed throughout its lifecycle (Möller and Grießhammer, 2022). At this juncture, sustainable technology should incorporate the evaluation of economic, environmental, and social impacts from its inception. This evaluation should persist throughout the research and development phase of the technology, guiding it toward sustainability during implementation, use, and eventual end-of-life processes. While certain initiatives have been launched in this regard, they are not always readily applicable and often fall short of encompassing the entirety of a technology's lifecycle (Bai et al., 2020; Thonemann et al., 2020).

Consequently, to make a substantial contribution to the field of technology sustainability assessment, we pose the following research question: Is it feasible to devise a straightforward means of measuring and guiding the progress of sustainability for a technology from its early stages of research and development?

This article analyses three case studies within the context of the SosIAMet research project, funded by the Basque Government from 2021 to 2023. This project aims to advance research and development (TRL 3-5 levels) in sustainable technologies for the metal sector (with a strong focus on the recycling stage). The analysis includes two aspects: First, it proposes to measure, in a prospective scenario of technology application, the contribution of technologies to the sustainability of the respective sector's value chain. Second, it considers assessing how researchers and technologists are integrating sustainability concepts into the design and development of a technology. Finally, the paper introduces a reference framework for evaluating the sustainability of technological research and development projects, making a significant contribution to the ongoing discourse on the early assessment of the sustainability of emerging technologies.

The subsequent sections of this work are structured as follows: Section 2 provides the research context that contextualises this study; Section 3 presents the project, including a brief explanation of the three case studies. Section 4 explains the methodology followed to analyse the case studies, including the framework derived from the analysis. Finally, Section 5 presents a discussion, conclusions, and an elucidation of the study's limitations.

## 2 Research context

The technologies currently integrated into various industries are the fruits of preceding research and development efforts. In recent years, many of these innovations have become pivotal elements of the so-called Fourth Industrial Revolution, or Industry 4.0. This revolution introduces a novel production landscape characterised by the convergence of information and communication technologies with digital manufacturing techniques (Kang et al., 2016). In theory, this fusion is poised to facilitate the implementation of circular and sustainable practices (Gupta et al., 2021; Machado et al., 2020). They are instrumental in diminishing material and energy consumption while minimising waste generation and emissions (de Mattos Nascimento et al., 2023; Laskurain-Iturbe et al., 2021). However, it is important to acknowledge that not all aspects of innovation in Industry 4.0 technologies necessarily promote sustainability.

For instance, Rejeski et al. (2018) contended that additive manufacturing (AM), when combined with IoT technology, had the potential to contribute to sustainability, but the full implications of its realisation remained challenging to assess. Similarly, Galaz et al. (2021) explored critical aspects and emerging risks, and discussed limitations associated with the implementation and use of AI applications.

Within the social dimension, some authors have analysed the potential of Industry 4.0 to enhance employee health and workplace conditions, while empowering individuals in their professional development (Birkel and Müller, 2021). However, some authors have also pinpointed significant gaps in the contribution of these technologies to social sustainability (Birkel and Müller, 2021; Khan et al., 2023; Machado et al., 2020). Notably, the utilisation of large language models like chatGPT is predicted to impact 80% of the US workforce, as they can potentially execute 50% of the tasks performed by 19% of US workers (Eloundou et al., 2023).

These research contradictions arise from the realisation that sustainability is not an inherent quality of new technologies but rather a characteristic that must be assessed and measured. Organisations must scrutinise how new technologies contribute to sustainability. Currently, there is a scarcity of scientific literature that delineates how these evaluations can be practically executed (Bai et al., 2020).

For instance, Stock et al. (2018) qualitatively assessed the contribution of an industrial technological solution to sustainable development, mainly in environmental and social terms, which was already developed. They introduced a multi-stage methodology wherein the initial macro-level evaluation focused on assessing the solution's business model, as well as its impact on the value chain and product life cycle. This was followed by a micro-level assessment, in which a set of indicators, chosen from the VDI 4605 guide of the German engineering association, were qualitatively evaluated in greater detail to discern their potential evolution. Both assessments involved researchers and experts in the realm of Industry 4.0 affiliated with TU Berlin and Fraunhofer IPK.

Similarly, Bai et al. (2020) devised a hybrid multi-situation decision method that evaluated 17 Industry 4.0 technologies based on their performance across the three dimensions of sustainability and various application sectors. This assessment was conducted through the perceptions of numerous experts regarding how each technology might impact the 14 specific targets encompassed in the Sustainable Development Goals (SDGs). The results provided insights into which technologies had the most substantial impact on each dimension of sustainability, based on experts' opinions. An essential recommendation from these and other studies is the necessity of assessing each technology on a case-by-case basis.

Ribeiro et al. (2020) delved into the literature on AM, and their findings were put into a framework designed to evaluate the sustainability of this technology. In a similar vein, Nelms et al. (2007) employed a framework applied in three phases to assess an intensive green roof technology in a residential building. The methodology engaged various stakeholders, who initially conducted a qualitative evaluation of the solution's potential impact on measurable aspects of sustainability following a prescribed protocol. Subsequently, a more detailed analysis was undertaken to identify how these aspects might influence systems or components of the building. The aim was to identify their impact at different stages of the product's life cycle and, whenever possible, quantify it. The ultimate goal of the framework was to help policymakers and building project developers identify and assess the consequences of employing sustainable technologies.

