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Prospective life cycle assessment of titanium powder atomization

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A R T I C L E I N F O

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A B S T R A C T

The environmental sustainability of titanium powders production mainly depends by atomization that is the most diffused technology in this field, ensuring the environmental advantages of high mass flow rate, energetical efficiency and reduced waste which have greatly encouraged its diffusion on an industrial scale. However, few quantitative assessment studies have been proposed on atomization sustainability and none of them consider the many technological evolutions of atomization that the industries are working on. This study proposes a prospective life cycle assessment (LCA), of the ex-ante type, of future new Electrode Induction Gas Atomization (EIGA) and Plasma Rotating Electrode Process (PREP) that will produce Ti6Al4V powders in 2035. This time point, referring to a medium-term view is considered to ensure the relevance and the reliability of technology forecasts based on quantitative estimates. Both the systems have been modelled through data retrieved from patents to assess their future impacts. The prospective LCA shows that in the future EIGA the average impact, in each indicator, will be 50% lower for electrical consumption and 98% lower for argon consumption compared to future PREP. The future EIGA and future PREP are more sustainable than the mature EIGA (of the crucible and crucible-free type) and mature PREP (of the traditional and supreme-speed plasma type) currently on the market. The average impact reductions, respectively passing from future to mature EIGA and PREP, are 65% and 23% for electricity consumption and 11% and 28% for argon consumption. The variabilities in technological solutions, scalability and future scenarios about electricity and argon production scale all the impacts without reverse the ranking. At a structural level, the most sustainable solutions are the optimization of the geometries of the titanium bar in the future EIGA and the optimization of the disposition of the plasma gun in the future PREP. This study shows which technological advancement increase the sustainability of EIGA and PREP atomization process in the future and to what extent in the two cases.

1. Introduction

In recent years, the demand and production of titanium powder have grown significantly worldwide, due to the many new applications in the biomedical and aeronautical sectors, in which the progresses of additive manufacturing have played a fundamental role (Takeda et al., 2020). This is mainly due to some advantages that additive manufacturing based on titanium powder can guarantee. In general, orthopaedic and dental implants can be realized in a personalized way and with an almost clear shape, otherwise not possible with other processing techniques or not economically advantageous (Jang et al., 2020). While, damaged aerospace components can be easily repaired and functionally graded materials can be fabricated thanks to the capability of feeding dissimilar powders (Liu et al., 2021). The global titanium powder market was worth USD 1.2 billion in 2022 and is projected to expand significantly from 2023 to 2032, with specific projections for different types of titanium powders and their market share growth. The global sponge production, i.e., a precursor of titanium powder, surpassed 341,000 metric tons (Jena et al., 2021). The additive manufacturing of titanium powders also allows for advantages in terms of environmental sustainability. The lightweight design and in particular the topology optimization allowed to reduce the quantity of material used in prostheses and aerospace components, while guaranteeing the mechanical characteristics (Rodriguez-Contreras et al., 2021). The reusability and the recyclability of both the powders discarded by additive manufacturing processes and the raw materials used to produce the powders provide interesting results in the logic of the circular economy (Moghimian et al., 2021). This is because the environmental impacts in the life cycle of titanium powder are strongly concentrated in the atomization phase, which can be avoided by reusing the powders although this option is only feasible to a small extent (Cappucci et al., 2020). Another impacting phase is the Kroll process which transforms the mineral (i.e., ilmenite or rutile) into metallic titanium which is then atomised (Landi et al., 2023). This step can be avoided by using scrap

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instead of ore.

To meet the growing demand for titanium powder and improve their physical properties both to increase the quality of the powder-made products and reach for new application fields, the production technologies have been improved in different ways. Novel chemistries for composite or blended powders have been obtained (e.g., Srinivasan and Ananth, 2022). The scraps were combined with the mineral as raw material for the production of the powders, so as not to be excessively dependent on mining operations which are not very sustainable on an economic and environmental level (e.g., Tebaldo et al., 2023). The structure of the technologies has been optimized to increase the performances production performances, for example by resisting higher working temperatures (e.g., Careau et al., 2023). In particular, the innovation of the atomizer, which is the heart of the process, is fundamental to achieve these objectives and is proceeding mainly by intervening on the structural components (Żrodowski et al., 2021) and on the geometric arrangement inside the reactor (Yurtkuran and Ünal, 2020).

Doubts about the environmental sustainability of powders produced by atomization have been raised for some time, undermining the very sustainability of additive manufacturing that uses them compared to other production methods (Ford and Despeisse, 2016). To shed light on the problem, the evaluation of the environmental sustainability of the production of titanium powder has been carried out in some studies. Most of the studies analysed only one existing production process or part of it, generally providing qualitative considerations on certain environmental issues (e.g., Xia et al., 2019; Colorado et al., 2020; Williams and Boyer, 2020). Few studies have proposed a rigorous analysis of environmental impacts, i.e., the life cycle assessment (LCA) of individual processes or components (Gao et al., 2018, 2021; Landi et al., 2023; Cappucci et al., 2020). Even fewer studies have analysed the environmental sustainability of the most recent developments and even the experimental state of production technologies. Jiao et al. (2020) qualitatively described the environmental issues related to the use of recycled materials in some evolutions of productive technologies. Spreafico et al. (2023) quantitatively evaluate the environmental sustainability of some specific improvement interventions on parts of reactors and limited to a case study to exemplify a methodology. From these studies it emerges that the atomization accounts for almost 80% of the impacts in the production of a titanium product through additive manufacturing (Cappucci et al., 2020). Within the powder production process, atomization is responsible for over 95% of impacts in most impact categories, with the exception of ecotoxicity and mineral resources scarcity, where it is surpassed by the metallurgical process of mineral transformation (Landi et al., 2023). In the most widespread atomization technologies, i.e., the gas type, the consumption of argon impacts on average 84%, if recycling solutions are not implemented (Santiago-Herrera et al., 2023).

The analysis of the literature therefore shows: the growing demand for titanium powders; the importance of the atomizer in the production of titanium powder; the main role of the atomizer in the generation of environmental impacts; the efforts that are being made to innovate the atomizer in order to improve the quality of the powders and the environmental sustainability. However, there is a lack of quantitative and rigorous analysis that quantify whether and how these atomizer innovations will be able to improve their environmental sustainability when implemented in mass production. In particular this study aims to answer the following research questions: What are the innovations on atomizers? How they affect environmental sustainability? Which impact categories benefit most from their introduction? Are the impacts of future atomizers smaller than those of the current ones? How are environmental impacts distributed among the different sources of energy consumption and auxiliary materials?

To fill the research gap, some recent developments of LCA methodology can be considered. Consequential LCA provides understanding on the potential effects of policies on market responses to support environmental decision making (Guinée et al., 2018). Dynamic LCA focusses on including the dynamics of parameters that are expected to change over time and to compare different development pathways (Sohn et al., 2020). Anticipatory LCA was created as a forward-looking, non-predictive tool that increases model uncertainty by including prospective modelling tools and social perspectives (e.g., Ganesan and Valderrama, 2022). Prospective LCA models the analysed technology at a future point in time when the product will reach the technological maturity and large-scale production (Arvidsson et al., 2023). The ex-ante LCA is a prospective LCA dealing with technologies before the commercial implementation and is used to guide R&D decisions to make the new technologies environmentally competitive as compared to the incumbent technology mix (van der Giesen et al., 2020; Tsoy et al., 2020).

