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Evaluating energy and resource efficiency for recovery of metallurgical residues using environmental and economic analysis

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ABSTRACT

Energy and resource efficiency are today key elements for the metallurgical industry in the context of the new European Green Deal. Although the currently available technologies have recently led to an optimisation of energy and materials use, the decarbonisation targets may not be met without the development of new and innovative technologies and strategies. In this context, the goal of the H2020 project CIRMET (Innovative and efficient solution, based on modular, versatile, and smart process units for energy and resource flexibility in highly energy-intensive processes) is to develop and validate an innovative and flexible circular solution for energy and resource efficiency in a metallurgical plant. The circular model proposed is composed of three units: (1) a metallurgical furnace for the recovery of valuable metals from industrial metallic wastes, (2) a unit for heat recovery from the furnace's exhaust gases, and (3) a digital platform for the optimisation of the whole process. Also, the circular model investigates the possibilities of substituting the metallurgical coke used in the furnace with biobased material (BIOCHAR). This study presents an environmental and economic assessment of the circular model, based on a real pilot testing campaign in which residues from non-ferrous metals production are treated for the recovery of metals, mechanical energy from waste heat, and inert fraction. Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) are used to assess the environmental and economic performances of the circular model. The results of the LCA and the LCC highlight the main environmental and economic hot spots of the proposed technologies. The environmental analysis showed the environmental positive effects of recovering secondary metals and energy. However, for some environmental impact categories (e.g. climate change), the benefits are balanced out by the high electricity and natural gas demand in the metallurgical furnace. In this regard, the substitution of metallurgical coke with BIOCHAR can significantly lower the environmental impacts of the whole process. The economic analysis showed the potential economic profitability of the whole process, depending mostly on the quantity and marketability of the recovered metals. For both environmental and economic analysis, the electricity demand in the metallurgical furnace represents the main barrier that can hinder the viability of the process. Therefore, looking for alternative energy sources (e.g. waste heat from other industries) is identified as the most effective strategy to push the sustainability of the whole process. As the proposed technology is under development, these preliminary results can provide useful insights and contribute to the environmental and economic optimisation of the technology.

1. Introduction

Energy and resource efficiency are key components to increase the sustainability and the competitiveness of the European industry. The goal of energy efficiency is to reduce the amount of energy currently used in industrial processes, while resource efficiency refers to the ability to use a reduced quantity of resources to produce the same product/service (EC, 2015). A significant increase in energy efficiency is indeed a key prerequisite for decarbonising the EU's energy system. In this regard, the recent European Green Deal (EC, 2019) can be a real game-changer, by setting the goal of reaching climate neutrality for

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List of Abbreviation

LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCIA	Life Cycle Impact Assessment
CFs	Characterisation Factors
IS	Impact Score
EF 2.0	Environmental Footprint 2.0
PV	Present Value
OPEX	Operational Expenditure
NPV	Net Present Value
CAPEX	Capital Expenditure
PDF	Probability Density Distribution
ORC	Organic Rankine Cycle
CVT	Continuous Variable Transmission
ETS	Emissions Trade Scheme

Europe by 2050. By boosting energy and resource efficiency, the new Green Deal deploys an unprecedented transformation of production and consumption practices on a scale over less than 30 years.

The European process industry is at the forefront in this transformation, being confronted with the development of new strategies towards increased energy and resource efficiency, that cannot be implemented with business-as-usual approaches. Among the process industries, the metallurgical sector, which comprises iron, steel, ferrous and non-ferrous metals productions, uses up to 33% of the total energy consumption and accounts for 46% of the total manufacturing value in the European Union (EC, 2014; Odysee and Mure databases, 2015). Within the metallurgical sector, the process of primary ironmaking is a major emitter of carbon dioxide (CO_2), both globally (7%), and within the European Union (4%) (Vogl et al., 2021). Although the metallurgical industries have responded to the new policies with efficiency improvements, there are still possibilities to develop new strategies for energy and materials efficiency. Considering that the metallurgical industry accounts for 11% of the total EU's gross domestic product, any development within this sector will have a strong impact on the European competitiveness, and it will play a key role in reaching the ambitious energy and resource efficiency targets set by the European Commission (EC, 2014).