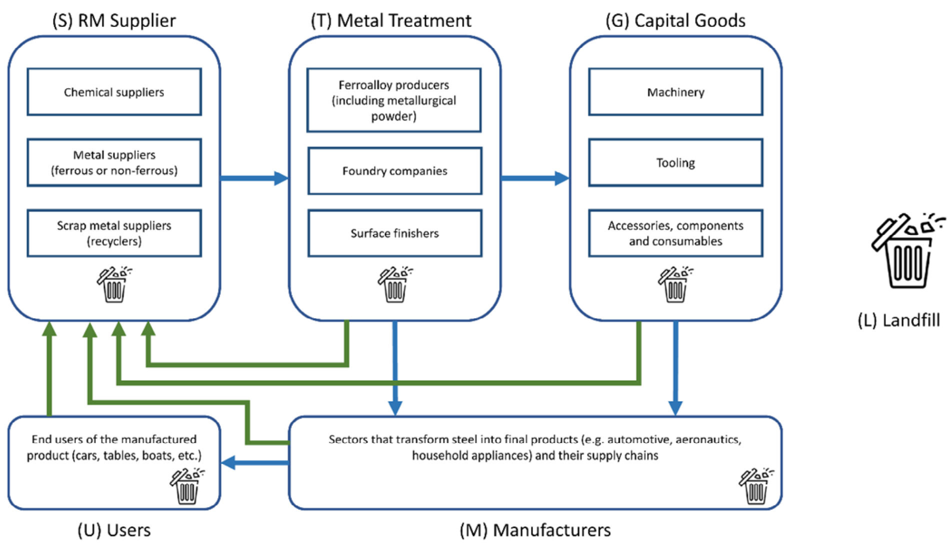
All of these studies share a common characteristic: they evaluate new technologies that are either currently in use or can be promptly implemented. For this same purpose, there are also general tools available that evaluate the impact of a new technology on the life cycle of a product or service through life cycle assessment (LCA) analysis (van der Giesen et al., 2020). LCA focuses on identifying the environmental impacts of products or services throughout their life cycle. Life cycle sustainability assessment (LCSA) also includes economic and social impacts in the measurement, encompassing all three dimensions of sustainability in the measurement. Nevertheless, these tools prove less suitable for assessing emerging technologies at the laboratory scale (Thonemann et al., 2020). For such scenarios, prospective LCA methodologies, also referred to as ex-ante LCA, have emerged. According to some authors (van der Giesen et al., 2020), ex-ante LCA "conducts an environmental LCA of a new technology before commercial implementation to guide R&D decisions aimed at making the technology environmentally competitive compared to existing technologies." Furthermore, adaptations for LCSA have also been developed (Keller et al., 2015; Wang et al., 2018). However, these assessment tools come with their own set of challenges. The most common issues include uncertainty about data availability for a comprehensive LCA study, uncertainty surrounding the technology's future performance, the performance of background systems that host these technologies, and even the potential market share of the technology (Adrianto et al., 2021; Arvidsson et al., 2018; Thonemann et al., 2020; van der Giesen et al., 2020). These challenges become even more apparent in the early stages of technology development (TRLs 1-3) (Thonemann et al., 2020), which primarily concentrate on conceptualisation, technology formulation, and proof of concept. Typically, researchers and technologists in these stages are predominantly focused on achieving functionality and often lack a profound understanding of sustainability implications. Many lack a holistic vision of the product or service's value chain that could benefit from technological advancements.

To advance the development of sustainable technologies that integrate sustainability criteria from their inception, it is essential to have frameworks, methods, techniques, or tools that facilitate straightforward assessments of a new technology's sustainability during its developmental phase. These tools should also provide researchers and technologists with clear guidance to steer them toward sustainable solutions right from the start, accounting for the entire technology life cycle. This approach will help identify and address of sustainability challenges in the early stages of technology development, ultimately contributing to more sustainable production and consumption.

## 3 Case studies

The study presented here was embedded within the SosIAMet (KK-2022/00110) research project ‘Sustainable smart technologies for the metal sector of the future’, funded by the Basque Government (Spain). The overarching goal of SosIAMet was to advance the development of AI-based and other smart technologies to foster the recovery, recycle and valorisation of materials within the sustainable metal sector of the future. It also contained a cross-cutting task focused on measuring the sustainability of the technologies to be developed.

**Figure 1** Metal sector value chain (see online version for colours)




The project encompasses various developments, including the design of new techniques and algorithms for the classification of scrap using cameras and sensors, on-line quality control to improve metallurgical valorisation processes, and advanced simulation models for new alloys and more sustainable metallic powders. The project has addressed the development of eight technological research projects with the participation of 57 researchers and technologists from eight research centres.

Figure 1 provides an overview of the value chain affected by the technologies developed in the SosIAMet project. Visualising the value chain proves instrumental in identifying the specific points where the evaluated technology will have a direct sustainable impact. Furthermore, the interconnected relationships among the value chain’s agents will enable the identification of indirect impacts at various points along the same chain. Following the identification of these impact points, the proposal will designate both direct and indirect indicators designed to quantify the impacts of each technological development.

Due to space constraints, this paper will present the case study analysis of three out of the eight technological research projects. The first case centres on the advancement of novel alloys, the second endeavours to enhance the real-time detection of aluminium alloys, and the third focuses on augmenting the productivity of a metal atomisation powder process.

### *3.1 Case study 1: new steel*

42CrMo4 steel is mainly used in the manufacture of critical high-strength components in complex machines integrated in the transport sector, such as gears, shafts, hitches and cardan joints, pistons in compressors, reinforcement structures in the construction sector and various components for agricultural machinery. In this steel, chromium (Cr) and molybdenum (Mo) are considered critical alloys due to their high price, supply risk or scarcity.