In this study, prospective LCA of the ex-ante type was applied to assess the impacts of future atomizers implementing technological innovations, not yet been introduced into the market. In addition, the impacts of the future technologies have been compared with those of mature technology extracted from the literature to provide a benchmark for titanium powder production. As is typically done in this type of LCA, to make up for the lack of data deriving from large-scale experimentation, literature analysis is used to obtain the results of tests on prototypes at laboratory scale. These data are then scaled according to experts' opinions to predict the future functioning of the technologies. The novelty of this study lies in the analysis of patents as a source of knowledge, both to retrieve experimental results and hypotheses about industrial scalability. In fact, patents typically contain such information as are requirements for passing the exam and, unlike scientific publications, are strongly focused on industrial research.

2. Materials and methods

The prospective LCA of the compared technologies was conducted through its canonical steps described in the following sections.

2.1. Functional unit and system boundary

The functional unit was defined as the production of 1 kg of powders made by Ti6Al4V, having a circular shape and a diameter less than 300 μm, and mechanical characteristics suitable for the creation of prostheses and aeronautical components. Both the choice of material and its characteristics were defined in order to be able to answer the research question. In this way it is possible to provide an analysis of the impacts of atomization for the applications that today and in the future are require it most, consistently with the characteristics of the powders required by these applications. The time of the study has been hypothesized between 2035 and 2040, consistently with the level of maturity of the considered technologies and their level of market penetration (van der Giesen et al., 2020). While for the study space, the European Union (EU) was arbitrarily selected.

A gate-to-gate system boundary was considered since the objective of the study is to analyse the environmental impacts of powder atomization (see Fig. 1). As consequence, the phases of bar melting and titanium drops solidifications within atomization have been included in the boundary, while titanium bar production, titanium powder packaging, distribution and end-of-life were excluded. In particular, since the waste (i.e., discarded powder) of each technology differs, energy and auxiliary materials consumptions have been considered gross of waste production. The impact of discarded powder was not considered, by hypothesizing that this powder is completely remelted for the production of new titanium bars, following the 100:0 approach (Allacker et al., 2017).

2.2. Compared technologies

The most widespread process for the production of titanium powders is based on the atomization of a titanium bar, obtained by melting titanium ores, i.e., ilmenite or rutile, with the possible addition of titanium waste (Dawes et al., 2015). In atomization, inside a reactor, the bar

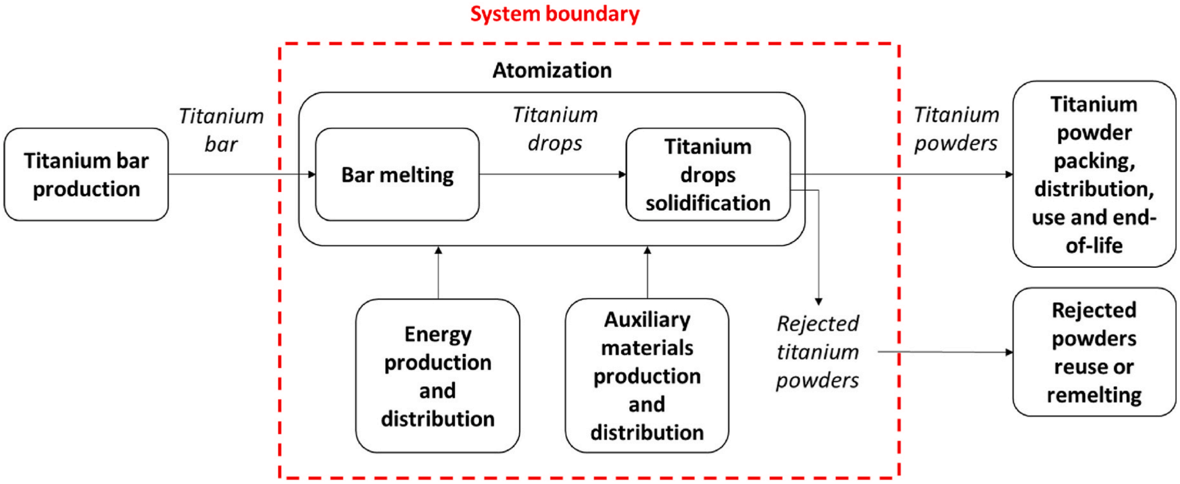


Fig. 1. System boundary.

is melted, creating droplets, which, solidifying through appropriate cooling, create powders. In this study, two of the most widespread atomization reactors worldwide were considered, i.e., the Electrode Induction Gas Atomization (EIGA) and the Plasma Rotating Electrode Process (PREP), for the production of Ti6Al4V powders (Sun et al., 2017). In turn, Ti6Al4V is the most used titanium alloy for the production of prosthetics and aeronautical components, especially with additive manufacturing (Aufa et al., 2022; Hou et al., 2021; Sutton et al., 2017).

In order to select the technologies that will be most widespread in the near future, a patent analysis of the patent literature was conducted. This is because several prospective LCA studies analyse patents due to their ability to reveal information about emerging technologies that have been proven to be technically viable and economically valuable for large-scale production (Arvidsson et al., 2018). In this regard, a patent intelligence analysis was conducted. First, a pool of patents relating to the production of titanium powders by atomizing bars, deposited in the last 10 years, was isolated. To do this, a query was launched in Orbit by Questel within the entire global patent database. The choice of Orbit does not affect the literature search results since other alternative tools, such as Google Patents, Espacenet or Patentscope, also query the same patent database that is managed and updated externally. Orbit was chosen since it displays and manages the results in a way deemed more user-friendly by the authors. Query was built combining the patent class B22F of the Cooperative Patent Classification, related to the production of metal powders, and keywords related to titanium, atomization and the presence of the bar as a raw material. A deliberately generic query was used in order to collect as many relevant patents as possible, preferring generic words to specific acronyms and using truncations to include lexical variants. The query was searched within title, abstract, description and claims of the patents, using the following the following string: "(B22F)/CPC AND ((TITANIUM OR TI+) AND (ATOMIZ + OR ATOMIS+) AND (ELECTR + OR BAR+))/TI/AB/CLMS/DESC AND EAPD $\geq$ 2012". The recovered patents were then manually analysed in the title and abstract to evaluate their relevance and were classified according to the claimed atomization technology.

The obtained results (see Fig. 2a) showed that EIGA and PREP are the clearly most patented technologies, followed at a distance by gas atomization (GA) and other technologies (e.g., water atomization and plasma spheroidization). The analysis of the patent publication trend (see Fig. 2b) showed a growing trend characterized by a strong increase starting from 2016 in the filing of patent applications by both EIGA and PREP. The analysis of the geographical origin of patent applications (see Fig. 2c) showed that the Chinese are clearly the most active in both EIGA and PREP patenting, followed at a distance by those of other states.

Therefore, in line with the current distribution of atomization technologies and above all with the future prediction obtained from patent intelligence, in this study the future evolutions of the EIGA and PREP reactors, called "future EIGA" and "future PREP" were considered.