Several strategies have been adopted in the past decade by the metallurgical sector to reduce the usage of primary energy and materials, such as optimisation of incoming energy and materials flows, adjustment of energy-related processes, and valorisation of process residues (Johansson and Söderström, 2011; Wang et al., 2020). However, the potential for further increase of energy and resources efficiency is limited when it relies only on traditional practices (Vogl et al., 2021). Therefore, new and innovative technologies are urgently needed to meet the stringent environmental targets set by the European Green Deal. For instance, the development of technologies to recover secondary energy and materials is a promising option, since most of the outflows from metallurgical industries are composed of by-products and waste heat (Jouhara et al., 2018; Zhao et al., 2017). Another promising field of research to promote decarbonisation is the replacement of metallurgical coke with an alternative biomass-based material. Metallurgical coke is today the most used reductant in metallurgical furnaces, while its production releases 27% of all emissions of the iron and steel sector (Bhaskar et al., 2020; JRC, 2012).

In this context, the H2020 European project CIRMET (*Innovative and Efficient Solution, Based on Modular, Versatile, Smart Process Units for Energy and Resource Flexibility in Highly Energy Intensive Processes*) aims at developing and validating a circular, innovative and flexible solution for energy and resource efficiency, and decarbonisation of the metallurgical industry. A general representation of the principles leading the CIRMET project is reported in Fig. 1. The circular solution proposed by CIRMET consists of the development of a **circular process**, which is a combination of different modular units (a pyrometallurgical process and a heat recovery unit). During the circular process, metals are recovered from metallurgical solid residues, and waste heat is transformed into mechanical energy to be reused directly in the plant. The circular process includes also the use of BIOCHAR, which is a bio-based substitute of the metallurgical coke and petcoke. Pyrometallurgical processes to valorise metallurgical residues can be rather complex, as it involves a huge number of reactions taking place usually in rigid process, occurring in big kilns at centralised plants. Consequently, it is fundamental that the process is adapted to the specifics of the residues being valorised, to increase recovery efficiency. To tackle the need of versatility in the pyrometallurgical processes, the proposed circular model offers a modularity perspective. Thanks to its flexibility, the proposed pyrometallurgical process, based on plasma heating system, can be enabled for the treatment of different kind of metallurgical residues, by applying some modifications of the process parameters.

As stated above, a decisive element for the breakthrough of new technologies is their potential to lead the metallurgical sector towards the environmental goals set by the European Commission. Another fundamental prerequisite is also the economic viability and profitability, which must drive private investments. Therefore, together with a thorough analysis of the technical aspects, evaluation methodologies must include environmental and economic analysis, to achieve an integrated perspective on the potential of new products and processes (Hoogmartens et al., 2014).

Building on this need, this paper presents an environmental and economic analysis of a real case study in which the above-mentioned circular process has been applied to treat metallurgical residues with high zinc content, occurring during the production of non-ferrous metals. The case study is based on a pilot plant located in the north of Spain, that has been tested to recover metals, heat, and inert materials. An alternative scenario in which BIOCHAR substitutes metallurgical coke in the process is also considered.