The objective of this technological project is to introduce more affordable, sustainable and abundant alloying elements (Mn, Al and N) to manufacture steels that maintain the same mechanical properties as 42CrMo4.

### *3.2 Case study 2: real-time detection of aluminium alloys*

The metal industry faces escalating challenges as quality standards for manufacturing rise, and regulations demand higher percentages of recycled materials. Meeting these demands requires secondary raw materials of higher purity and more agile production control. Laser-induced breakdown spectroscopy (LIBS) technology emerges as a crucial tool, providing real-time advanced sensorisation. LIBS holds immense potential for automating processes and digitising operations through precise chemical analysis, addressing the evolving landscape of metal manufacturing.

In a pioneering technological initiative, the integration of LIBS technology with advanced machine learning-based data analysis techniques takes centre stage. This research aims to enhance the efficiency of separating mixed metal scrap, particularly alloys like aluminium and steel, while also refining control over the recycled aluminium casting process.

### *3.3 Case study 3: enhancing the efficiency of powder atomisation processes*

The use of a gas to break a melt stream is termed gas atomisation and is widely employed as an effective method to produce fine and spherical metal powders. It is one of the leading methods in the manufacture of powders used in the powder metallurgy industry and AM technologies. These methods build objects from three-dimensional computer-aided design by repeated layer deposition, as opposed to traditional manufacturing methodologies, which are based on material removal. In order to ensure good packing behaviour and limit porosity, the size of the atomised metal used in AM must be within a range that depends on the particular machine used.

The principle of the gas atomisation process involves transferring kinetic energy from a high-speed gas jet to a liquid metal stream, causing it to become unstable. The liquid metal column is first broken into large droplets or ligaments by the expanding gas in the primary atomisation stage. The large droplets are then further disintegrated during secondary atomisation, forming smaller droplets that ultimately solidify in flight as metal particles. The main sustainability objectives of the gas atomisation process are to reduce the amount of gas used for atomisation (currently very high), ensure production and handling of the product with less risk to the worker, or by seeking to use environmentally friendly methods that reduce the carbon footprint of the overall process.

The third technological research lines of the SosIAMet project presented in this article focused on studying the operational conditions and optimal geometric variables that allow increasing the productivity of the gas atomisation process. This involves producing metal powders with narrower particle size distributions and centred in the required size range. In addition, due to the known influence of the GMR parameter (gas-to-metal mass flow rates) on the process, a series of experimental atomisations were conducted by varying this ratio to compare the powders produced in each experiment. Moreover, the influence of pre-heating the atomising gas and optimising critical components were also analysed.

## 4 Case studies analysis methodology

To assess the sustainability of emerging technologies during their conception and development phase, the authors of this study considered adopting a two-pronged approach. First, they considered the sustainability of the technology's design, and second, they scrutinised how research groups and the organisations supporting them developed these technologies. This dual approach promotes a holistic assessment of the technology's sustainability throughout its entire value chain. It also provides a comprehensive understanding of how research teams, within their technology centres, address sustainability concerns.

In order to standardise the analysis, it was decided to design a framework for sustainability assessment for emerging technologies. An expert panel specialised in sustainability issues was established within the SosIAMet project to systematically analyse the case studies. The expertise of participants on the topic of inquiry and the search for scientific consensus are important requirements in any qualitative methods used for theory building (Brady, 2015). In this study, the expert panel was constituted by individuals with expertise in sustainability and an understanding of environmental regulations related to businesses, particularly in the context of the circular economy. The primary objective was to reach a consensus on an assessment methodology that would be user-friendly for researchers and aligned with the sustainability practices already in place at technological centres.

The panel of experts was comprised of five individuals with varying professional backgrounds, blending academic research and practical sustainability experience, including:

- Three sustainability experts responsible for sustainability initiatives in different technological centres affiliated with Basque Research & Technology Alliance (BRTA).
- Two academic researchers specialising in the field of sustainable production.

The diverse composition of this expert panel (Table 1) facilitated the analysis of the case studies and the development of an evaluation framework that seamlessly integrated the academic knowledge of the researchers with the real-world, practical insights of sustainability experts operating in research centres.

**Table 1** Experts involved in the development of the evaluation system

| *Expert type* | *Workplace* | *Area of knowledge* | *Years of experience* |
|---|---|---|---|
| Professor | University | Sustainable production researcher | More than 20 years |
| Professor | University | Sustainable production researcher | More than 20 years |
| Researcher | Technological centre 1 | Sustainability and safety R&D engineer | More than 20 years |
| Expert | Technological centre 2 | Responsible for the R&D&I, quality and environment management system | More than 20 years |
| Researcher | Technological centre 3 | Life cycle sustainability assessment and circular economy expert | More than 20 years |