The functioning of the EIGA and the PREP can be summarized as follows. In the EIGA, a titanium bar (also called electrode), rotating and typically arranged vertically, is melted by passing through a coiled inductor which is electrically powered. The molten titanium, in the lower part of the bar, falls due to gravity and is then hit by a flow of

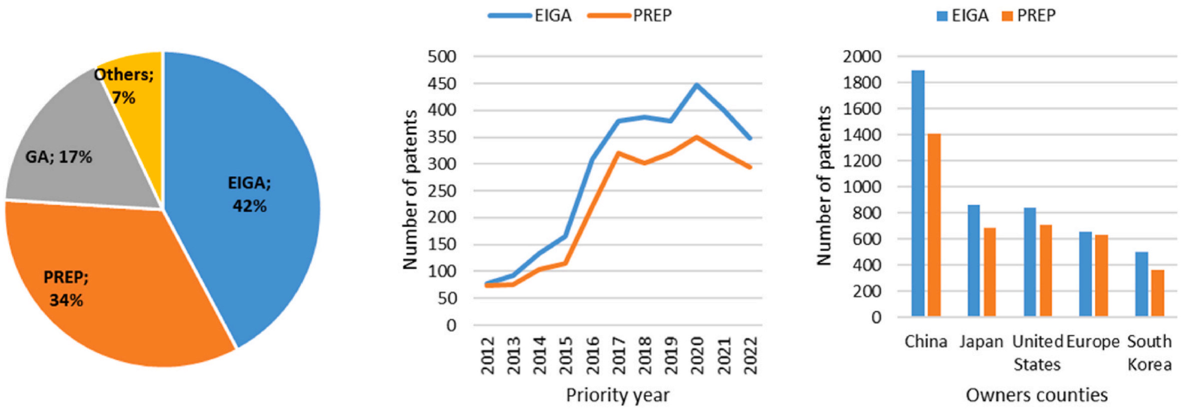


Fig. 2. Patent intelligence about titanium powder atomization. (a) Distribution of patented atomization technologies, (b) publication trend, (c) geographical distribution of the patent owners.

argon which breaks it, creating drops. The latter, as they fall by gravity, cool and solidify, giving rise to dust. In the PREP, the titanium bar (still called electrode) is arranged horizontally and rotates at high speed. A plasma torch, powered by argon, positioned along the axis of the bar melts it, directly creating drops of molten titanium which spread in every direction of the reactor. The same drops cool and create dust by solidification as in EIGA. Fig. 3 provides a schematic representation of thefunctioning of the two reactors, without including structural elements without including structural elements that may vary between future and mature technologies.

To offer a meaningful overview, some future EIGA and future PREP models, all patented, were analysed in this study. Each patent, and therefore each model, was carefully selected through a patent analysis conducted in a systematic way following the approach of Spreafico et al. (2023) to guarantee the reliability of the sources. The patents in the reference pool, collected as explained above, were automatically filtered retaining only those granted and currently alive, i.e., for which the owner is paying maintenance fees. To ensure consistency in relation to the time of the study, the patents were further filtered, retaining only those with the date of first filing (i.e., priority year) in the last five years. Net of all filters, 1366 patents related to the future EIGA and 173 patents relating to a future PREP were analysed. Among all these patents, five were selected, of which three for EIGA and two for PREP. This drastic selection was carried out because each patent was considered, for the extraction of data for the inventory, only if: (i) Completely characterizes the future EIGA or the future PREP, in relation to all the parameters that must be used for the calculation of electricity and argon consumption; (ii) Validate the extracted data with experimental results where the powders produced guarantee all the requirements established in the functional unit; (iii) Provides quantitative assumptions about industry-wide data scale-up.

In addition to these models, two mature EIGA models, were also considered, described in Chen et al. (2023) and Spitans et al. (2020) and two of mature PREP models (Han et al., 2020; Liu et al., 2020) to provide a benchmark for titanium production to compare the future technologies. Both mature EIGA and mature PREP models were selected because they are very widespread on the market. This was done since a prospective LCA is needed for a comparative assessment of emerging and mature technologies, ensuring the comparability of the results from emerging and mature technologies to support eco-design (Thonemann et al., 2020).

For both EIGAs, integration with an Argon recycling system was considered which is commonly used for the production of Ti6Al4V powder for the applications considered (Cappucci et al., 2020). This system consists of argon purification from residual dust through baghouse filtration, after the argon has been separated from the dust by cyclonic separation downstream of the atomizer.

Table 1 reports the features of all the considered technologies.

As can be seen from Table 1, there is great variability in the energy and argon consumption parameters of the different patented technologies. From the analysis of the considered patents, it can be seen that the consumption increases as the quality of the produced powder increases and as the grain size decreases. This study considers all these technologies because they allow the realization of the functional unit, even if some of them allow us to go well beyond the declared purposes for the quality of the output. Reading the results of the prospective LCA will therefore also have to take into account that future technologies are working to improve the quality of the output. The results on future technologies will therefore be precautionary in relation to the future scenario. However, this is in line with prospective LCA which is by nature much more uncertain than traditional LCA. In any case, the proportionality between electricity and argon consumption and impacts offers the user the possibility of scaling the results in relation to less precautionary scenarios, for hypothetical purposes only.

2.3. *Prospective life cycle inventory modelling of the foreground system*

The overall consumption of electricity and argon was included in the foreground system of each technology considered. In particular, in each considered technology, the electricity consumption was calculated based on the energy absorption of the atomizer and the quantity of processed material, explicitly stated in the considered patents and papers. This approach was preferred to the use of calculation methods due to the typical scarcity of patent information, the purpose of which is anything but informative. For this reason, some interesting patents but lacking salient information were not considered in the analysis, excluding hazardous hypotheses and assumptions. The lack of information in patents depends on the low TRL of what is disclosed and on the availability of laboratory-scale data and mostly qualitative estimates on scale-up.

The energy consumption relating to the compressor for the introduction of argon into the reactor was considered negligible. This is

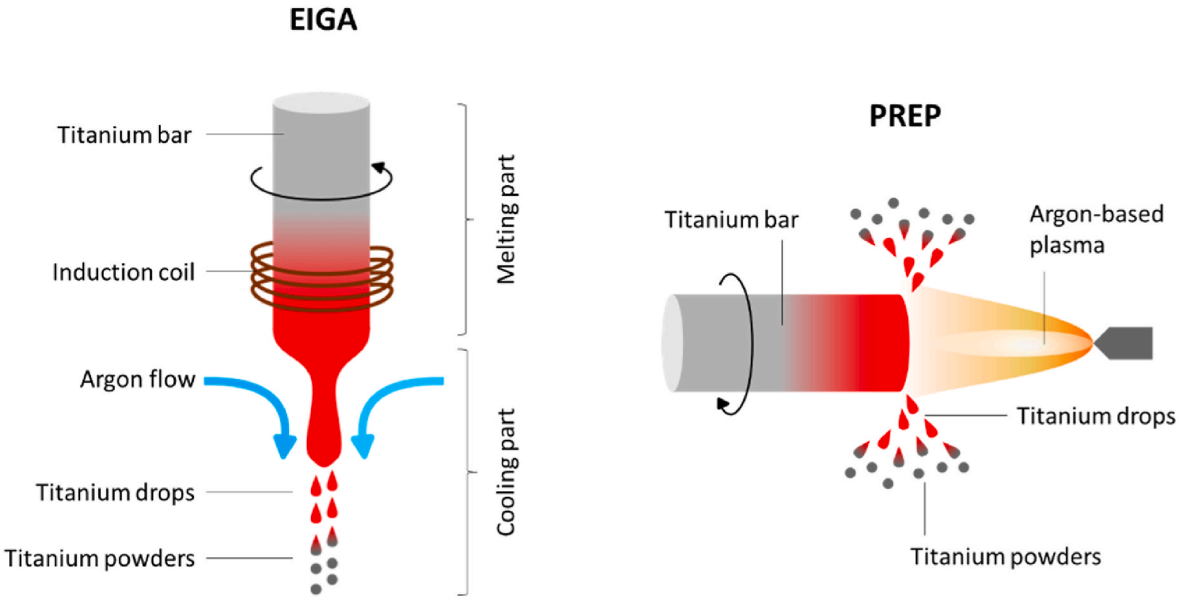


Fig. 3. Schematic representation of the working principle of EIGA and PREP reactors for producing titanium powders.