To understand the environmental and economic performances of the proposed circular model, a Life Cycle Assessment (LCA) and a Life Cycle Costing (LCC) are performed using data directly collected at the pilot plant. While LCA is a well-established and standardised methodology, which counts a plethora of applications within the metallurgical processes, only a very few LCCs applied to the metallurgical sector have been published (to name a few (Albuquerque et al., 2019; Gardner et al., 2007; Mistry et al., 2016; Schau et al., 2011)). To the knowledge of the authors, even a smaller number of studies have combined LCA and LCC, although there is an increasing interest in the metallurgical sector for combining (or even integrate) the two analyses. Hong et al. (2012, 2017), for instance, coupled LCA and LCC analysis to draw recommendations for lead and aluminium alloys production, finding the key elements that could boost, separately, both environmental and economic performances. Previous literature reveals the potential and the rising interest for combined environmental and economic studies, but it also highlighted the differences and the unresolved issues, especially when setting the general framework of the two analyses (for more details, see (Atia et al., 2020; Norris, 2001)). Therefore, studies combining LCA and LCC in the metallurgical sector are strongly needed.

Considering all above, the present paper aims at answering different needs and questions. First, it provides an environmental and economic profile of innovative technologies for materials and energy efficiency and decarbonisation within the metallurgical sector. Second, it provides a further case study on the possibilities and challenges to be tackled when combining LCA and LCC to evaluate new technologies.

2. Methods

2.1. The circular process

The pyrometallurgical treatment and the valorisation of mixed metallurgical residues is a complex process, and accurate control of the

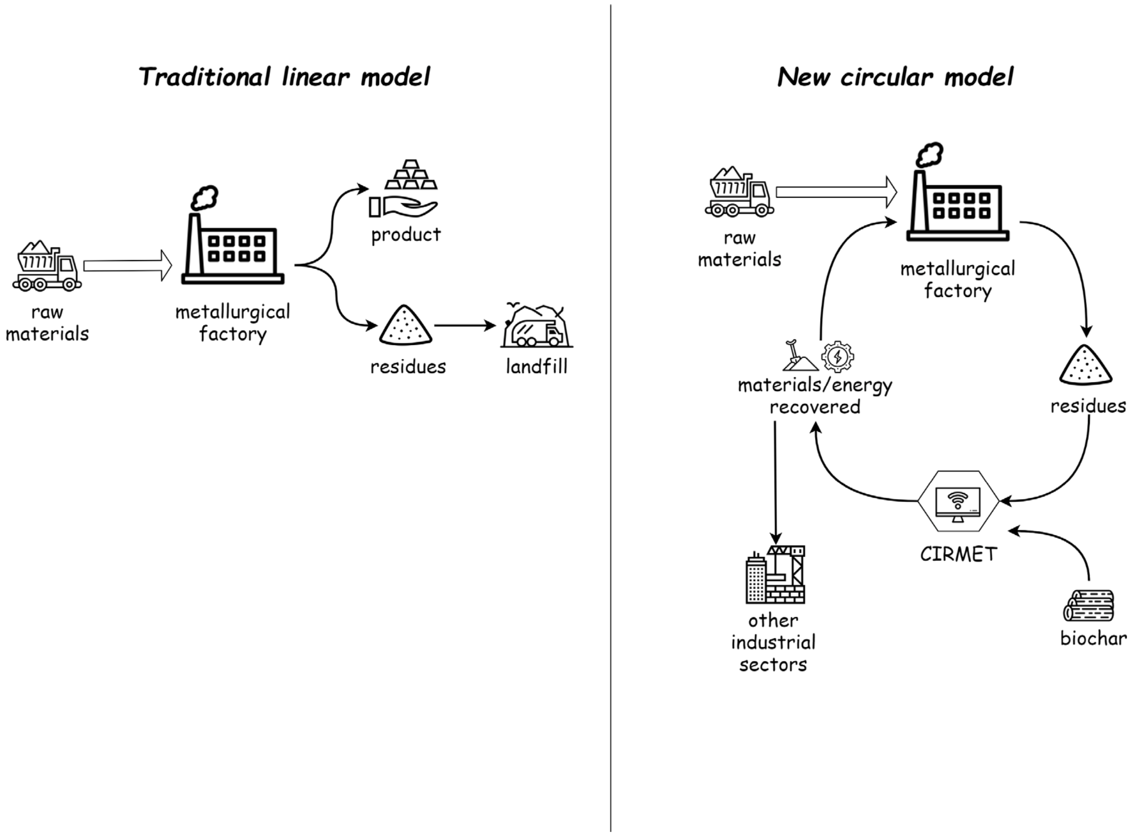

Fig. 1. Overview of the circular solution proposed by CIRMET. The figure depicts the differences between the old linear model and the new circular model, where the residues from the metallurgical process are collected and valorised allowing the recovering of secondary raw materials and heat.