**Table 2** Principles for developing sustainable technological R&D

| *Principles for developing sustainable technological R&D* |
|---|
| *(1) Design for sustainability and circularity*. Design technological R&D projects so that their application aligns with the sustainable production principles. |
| *(2) Conserve resources and preserve their value*. Preserve the value of material resources, water and energy as long as possible within the research facilities (internal recirculation) and consider sharing resources with other organisations (external recirculation or cross technological symbiosis). |
| *(3) Manage waste* in a sustainable way by promoting waste reduction and reuse activities. Recycle as much as possible by minimising the disposal of waste in landfills. |
| *(4) Pursue a risk-free environment*. Develop technological projects based on chemical substances, physical agents, and technologies that pose minimal or no risk to the environment and people's health. |
| *(5) Prioritise the well-being of researchers*. Incorporate the safety, health, and well-being of researchers into daily work. Choose work practices and workplaces that maintain the physical, functional, and psychological comfort of researchers or technologists. |
| *(6) Increase commitment to sustainability*. Promote commitment to sustainability at the research group level in a manner aligned with the workplace sustainability culture. Empower researchers and develop their talents. Promote diversity, equity and inclusion. |
| *(7) Make a positive contribution to the community*. Contribute positively to the economic, environmental, social, cultural and physical environment of the communities in which the technology research centre operates and those where its decisions may have an impact. |
| *(8) Promote collaboration with value chain stakeholders*. Establish effective communication and collaboration with all stakeholders in the value chain to make the processes and products generated from research more sustainable. |
| *(9) Measure and optimise sustainable processes*. Define a set of 'performance indicators' to optimise research processes. Monitor the short- and long-term sustainability performance of the research system by encouraging digitisation. |
| *(10) Promote the use of the best research methods and technologies that favour the sustainability of the project activity*. Provide information on the potential sustainability benefits and risks of technological projects. |

*Source:* Based on Viles et al. (2022)

The formulation of the sustainability assessment framework for emerging technologies was based on the definition of sustainable production principles introduced by Viles et al. (2022). These principles encapsulate fundamental attributes that facilitate comprehension and elucidate the operation of sustainable production, recognising that technology is an integral component of production systems. Therefore, they served as the foundation for a consensus-building process in crafting an evaluation model for emerging technologies. Following a thorough analysis of the sustainable production principles (Viles et al., 2022), the expert panel concurred that an adaptation of the same ten conceptual principles that delineate the functionality of sustainable production could be effectively applied to assess the sustainability of emerging technologies.

Table 2 contains the definition of the principles for developing sustainable technological R&D. To assess whether each new technological development complies to these principles, a checklist is provided for each principle. This enables both quantitative and qualitative assessments of how well the principles have been applied.

**Table 3** Summary of sustainable activities carried out within the framework of the SosIAMet project (qualitative assessment)

| *General summary* | |
|---|---|
| 1 | Only 35.7% of the research and development groups say that there are recirculation actions of materials, water and/or energy among this project and other projects of the same team or other units of the research centre. |
| 2 | 100% of the research and development groups say that there is selective waste collection in the centre. There is no sign of a proactive attitude. |
| 3 | 57.1% of the research and development groups say that they are carrying out sustainable mobility actions as part of the development of this project with the aim of reducing emissions. |
| 4 | 78.6% of the research and development groups responded positively to questions related to worker well-being (functional, psychological, and physical). |
| 5 | Only 14.3% of the research and development groups recognise that the centre's sustainability policies (such as decarbonisation and energy efficiency) have any impact on the project's development and only 21.4% plan actions aimed at environmental or social improvement in the development of the project (not linked to the technical objective of the project itself). |
| 6 | Only 50% of the research and development groups plan to produce informative (non-scientific) project material. |
| 7 | Only 7.1% of the research and development groups include partners or collaborators with sustainability criteria in their projects. |
| 8 | In 100% of the research groups, economic and operational controls are common activities, but environmental and social controls are not. LCA in general is neither requested nor mandatory. |
| 9 | Only 7.1% of the research and development groups have made technology purchases based on sustainable criteria. |
| 10 | Only 28.6% of the research and development groups consider the risks and benefits related to the sustainability of the technological research they are conducting. |

Leveraging the insights of the experts, a consensus was eventually attained regarding the principles that would constitute the bedrock of the emerging technology evaluation. Subsequently, a comprehensive checklist for their evaluation was devised. The formulation of this checklist took into account not only the definition of each principle, but also a set of indicators that help quantify the application of these principles (Viles et al., 2023) and the practices and indicators adopted by the technology centres within the scope of their integrated quality, environmental and safety standards. All the elements detailed – the principles delineating the development of sustainable technology, the corresponding checklist, and the outcomes of their practical application – were combined to form a comprehensive reference framework for the assessment of emerging sustainable technologies. The checklist for each of them is detailed in Annex.

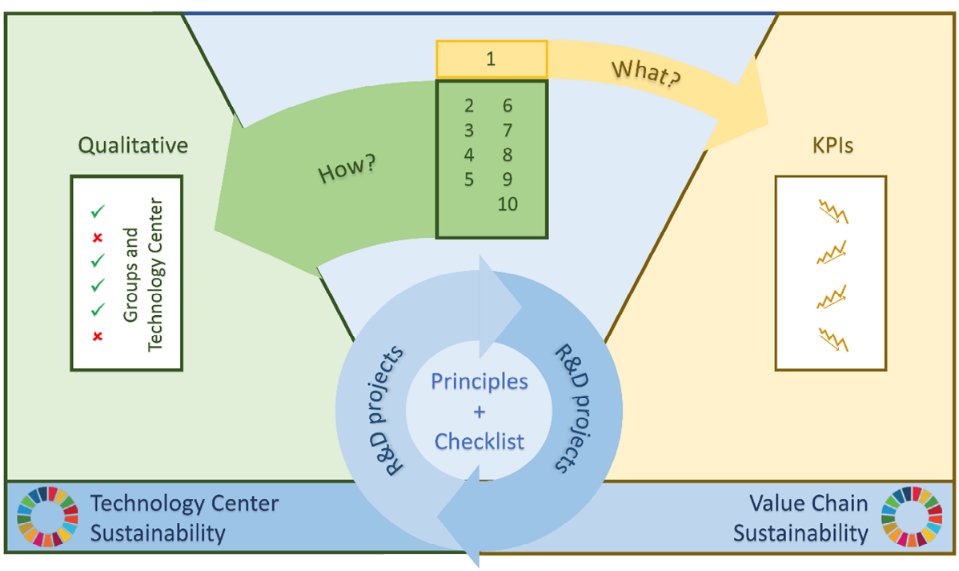
The application of the checklist encompassing Principles 2 to 10 facilitated the evaluation of the conduct of each research group within the SosIAMet project concerning sustainable research in the context of their respective research centres. Table 3 presents the collective findings from the evaluation of all participating research groups, spanning eight different research centres.