Table 1

Features of the considered technologies. Data in brackets refers to the lab-scale results reported ion patents if no testing has been carried out on all the data declared in the patents.

Technology	Source	Manufacturer (patent owner)	Electrode diameter [mm]	Electrode length [mm]	Feeding speed [mm/min]	Rotating speed [rpm]	Power [kW]	Argon pressure [bar]
Future EIGA	CN113210616	China iron & steel research institute	50–70	500–1000	15-20 (10–20)	4–5	25-30 (20–30)	35-39 (30–39)
	CN112981177	Shanghai Jiao Tong University	50	n.a.	40-60 (40)	n.a.	20-40 (30)	35 (45)
	CN110125425	Sipman Additive Technology	50-150 (45)	n.a.	30-150 (55–60)	0.5–2.7	20-130 (35)	55 (68)
Mature EIGA	Chen et al. (2023)	Shenyang Institute of Science and Technology	50	1000	39	5.5	60	55–70
	Spitans et al. (2020)	ALD Vacuum Technologies GmbH	50	n.a.	30	n.a.	60.9	n.a.
Future PREP	CN114178538	Southwest Jiaotong University	30	150–200	90-120 (90)	30000-35000 (30000)	100-120 (120)	n.a.
	CN112548109	Northweat Institute for non frerrous metal research	70-90 (70)	n.a.	108-156 (135)	2000–3500	105-125 (105)	1.8-2.1 (2)
Mature PREP	Han et al. (2020)	Sino-Euro Materials Technologies of Xi'an Co., Ltd	75	700	30	16000-22000	70	n.a.
	Liu et al. (2020)	Sino-Euro Materials Technologies of Xi'an Co., Ltd	55	700	24	9000–23000	75	n.a.

because using the formulas to calculate the theoretical energy consumption of a gas compressor in the worst situation, i.e., compressing argon to 55 bar with the flow rates declared in the documents considered, the energy consumption of the compressor is much lower 1% of the atomizer's energy consumption. Therefore, this energy consumption falls within the cut-off criterion. This is in line with the other studies that have carried out the LCA of atomization, cited in the introduction, which never claim to have considered the energy consumption of the compressor.

The modelling of the foreground system of the future EIGA and the future PREP was based on the analysis of their patents in order to make the analysis as close as possible to the interests of the industry regarding the development of these technologies. The collection of patents and the extraction of information for the inventory from them was conducted by applying the methodology of Spreafico et al. (2023) to guarantee the reliability and quality of the data.

The extraction of quantitative data from the selected patents, relating to the experimental results and the scale-up, was carried out following the approach of Thonemann and Schulte (2019). The lab-scale data are those actually obtained, while the scale-up data represent best-case assumptions where a range of possibilities are presented in the patent. In each patent, the lab-scale data and scale-up data relating to the power of the atomizer, the diameter of the processed bar and the feeding speed of the bar were extracted.

For modelling the mature EIGA and mature PREP, the data described in the studies of Chen et al. (2023); Spitans et al. (2020), Han et al. (2020) and Liu et al. (2020) were considered.

Since in all the future EIGA patents obtained with the initial search query the innovation on argon recycling systems was not claimed, for both EIGAs, recycling was modelled in the same way. In particular, it was considered to recycle almost all of the argon, integrating only 0.007 kg of new (not recycled) argon per 1 kg of powder produced (Cappucci et al., 2020). Electricity consumption for argon recycling (purification) was not considered as it was negligible for the 1% cut-off criterion (Cappucci et al., 2020).

In patents about future PREP the values of the argon flow are not reported as well as any solution or declaration to reduce it compared to the current situation. Therefore, for the future PREP and the mature PREP, an argon consumption of 0.53 kg/min was considered (Cui et al., 2021), compatible with the powers of the plasma torches considered.

To model the discarded powder produced by atomization, morphologic atomization efficiency for Ti6Al4V powder generally used for the considered applications of 90% and 99% actually achievable respectively by mature EIGA and mature PREP (Popovich et al., 2017) was considered respectively or both EIGAs and both PREPs. This is because patents about future EIGA and future PREP do not claim an improvement in this aspect. Efficiency was considered in the calculation of electricity consumption and argon consumption in all technologies.

Table 2 presents all the data from the foreground prospective life cycle inventory (LCI) of all the considered technologies, also specifying the layout and reporting the values deriving from the arithmetic mean. The patents report the data relating to the scale-up, which were used in the analysis, and, for completeness, those referring to the lab-scale, in brackets.

2.4. Prospective LCI modelling of the background system

The production processes and distribution of electricity and argon were modelled in the background system. The choices underlying the modelling were aimed at guaranteeing a balanced comparison between the space-time boundaries of the study, the analysed technology and the background systems (Arvidsson et al., 2018). The upstream data sources for modelling the electricity and argon productions and distributions were "market group for electricity, medium voltage – Europe" and "argon, liquid – Global", obtained by Ecoinvent database version 3.9.

To account for the time and space of the analysis in the modelling of the background system, in terms of changes in future electricity mixes,

Table 2

Prospective LCI modelling of the foreground system of the compared technologies. Data in brackets refers to the lab-scale configuration.

Technology	Source	Electricity consumption [kWh]	Argon consumption [kg]
Future EIGA	CN113210616	1.59-1.77 (2.11–3.47)	0.02-0.03 (0.04–0.05)
	CN112981177	1.03 (1.56)	0.02
	CN110125425	0.84 (1.62)	0.02
	Mean	**1.31 (2.37)**	**0.02 (0.03)**
Mature EIGA	Chen et al. (2023)	3.19	0.02
	Spitans et al. (2020)	4.21	0.03
	Mean	**3.70**	**0.02**
Future PREP	CN114178538	4.36 (6.99)	1.86 (1.93)
	CN112548109	0.88 (0.98)	0.25 (0.30)
	Mean	**2.62 (3.98)**	**1.05 (1.12)**
Mature PREP	Han et al. (2020)	1.95	0.89
	Liu et al. (2020)	4.86	2.06
	Mean	**3.40**	**1.48**

gas production and road transport, the upstream data sources have been modified by integrating a future scenario through Premise (Sacchi et al., 2022). The considered future scenario was the REMIND SSP-NPi Integrated Assessment Model (Baumstark et al., 2021), referred to the year 2030. This scenario is based on SSP2 “Midle-of-the-road” socio-economic pathway, characterized by medium challenges to mitigation and adaptation, a moderate global population growth, a final energy demand in 2050 around 600 EJ and a global mean surface temperature (GMST) increasing equal to $\sim$3.3 °C by 2100. In the scenario, society and economic trends are extrapolated from historical developments and a climate policy is based on the implementation of National Policies. This scenario was chosen cautiously as it is moderate and has already been adopted by other prospective LCA studies based on similar time and space boundaries (Watanabe et al., 2022; Mishra et al., 2022).