process parameters is paramount. Metallic elements in metallurgical residues are not usually found in metal form, but rather in oxide form and in more complex ternary and quaternary metal compounds. Also, metallurgical residues present a high heterogeneity, because their composition depends on several aspects of the manufacturing process steps and stages. Therefore, a preliminary characterisation of the residues can facilitate the correct mixtures with carbon-based reducing agents, and also with specific additives and binders used to agglomerate briquettes or pellets. Considering all the above, residues characterisation and full control on the process parameters are fundamental aspects, allowing a pyrometallurgical process to adapt to the specifics of the residues being treated. For instance, they can help identify composition ranges where specific operational parameters are always valid, or they can help adapting the operational parameters depending on the residues' characteristics. In this framework, the modularity perspective offered by the proposed circular process aims at providing a flexible solution for the valorisation of metallurgical residues, able to adapt to several process conditions and different compositions of treated residues. The proposed circular process consists of the development of three modular units: **(i) the EFFIMELT furnace**, to recover metals from metallurgical solid residues, **(ii) the heat recovery unit RECUWASTE**, which transforms waste heat into mechanical energy to be reused directly in the plant, **(iii) the digital platform AFF40**, ensuring full control of the process parameters, enabling the process to adapt to the residues being treated. The solution includes also the **(iv) use of BIOCHAR**, which is a bio-based substitute of metallurgical coke and petcoke. A simplified representation of the process scheme is represented in Fig. 2. Metallurgical residues (rich in non-ferrous metals oxides) enters EFFIMELT together with other inputs, such as metals scraps (to form the metal bath), metallurgical coke (acting as reductant), and energy in the form of electricity and natural gas. In EFFIMELT, several metal oxides are reduced to their elemental form. Depending on their characteristics, some of them are dissolved in the molten metal bath, while those with a low vaporisation point are gasified and leave the furnace with exhaust gases, to be subsequently re-oxidised. Non-reduced metal oxides and other inert compounds are collected in the slags as process inert fraction. The high-temperature flue gases pass through the heat recovery unit RECUWASTE, where part of the heat is recovered and then transformed into mechanical energy to produce compressed air in a compressor. After RECUWASTE, the lower temperature flue gases pass through a filter baghouse, filtering and collecting the dust particles of the gasified elements that have been previously oxidised. This by-product, called dust concentrate, contains high purity metal oxides (such as ZnO), which can be used by smelters and other hydrometallurgical processes to produce new secondary metals, substituting primary ores to produce new primary metals. The recovered metals alloy from the metal bath in EFFIMELT can be reused again to produce secondary metals (e.g. copper). The inert fraction, that is the vitreous fraction remaining from the initial residues, can be recovered and further valorised as inert aggregates in construction activities (e.g. road construction).

Finally, BIOCHAR, produced through the torrefaction of biomasses, is also tested to be used as an alternative to metallurgical coke as the reductant in EFFIMELT. The substitution of fossil-derived coke with biomass-derived BIOCHAR is expected to further lower carbon and energy consumption, reducing the fossil carbon footprint of the whole system (Khanna et al., 2019).

A detailed technical description of the circular process can be found in supplementary note 1 in the supplementary materials.