## *4.1 Emerging technology assessment framework*

Figure 2 shows, at a conceptual level, the proposed reference framework for assessing emerging technologies. As illustrated, the assessment focuses on evaluating whether and how the ten principles that the panel of experts agreed upon as a definition of sustainable technological development are met.

As also shown in Figure 2, this evaluation encompasses an assessment of the potential impact these technologies may have on sustainable production in the future (‘What sustainable technology is being developed’ in Figure 2). It also takes into account how the current development of these technologies affects the sustainability of the technology centres where they are being created (‘How is it developing’ in Figure 2).

**Figure 2** Emerging technology assessment conceptual framework (see online version for colours)




Principle 1, denoted as ‘Design to create a sustainable technology’, emphasises that when designing research projects focused on developing technologies, it is important to consider the sustainability criteria that will be used to evaluate the organisations affected by the technology. In line with this concept, the proposed framework encourages the formulation of objectives related to how the technology under development can help meet sustainable production principles within the organisations that will adopt it, as well as across their entire value chain. The evaluation of this principle also involves identifying a set of key performance indicators (KPIs) for each technology ('KPIs' in Figure 2), aligned with the sustainability objectives defined for each specific case. Monitoring these indicators throughout the technology development process will guide researchers in assessing the progress of the emerging technology's sustainability. For instance, they will provide a means to monitor and guide the technology's sustainability as it advances through subsequent development projects.

Principles 2 through 10 evaluate how the development of the technology impacts the sustainability of the technology centre in which the research group operates. Like Principle 1, these principles are paired with checklists designed to gauge the application of each criterion ('qualitative' in Figure 2). These checklists have been developed with input from individuals responsible for technology centre sustainability, as well as considerations of relevant environmental regulations. As a result, the analysis derived from these checklists offers feedback to the technology centre regarding the integration of sustainability criteria into the daily activities of its researchers. In this case, the checklist collects both qualitative and quantitative data from research and technology development groups (see Annex for details).

The application of the proposed assessment framework allowed the definition of a set of key indicators for each technological innovation. These indicators were chosen by consensus among the project researchers and are aimed at assessing the sustainability of ongoing technological development. The selection of these indicators was guided by the questions posed in Principle 1 (see Annex), taking into account the future impact of the technology on the value chain. These indicators chosen for each case will serve as a valuable reference for monitoring the progress of the technology's sustainability throughout its further development.

Finally, incorporating sustainability principles and regular assessment using the checklist can lead to a cascade of positive impacts. By fostering a culture of sustainability within the research centre and throughout the value chain, the research project will not only contribute to the organisation's sustainability but also support broader global sustainability goals, such as the United Nations SDGs.

Within this framework, it is suggested that, beyond detailing the indicator, a baseline value (representing the current value of the indicator for the existing technology) is established for each. This is accompanied by a target value (indicating the potential value of the indicator upon full implementation of the technology under development) and a current value (reflecting the current status of the technology undergoing evaluation). While at times the current value aligns with the objective, challenges in implementing the solution in the industry often stem from the complexities of scaling the results obtained in the technology centre. In other cases, the calculation of the indicator does not apply to the level of development of the technology being evaluated. However, the indicator that measures a sustainable goal of technology development should not be ignored for this reason.

Table 4 offers insight into the selected indicators for the three analysed projects and their evolution over the course of project implementation. For confidentiality reasons all indicators will be expressed as a percentage. This explains the lack of a base value for some of the indicators in the table.

**Table 4** KPIs for sustainability evaluation and monitoring for the three projects

*CASE 1. KPIs for sustainability evaluation and monitoring*

| *Indicator type* | *Indicator* | *Impact on metal life cycle* | | | *Indicator formula* | *Expected trend* | *Baseline* | *Current value* | *Target value* |
|---|---|---|---|---|---|---|---|---|---|
| | | *(S) RM supplier* | *(T) Metal treatment* | *(U) Users* | | | | | |
| DIRECT | Amount of steel scrap in the composition | Greater valorisation of steel scrap | Greater diversification of RM admissible | | % scrap with steel residues/Tn steel for automotive use | | 0.0% | 100.0% | 100.0% |
| DIRECT | Amount of Cr and Mo in the composition | | Lower consumption of critical RM | | % Cr and Mo in steel recipe | | 1.1% Cr 0.3% Mo | 0% Cr 0% Mo | 0% Cr 0% Mo |
| DIRECT | Amount of secondary aluminium scrap in the composition | Greater valorisation of aluminium scrap | Greater ease of use of recycled RM | | % of secondary aluminium scrap used | | 0.0% | 3%–4% | 3%–4% |
| INDIRECT | Final product weight | | | Lower fuel consumption | % reduction in the real weight of manufactured parts | | AV | N/A | 7% |