2.5. *Life cycle impact assessment*

The following impact categories according to ReCiPe method were assessed with a hierarchist value perspective: global warming, fossil resource scarcity, mineral resource scarcity, terrestrial acidification, freshwater eutrophication, ozone formation, fine particulate matter formation, stratospheric ozone depletion, and water consumption (Huijbregts et al., 2016). The hierarchist value perspective is selected since it is often-employed middle-ground scenario reflecting a level of evidence considered acceptable by international bodies (Wickerts et al., 2024).

3. Results

3.1. *Baseline configuration*

Table 3 reports the impacts of all the compared technology, referred to electricity and argon consumption, in the considered future scenario (SSP-NPi) referred to year 2030.

Fig. 4 graphically compares the overall impacts of future EIGA and future PREP arising from electricity and argon consumption.

Fig. 5 divides the overall impacts of future EIGA and future PREP between electricity and argon consumption.

As can be seen from Figs. 4 and 5, the impacts of the future EIGA are lower than those of the future PREP in every indicator. This is due, passing from future EIGA to future PREP, to the reduction of the impacts arising from electricity consumption (50% on average) and argon consumption (98%).

Fig. 6 compares the impacts of future EIGA with mature EIGA (left) and future PREP with mature PREP (right).

Fig. 7 divides the overall impacts of mature EIGA and mature PREP between electricity and argon consumption.

As can be seen from Figs. 6 and 7, the impacts of the future EIGA are lower than those of the mature EIGA in each indicator. This is due especially thanks to the reduction, passing from mature EIGA to future EIGA, of the impacts of electricity consumption (65% on average) and argon consumption (11%). The impacts of the future PREP are lower than those of the mature PREP in every indicator, thanks to the reduction, passing from mature PREP to future PREP, of the impact of electricity consumption (23% on average) and that of the impact of argon consumption (28%).

Table 3
Environmental impact of future and mature EIGA and PREP in the considered future scenario, related to argon and electricity consumption.

Indicator	Unit	Future EIGA		Mature EIGA		Future PREP		Mature PREP	
		Electricity	Argon	Electricity	Argon	Electricity	Argon	Electricity	Argon
Global warming (GW)	**kg CO2 eq**	3.20E-01	1.69E-02	9.06E-01	1.88E-02	6.42E-01	8.64E-01	8.33E-01	1.21E+00
Terrestrial acidification (TA)	**kg SO2 eq**	8.41E-04	3.32E-05	2.38E-03	3.69E-05	1.69E-03	1.69E-03	2.19E-03	2.37E-03
Freshwater ecotoxicity (FEc)	**kg 1,4-DCB eq**	5.30E-02	8.56E-04	1.50E-01	9.52E-04	1.06E-01	4.37E-02	1.38E-01	6.11E-02
Marine ecotoxicity (ME)	**kg 1,4-DCB eq**	6.66E-02	1.11E-03	1.88E-01	1.23E-03	1.33E-01	5.67E-02	1.73E-01	7.93E-02
Terrestrial ecotoxicity (TE)	**kg 1,4-DCB eq**	3.29E+00	8.05E-02	9.31E+00	8.94E-02	6.59E+00	4.11E+00	8.56E+00	5.75E+00
Fossil resource scarcity (FRS)	**kg oil eq**	7.15E-02	3.87E-03	2.02E-01	4.30E-03	1.43E-01	1.97E-01	1.86E-01	2.76E-01
Freshwater eutrophication (FEu)	**kg P eq**	1.39E-04	6.09E-06	3.92E-04	6.77E-06	2.78E-04	3.11E-04	3.61E-04	4.35E-04
Marine eutrophication (MEu)	**kg N eq**	4.55E-05	2.46E-06	1.29E-04	2.73E-06	9.11E-05	1.25E-04	1.18E-04	1.75E-04
Human carcinogenic toxicity (HCT)	**kg 1,4-DCB eq**	2.16E-02	1.04E-03	6.12E-02	1.15E-03	4.34E-02	5.29E-02	5.63E-02	7.40E-02
Human non-carcinogenic toxicity (HNCT)	**kg 1,4-DCB eq**	5.91E-01	1.50E-02	1.67E+00	1.67E-02	1.18E+00	7.66E-01	1.54E+00	1.07E+00
Ionising radiation (IR)	**kBq Co-60 eq**	1.71E-01	9.06E-03	4.84E-01	1.01E-02	3.43E-01	4.63E-01	4.45E-01	6.47E-01
Land use (LU)	**m2a crop eq**	3.30E-02	1.76E-03	9.32E-02	1.96E-03	6.61E-02	9.00E-02	8.57E-02	1.26E-01
Mineral resource scarcity (MRS)	**kg Cu eq**	4.27E-03	1.78E-04	1.21E-02	1.98E-04	8.56E-03	9.09E-03	1.11E-02	1.27E-02
Stratospheric ozone depletion (SOD)	**kg CFC-11 eq**	2.00E-07	1.07E-08	5.66E-07	1.19E-08	4.01E-07	5.45E-07	5.20E-07	7.62E-07
Fine particulate matter formation (FPMF)	**kg PM2.5 eq**	2.65E-04	1.05E-05	7.49E-04	1.16E-05	5.31E-04	5.35E-04	6.89E-04	7.48E-04
Ozone formation, Human health (OFHH)	**kg NOx eq**	4.30E-04	2.13E-05	1.22E-03	2.36E-05	8.62E-04	1.08E-03	1.12E-03	1.52E-03
Ozone formation, Terrestrial ecosystems (OFTE)	**kg NOx eq**	4.50E-04	2.23E-05	1.27E-03	2.48E-05	9.01E-04	1.14E-03	1.17E-03	1.59E-03
Water consumption (WC)	**m3**	4.64E-03	1.31E-03	1.31E-02	1.45E-03	9.30E-03	6.68E-02	1.21E-02	9.35E-02

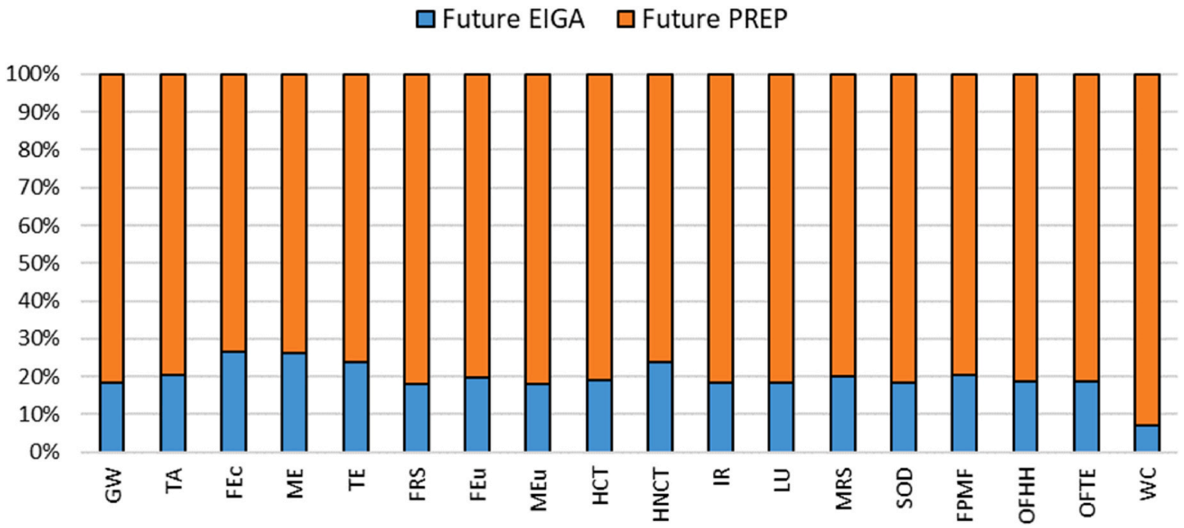


Fig. 4. Comparison of the overall impacts of future EIGA and future PREP.

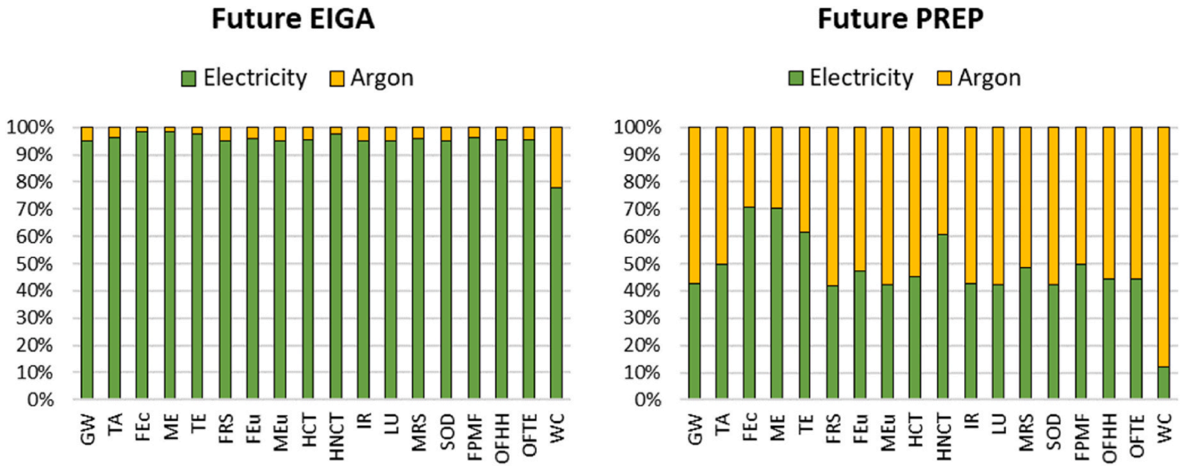


Fig. 5. Impacts comparison of electricity and argon consumption in future EIGA and future PREP.

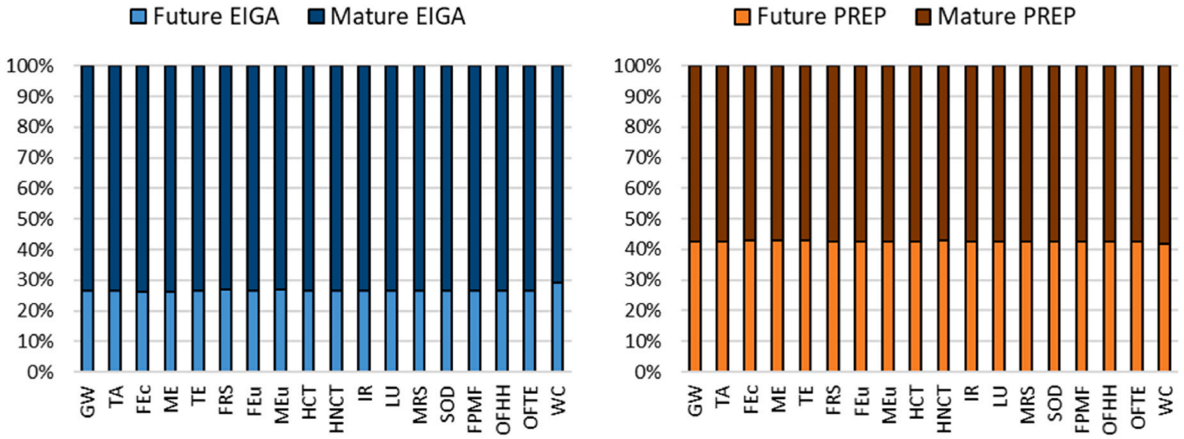


Fig. 6. Overall impacts comparison of (left) future EIGA and mature PREP, (right) future PREP and mature PREP.

3.2. Sensitivity analysis

The sensitivity analysis of the results of future EIGA and future PREP was assessed considering the variations between the different models, the configurations (laboratory scale and scale-up) and scenarios, in relation with different narratives and time.

The considered patents led to very different impacts. In the future EIGA, the average standard deviations of the impacts of electricity consumption and argon consumption are equal to 67% and 64% of the values of the average impacts of electricity and argon. In the future

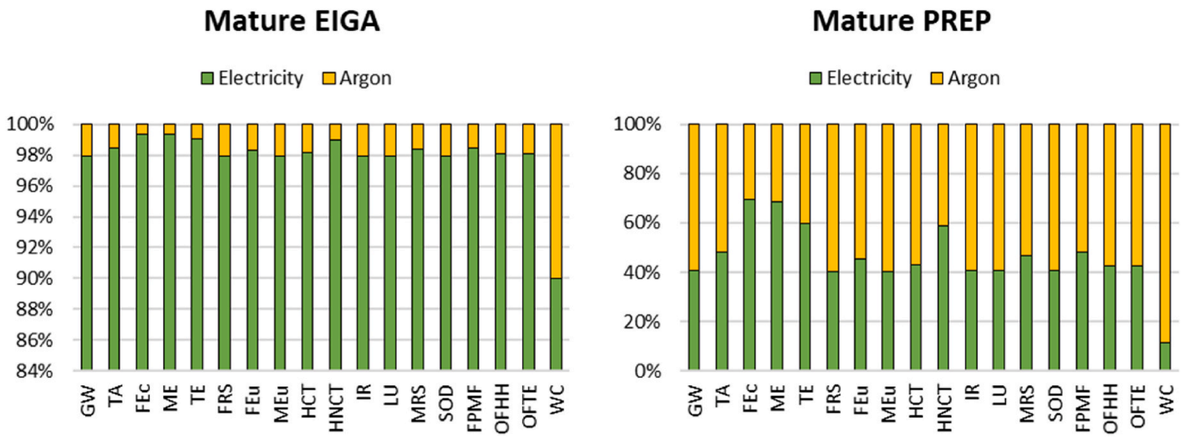


Fig. 7. Impacts comparison of electricity and argon consumption in mature EIGA and mature PREP.

PREP, these values are instead equal to 112% for electricity consumption and 89% for argon consumption.

Moving from laboratory scale to scale-up configuration, notable reductions in environmental impacts were found both in future EIGA and in future PREP (see Fig. 8). The greatest reductions were found in the future EIGA both for the impact of electricity and for argon consumption. The reductions in the impacts of electricity are always greater than the reductions in the impacts of argon.