*CASE 2. KPIs for sustainability evaluation and monitoring*

| *Indicator type* | *Indicator* | *Impact on metal life cycle* | | | *Indicator formula* | *Expected trend* | *Baseline* | *Current value* | *Target value* |
|---|---|---|---|---|---|---|---|---|---|
| | | *(S) RM supplier* | *(T) Metal treatment* | *(L) Landfill* | | | | | |
| DIRECT | Analysis time for detection | | Reduction in production lead time | | % Reduction in analysis time per cast | | AV | 35% | 35% |
| INDIRECT | Amount of waste generated | | | Reduction in the amount of aluminium shavings | % Reduction in the weight of waste generated per sample | | 5% | N/A | 0% |
| INDIRECT | Energy Consumption fusion STAGE | | Reduction of energy consumption | | % Reduction of energy intensity (Kwh energy/TN of casting) | | AV | N/A | 20% |

*CASE 3. KPIs for sustainability evaluation and monitoring*

| *Indicator type* | *Indicator* | *Impact on metal life cycle* | | | *Indicator formula* | *Expected trend* | *Baseline* | *Current value* | *Target value* |
|---|---|---|---|---|---|---|---|---|---|
| | | *(T) Metal treatment* | *(G) Capital goods* | *(L) Landfill* | | | | | |
| DIRECT | Atomisation process performance | Lower production cost | Part RM price reduction | | % performance increase for three technologies (*) | | 12% | 20.00% | MAX |
| | | | | | | | 26% | 35.00% | MAX |
| | | | | | | | 27% | 30.00% | MAX |
| DIRECT | Energy consumption of the atomiser | Lower energy consumption | Part RM price reduction | | % GMR reduction | | AV | 57% | MAX |
| DIRECT | Amount of powder waste out of range for manufacturing | | | Lower amount of metal powders | % reduction of powders out of range for landfill | | 35 | 15 | MIN |
| INDIRECT | Amount of ceramic waste to landfill | | | Less amount of ceramic waste | % reduction of ceramic waste for three technologies (*) | | AV | 41.00% | MAX |
| | | | | | | | AV | 25.00% | MAX |
| | | | | | | | AV | 12.50% | MAX |
| INDIRECT | Improves staff working conditions | Less exposure to loud noises | | | % reduction in exposure time to loud noises | | Same reduction as the previous indicator | | |

Note: (*) 1 BJ (0–20 µm); 2 L-PBF (20–53 µm); 3 DED (53–110 µm).

## 5 Discussion and conclusions

The idea that each innovation project should not only advance technological capacity but also contribute to improving sustainability is a valuable and forward-thinking concept. It aligns with the growing emphasis on sustainable development and the role of technology in addressing environmental and societal challenges. By integrating sustainability considerations into innovation projects, organisations and research centres can work towards a more environmentally friendly and socially responsible future.

However, the intricate and dynamic relationship between the environment and technology underscores the complexity of sustainable technological development. Technologies, in their resource utilisation and environmental impact, necessitate careful management. In this regard, technology assessment assumes a pivotal role. Over the past decade and persisting today, numerous authors have emphasised the imperative to devise more effective approaches to sustainable technology assessment (Bai et al., 2020; Ibáñez-Forés et al., 2014; Tran and Daim, 2008).

Consequently, this study offers a comprehensive framework for evaluating the sustainability of emerging technologies based on the analysis of eight case studies (three of them presented in this paper) framed in a research project. This framework encompasses a set of defining characteristics for sustainable technological development, delineated as ‘principles’, along with an accompanying evaluative tool known as a ‘checklist’.

A notable innovation within this evaluation framework, in contrast to other technology evaluation systems, is its adoption of a dual-pronged approach. One facet relates to the assessment of a technology’s sustainability taking into account its utilisation and eventual decommissioning. The other aspect focuses on how a technology contributes to sustainability from its inception. This holistic dual approach integrates the comprehensive analysis of a technology’s impact on sustainability throughout its entire value chain, from its creation to its obsolescence. It aligns with the viewpoints of scholars advocating for the inclusion of sustainability considerations within the early stages of a technology’s life cycle, bringing the assessment of sustainable technologies closer to R&D decision-making processes (Möller et al., 2021).

Moreover, this framework offers a qualitative evaluation in addition to quantitative methods. This dual approach not only simplifies assessment but also widens its applicability, especially in the early phases of technology development. To address the challenge recognised in the literature, which pertains to the inaccuracy and difficulty of assessing the sustainability of emerging technologies due to the absence of precise data, the framework proposes the selection of KPIs linked to the technology’s development and chosen by researchers, technologists and sustainability experts. These KPIs are readily measurable and serve as guiding tools for subsequent evaluations. The combination of qualitative and quantitative evaluations tackles the existing challenges by avoiding dependencies on data that may not be available or may be based on estimations that diverge from the actual context (Bisinella et al., 2021; van der Giesen et al., 2020).

In terms of practical implications, the concept of technology assessment suggests that a technology should be evaluated within the specific environment where it is intended to function (Eriksson and Frostell, 2001). Therefore, as an initial validation of the proposed evaluation framework, this study presents the results of evaluating several technological developments within the SosIAMet research project, applying the framework to a set of cases. These evaluations take into account the value chain of the metal sector, which stands to gain from the technological developments under scrutiny.