To study the influence of the scenario, other scenarios where considered: The "present time" scenario, which represents a background system that aesthetically does not change in the future, where market processes of electricity and argon, obtained from the Ecoinvent database were not modified; The SSP2-NPi scenario referred to 2040. The SSP2-PkBudg1150 scenario, referred to 2030 and 2040, which differs from SSP2-NPi scenario for the GMST increase by 2100 equal to 1.6–1.8 °C, and the climate policy related to the achievement of Paris Agreement objective. The SSP2-PkBudg500 scenario, referred to 2030 and 2040, which differs from SSP2-PkBudg1150 only for the GMST increase by 2100 equal to 1.2–1.4 °C. In addition, since most of the patents come from China, these patented technologies are more likely to be adopted in China as well. For this reason, background data from China were also discussed as part of the sensitivity analysis. In particular, consistently with the time scope, the influence of the Chinese electricity mix was also shown. This was done by selecting the upstream data source for modelling the electricity production and distribution "market group for electricity, medium voltage – China" obtained by Ecoinvent database version 3.9. This dataset was updated with the SSP2-NPi scenario referred to 2030, following the same procedure explained in Section 2.4. The same scenario was not applied to the argon dataset since it refers to the global scale (see Section 2.4). As result, Fig. 9 shows the percentage comparison between the impacts of electricity and argon production in the considered scenario (SSP2-NPi, 2030) and those in the other scenarios. As can be seen, all compared scenarios reduce the impacts of both electricity and argon production with the exception of the present time scenario and the Chinese scenario in some impact categories. In particular, the impacts decrease as the time horizon increases and, with the same reference year, moving from the SSP2-NPi scenario to the more optimistic SSP2-PkBudg1150 and then to the SSP2-PkBudg500.

4. Discussion

This study confirmed that mature EIGA is more sustainable than mature PREP, in line with Cappucci et al. (2020). Furthermore, the study confirmed the environmental advantage of EIGA compared to PREP also in the future time, since future EIGA was more sustainable than future PREP.

Technological developments have proven useful in reducing impacts in both EIGA and PREP (Fig. 5). Substantial reductions in electricity consumption in future EIGAs and future PREPs were achieved by following different eco-design strategies, which can be extrapolated from the considered patents. The patented future EIGAs operate with an inductor that is on average 38% less powerful than that of mature EIGAs, reducing the feeding rate by only 5%. This is because the patents CN113210616 and CN112981177 propose certain ratios between diameter, length and feeding speed of the processed bar that allow it to melt at the lowest possible temperature, thus reducing the power required from the inductor. While patent CN110125425 has innovated the induction coil, proposing an original geometry that transmits the same energy to the bar to be processed, while reducing the power. The patented future PREPs, compared to mature PREPs, work with higher

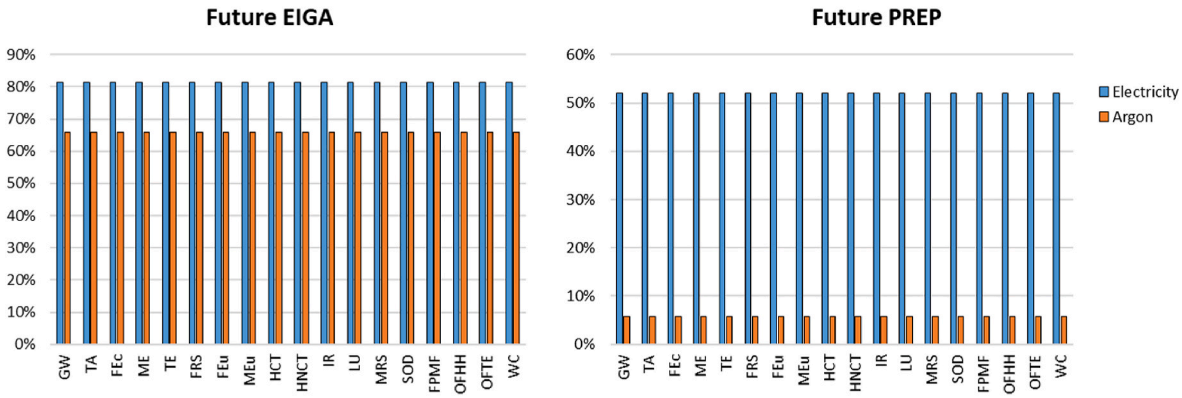
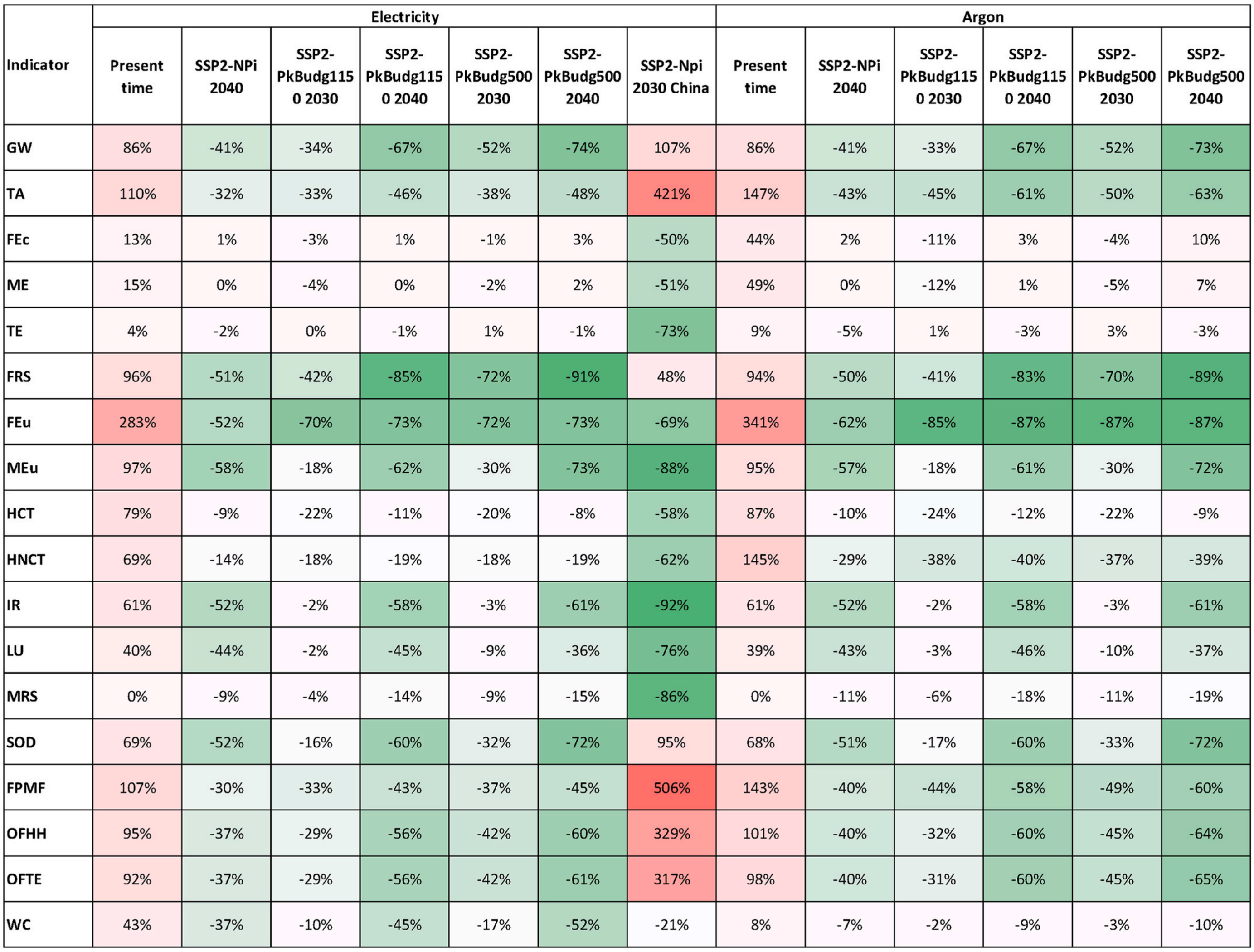


Fig. 8. Impacts reductions moving from lab-scale to scale-up in future EIGA and in future PREP.



Indicator	Electricity							Argon					
	Present time	SSP2-NPi 2040	SSP2-PkBudg1150 2030	SSP2-PkBudg1150 2040	SSP2-PkBudg500 2030	SSP2-PkBudg500 2040	SSP2-Npi 2030 China	Present time	SSP2-NPi 2040	SSP2-PkBudg1150 2030	SSP2-PkBudg1150 2040	SSP2-PkBudg500 2030	SSP2-PkBudg500 2040
GW	86%	-41%	-34%	-67%	-52%	-74%	107%	86%	-41%	-33%	-67%	-52%	-73%
TA	110%	-32%	-33%	-46%	-38%	-48%	421%	147%	-43%	-45%	-61%	-50%	-63%
FEc	13%	1%	-3%	1%	-1%	3%	-50%	44%	2%	-11%	3%	-4%	10%
ME	15%	0%	-4%	0%	-2%	2%	-51%	49%	0%	-12%	1%	-5%	7%
TE	4%	-2%	0%	-1%	1%	-1%	-73%	9%	-5%	1%	-3%	3%	-3%
FRS	96%	-51%	-42%	-85%	-72%	-91%	48%	94%	-50%	-41%	-83%	-70%	-89%
FEu	283%	-52%	-70%	-73%	-72%	-73%	-69%	341%	-62%	-85%	-87%	-87%	-87%
MEu	97%	-58%	-18%	-62%	-30%	-73%	-88%	95%	-57%	-18%	-61%	-30%	-72%
HCT	79%	-9%	-22%	-11%	-20%	-8%	-58%	87%	-10%	-24%	-12%	-22%	-9%
HNCT	69%	-14%	-18%	-19%	-18%	-19%	-62%	145%	-29%	-38%	-40%	-37%	-39%
IR	61%	-52%	-2%	-58%	-3%	-61%	-92%	61%	-52%	-2%	-58%	-3%	-61%
LU	40%	-44%	-2%	-45%	-9%	-36%	-76%	39%	-43%	-3%	-46%	-10%	-37%
MRS	0%	-9%	-4%	-14%	-9%	-15%	-86%	0%	-11%	-6%	-18%	-11%	-19%
SOD	69%	-52%	-16%	-60%	-32%	-72%	95%	68%	-51%	-17%	-60%	-33%	-72%
FPMF	107%	-30%	-33%	-43%	-37%	-45%	506%	143%	-40%	-44%	-58%	-49%	-60%
OFHH	95%	-37%	-29%	-56%	-42%	-60%	329%	101%	-40%	-32%	-60%	-45%	-64%
OFTE	92%	-37%	-29%	-56%	-42%	-61%	317%	98%	-40%	-31%	-60%	-45%	-65%
WC	43%	-37%	-10%	-45%	-17%	-52%	-21%	8%	-7%	-2%	-9%	-3%	-10%

Fig. 9. Comparison of impacts of argon and electricity between the considered scenario (SSP2-NPi, 2030) and the others.

powers (+54%) and higher feeding rate (+108%). Patents CN114178538 and CN112548109 proposed a geometric and parametric configuration of the reactor components aimed at reducing the fusion energy of the bar, while guaranteeing respectively the mechanical resistance or the reduction of inhomogeneities in the powder. Both configurations result from the application of empirical formulas.

Having quantified the impacts reduction benefits of these patented solutions, this study can answer to some studies in the literature that have criticized the future development of additive manufacturing due to the sustainability of atomization (Faludi et al., 2015; Hao et al., 2010; Ford and Despeisse, 2016). The limitation of all such studies was to provide prospective considerations on sustainability based on the analysis of current technologies. At the same time, the results of this study also contrast with studies which in response to the aforementioned studies proposed alternative solutions to atomization, such as powder recycling having other problems related to powder quality (e.g., Cacace et al., 2020).

Finally, the greater sustainability of the future EIGA compared to the future PREP depends entirely on the recycling of argon in the future EIGA. To understand how the impacts of the future EIGA would change if recycling were not implemented, two options have been hypothesized: (1) injection of 31–33 kg/min, as currently occurs (Drawin et al., 2020); (2) input of 27.8 kg/min as foreseen by patent CN111842912, extracted from the same patent pool that was built in this study and relating to the cooling part of an EIGA. In the first case the impacts of argon consumption would increase by over 4400–4700 times, while in the second by over 3900. In both cases, the future PREP would have more than 99% less impact than the future EIGA without argon recycling.

This study has some limitations. The significance of the future EIGA and future PREP modelling is reduced by the data quality criteria that were considered to select the sources. Therefore, the future EIGA and the future PREP do not collect all the solutions that the industries are working on, but only those that have already been patented and have been presented in a rigorous and preferably quantitative manner. The impacts of future EIGA and future PREP are probabilistic in relation to technological aspects. The different considered developments of the future EIGA and future PREP are characterized by great variability in the working parameters and environmental impacts, as explained in sensitivity analysis. The impacts of future EIGA and future PREP refer to their configurations after the scale-up. The doubt in this case is whether these technologies will actually be able to benefit from the scale factor as claimed in the patents considered and modelled in this study. If this is not the case, the possible increase in environmental impacts should be considered, as shown in Fig. 6. Uncertainty considerations should also be taken into account when modelling the future scenario. A possible increase in environmental impacts could occur if the scenario considered is too optimistic (see Fig. 7).

5. Conclusions

The main result of this study is the estimate of the possible environmental impacts of future EIGA and future PREP in future time by considering recent patented solutions. From this result some new conclusions emerge compared to previous literature which is confined to the analysis of current atomization technologies.

- The future EIGA resulted less impactful than future PREP in all indicators, thanks above all to the drastic reduction in argon consumption for its recycling (in the EIGA) and secondly in electricity consumption.
- The future EIGA was more sustainable than the mature EIGA thanks to the proposal of optimal geometries of the titanium bar to be processed and the induction coil.
- Future PREP was found to be more sustainable than mature PREP thanks to the empirical research of a combination of operating parameters of the plasma gun and the reactor aimed at minimizing energy.

All these results must be read in light of the severe selection of sources, which may have excluded possible solutions that will be implemented in the future EIGA and future PREP, just because they have not yet been patented or rigorously described. The results are characterized by great variability due to heterogeneous technological aspects. Uncertainties deals with the nature of the study, which is forecast, in the scale-up estimates and in the definition of the future scenario.

Future developments to improve the LCA model could concern obtaining large-scale production data. Another goal is to gather new sources for analysis that can be equally representative of future EIGA and PREP developments that industries are working on.

CRediT authorship contribution statement

Christian Spreafico: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare no conflict of interest.

Data availability

Data will be made available on request.

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