Table 4 shows that the KPIs vary depending on the technology being assessed. In some cases, the KPIs do not address all three aspects of sustainability (economic, environmental and social). For example, among the case studies presented, only case 3 has an associated social KPI. That is because the other two technologies under development 'a priori' will not directly affect the well-being of people and the sustainable development of society. Moreover, from a utility point of view, in the three cases evaluated, KPIs have been defined allowing researchers to be aware of the potential impact that the development of the technology will have on sustainable production. They also allow for evaluating operational, economic, environmental, and social objectives as the technology is developed. This provides traceability of research projects regarding sustainability, helping to address the complexities of sustainability issues in technology from the outset. This information is also intended to assist scientists faced with the need to engage with the content of the science they develop and the SDG framework (Schrage et al., 2023).

Upon scrutinising the results (see Table 3), it is clear that there is substantial room for improvement in the involvement of researchers and technologists in sustainability within the evaluated technology centres. These improvements should primarily focus on integrating sustainable criteria into partner and collaborator selection during technological developments, incorporating sustainable criteria into the procurement of technology used in these projects, and fostering awareness regarding the vital importance of controlling environmental sustainability at every stage of development. These reflections find common ground with the viewpoints of other scholars (Ávila et al., 2017; Lizarralde et al., 2020). The information gathered through the evaluation of how researchers and technologists have been conducting their technological projects serves as valuable feedback for sustainability management in the research centres where these technologies are developed.

Furthermore, this evaluation framework advances sustainable development by enabling the assessment of a new technology's sustainability from its inception. This entails identifying, from the outset and with the information available at any given time, the sustainability aspects enhanced by the technology and the extent to which it will do so within the future value chain it influences. Simultaneously, the framework helps identify aspects of sustainability that may be adversely affected by the technology's development. Identifying these aspects in the early development phases permits monitoring and the pursuit of countermeasures to mitigate any potential adverse effects as the technology progresses.

Finally, a limitation of this study could be the potential bias introduced by the experts who shaped the framework. While their expertise complemented each other, their shared geographical background may somewhat influence their perspective, as it is rooted in their cultural context. Hence, it is advisable to apply this evaluation framework to diverse technology projects in various global contexts to validate the checklist more comprehensively or propose necessary enhancements.

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## Annex

| *(1) Design for sustainability and circularity. Design technological R&D projects so that their application aligned with the sustainable production principles* | | | |
|---|---|---|---|
| *Questions* | *Yes* | *No* | *Complete, if necessary* |
| In the future, would the implementation of the project contribute to sustainable development by reducing the extraction of natural resources (raw materials, energy, water) necessary for the development of metal/metallurgy sector processes? If yes, please specify how. | | | |
| In the future, would the implementation of the project contribute to the circular economy by facilitating the sustainable management of waste from metal/metallurgy sector processes: by reducing, reusing and/or recycling waste to minimise its disposal in landfills? If yes, please specify how. | | | |
| In the future, would the implementation of the project contribute to sustainable development by reducing the risk to the environment (physical agents, chemicals, GHG) and to human health generated by metalworking processes? If yes, please specify how. | | | |
| In the future, would the implementation of the project contribute to sustainable development by improving the safety and well-being (physical, functional and psychological) of workers in the metal/metallurgy sector? If yes, please specify how. | | | |
| In the future, could the implementation of the project contribute to sustainable development by increasing the commitment of companies in the metal sector to sustainability by ensuring diversity, equity and inclusion in the workplace where the technology is implemented? If yes, please specify how. | | | |
| In the future, would the implementation of the project contribute positively to the sustainable development of the community in the economic, environmental, social, cultural and physical environment? If yes, please specify how. | | | |
| In the future, would the implementation of the project lead to more effective collaboration between the different actors in the value chain to make the processes and products of the sector more sustainable? If yes, please specify how. | | | |
| In the future, would the implementation of the project contribute by improving the measurement of sustainability in the processes where it is applied and by promoting the digitalisation of the metal/metallurgy sector? If yes, please specify how. | | | |

**Annex (continued)**

| *(2) Conserve resources and preserve their value. Preserve the value of material resources, water and energy as long as possible within the research facilities (internal recirculation) and consider sharing resources with other organisations (external recirculation or cross technological symbiosis).* | | | |
|---|---|---|---|
| *Questions* | *Yes* | *No* | *Complete, if necessary* |
| Is there any provision for excessive electricity consumption in the development of the technology project (project)? If yes, specify the cause. | | | |
| Is there any provision for excessive water consumption in the development of the project? If yes, specify the cause. | | | |
| Is there recirculation of materials, water and/or energy between this project and other projects of the same team or other units of the research centre? If yes, specify which. | | | |
| Is there any equipment required for the project that is not currently available? If yes, specify which. | | | |
| Are equipment/facilities shared with other organisations during project development? If yes, specify which. | | | |
| *(3) Manage waste in a sustainable way by promoting waste reduction and reuse activities. Recycle as much as possible by minimising the disposal of waste in landfills.* | | | |
| *Questions* | *Yes* | *No* | *Complete, if necessary* |
| Is there any forecast on the type and quantity of waste that will be generated during the development of the project? If so, please indicate the nature of the waste. | | | |
| Is there a waste management plan for the development of the project taking into account the hierarchy of reduce, reuse and recycle? If yes, please specify. | | | |
| Is there a selective collection of waste generated during the project? If yes, specify the type of containers available. | | | |
| Is part of the waste generated during project development expected to be used/sold/donated for secondary purposes? If yes, specify how it will be used. | | | |
| *(4) Pursue a risk-free environment. Develop technological innovations based on chemical substances, physical agents and technologies that do not present or reduce the risk to the environment and people's health.* | | | |
| *Questions* | *Yes* | *No* | *Complete, if necessary* |
| Are toxic chemicals and/or pollutants used during project development? If yes, specify the type and quantity of substances potentially hazardous to health and the environment. If applicable, provide SDS (safety data sheets). | | | |

**Annex (continued)**

| *(4) Pursue a risk-free environment. Develop technological innovations based on chemical substances, physical agents and technologies that do not present or reduce the risk to the environment and people's health.* | | | |
|---|---|---|---|
| *Questions* | *Yes* | *No* | *Complete, if necessary* |
| Within the framework of the development of this project, and if applicable, is the admissible noise and temperature level for the development of the project controlled? | | | |
| Within the framework of the development of this project and with the objective of reducing emissions, have actions been established to achieve a more sustainable mobility (e.g., using a type of transport with low GHG emissions, conducting on-line work meetings, etc.). | | | |
| *(5) Prioritise the well-being of researchers. Incorporate the safety, health, and well-being of investigators into daily task. Choose work practices and workplaces that maintain the physical, functional, and psychological comfort of researchers or technologists.* | | | |
| *Questions* | *Yes* | *No* | *Complete, if necessary* |
| Within the framework of the project, are researchers informed about occupational risk prevention? If yes, please specify how. | | | |
| If relevant to the project, do the researchers have the necessary personal protective equipment (PPE)? | | | |
| Does the project team have enough resources (time, laboratories, and appropriate equipment) to successfully carry out the project? If any of them are lacking, please state which. | | | |
| If applicable, are there clear guidelines for conflict management within the project team? | | | |
| Are there guidelines or procedures in place for researchers to make suggestions on environmental management, ORP, quality or other issues? If so, specify what type. | | | |
| *(6) Increase commitment to sustainability. Promote commitment to sustainability at the research group level in a manner aligned with the workplace sustainability culture. Empower researchers and develop their talents. Promote diversity, equity and inclusion.* | | | |
| *Questions* | *Yes* | *No* | *Complete, if necessary* |
| Does the project activity itself require compliance with specific environmental regulations or legislation (e.g., hazardous waste permits, etc.)? Are there any costs associated with non-compliance? If yes, please specify. | | | |
| Are the centre's sustainability policies (such as decarbonisation and energy efficiency) recognised as having any impact on the project's development? If yes, please specify. | | | |

## Annex (continued)

| *(6) Increase commitment to sustainability. Promote commitment to sustainability at the research group level in a manner aligned with the workplace sustainability culture. Empower researchers and develop their talents. Promote diversity, equity and inclusion.* | | | |
|---|---|---|---|
| *Questions* | *Yes* | *No* | *Complete, if necessary* |
| Are there actions aimed at environmental or social improvement in the development of the project (not linked to the technical objective of the project itself)? If yes, specify which. | | | |
| Has gender parity been taken into account in the research team working on the development of the project? Specify the percentage of women responsible for tasks in the project. | | | |
| Does the team include people with functional diversity? If yes, specify the percentage of people with functional diversity in the work team. | | | |
| Is it foreseen that the researchers will receive some type of training during the development of the project? If so, please specify what type. | | | |
| *(7) Make a positive contribution to the community. Contribute positively to the economic, environmental, social, cultural and physical environment of the communities in which the technology research centre operates and those where its decisions may have an impact.* | | | |
| *Questions* | *Yes* | *No* | *Complete, if necessary* |
| Have the companies that could benefit from the knowledge generated by the project been identified? If so, specify how many. | | | |
| Are there activities to disseminate the project and publicise its potential impact on society? If yes, specify how many activities and what type. | | | |
| Are specific dissemination materials planned for the project in several languages? If so, please specify what type. | | | |
| Are jobs expected to be created as a result of the project (direct jobs, pre- or post-doctoral contracts, training grants...) If yes, specify how many and if they belong to the local community. | | | |
| *(8) Promote collaboration with value chain stakeholders. Establish effective communication and collaboration with all stakeholders in the value chain to make the processes and products generated from research more sustainable.* | | | |
| *Questions* | *Yes* | *No* | *Complete, if necessary* |
| Are new synergies expected to be generated between stakeholders as a result of the development of the project? If so, please state which. | | | |
| Are sustainability criteria considered for the selection of suppliers and/or project collaborators? If yes, specify which. | | | |
| Are sustainability criteria considered during project development with the end user in mind? If yes, specify which. | | | |

## Annex (continued)

| *(9) Measure and optimise sustainable processes. Define a set of 'performance indicators' to optimise research processes. Monitor the short- and long-term sustainability performance of the research system by encouraging digitisation.* | | | |
|---|---|---|---|
| *Questions* | *Yes* | *No* | *Complete, if necessary* |
| Is there an environmental management system in place? If yes, specify which. For example: ISO 14001, EMAS, PAS 2050, etc. | | | |
| Does the project require a life cycle assessment (LCA)? | | | |
| Is the project managed digitally in terms of documentation storage, project tracking, impact measurement, etc.? | | | |
| Does the project have a system for measuring productivity, costs and/or project progress? If yes, specify what type. | | | |
| *(10) Promote the use of the best research methods and technologies that favour the sustainability of the project activity. Provide information on the potential sustainability benefits and risks of research or technological innovation.* | | | |
| *Questions* | *Yes* | *No* | *Complete, if necessary* |
| Do the research activities incorporate best available technologies (BAT)? If yes, specify which. | | | |
| For the implementation of the project, have technology procurement and purchases been or will be made based on sustainable criteria? If so, specify what type. | | | |
| Are the risks and benefits linked to the sustainability of the project considered? If yes, explain what they would be. | | | |
| Are there any limitations to making the equipment used in the project's development more sustainable? If yes, please specify. | | | |