2.2. Goal and framework of the environmental and economic analyses

The study presents an environmental and economic analysis of the proposed circular process, based on data collected during testing campaigns of a real pilot-scale demonstrator, located in the North of

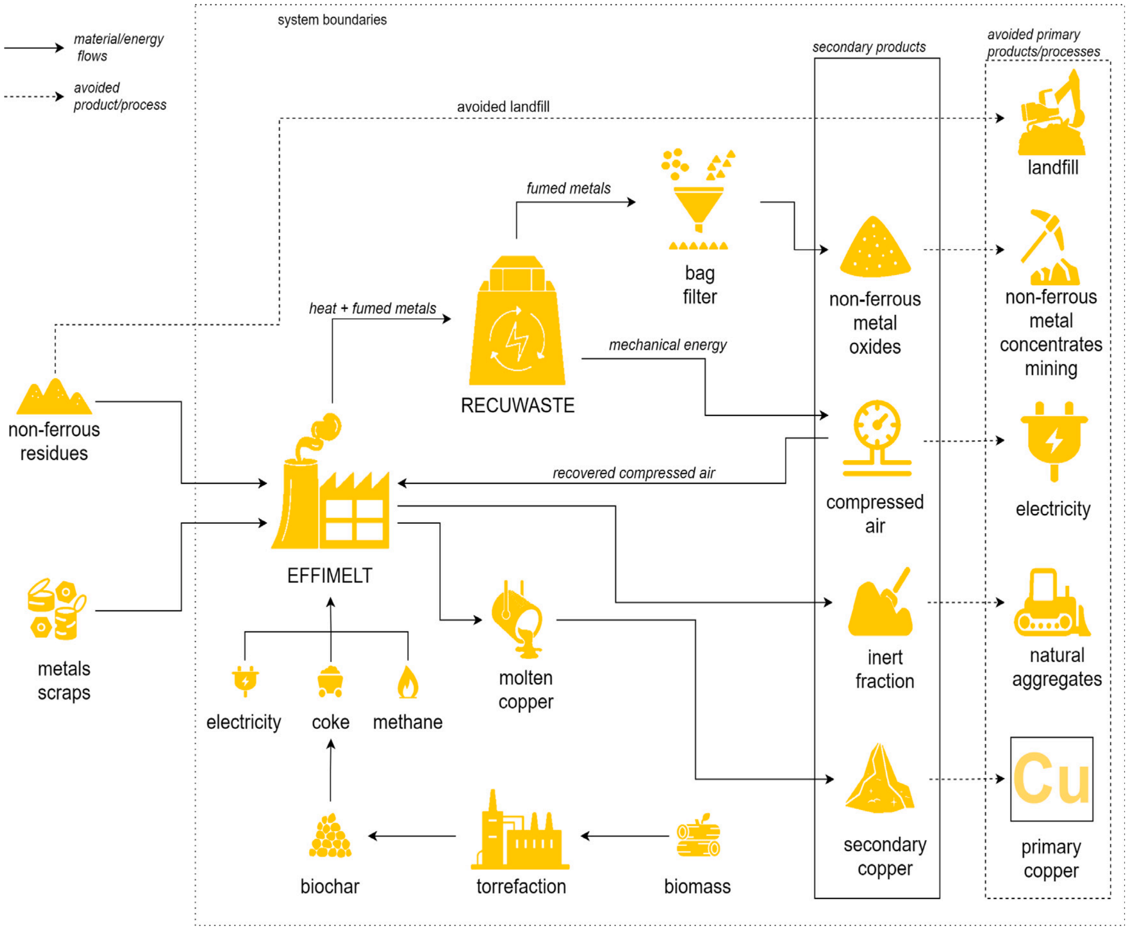

Fig. 2. The proposed circular model. Residues from non-ferrous metals production are treated in EFFIMELT and RECUWASTE to recover non-ferrous metal oxides, heat, inert fraction and secondary copper. An alternative scenario in which BIOCHAR substitutes coke is also proposed.

Spain. The demonstrator has been tested to treat residues with high content of zinc, produced during non-ferrous metals production, with the final recovery of metals (zinc oxide and molten copper), heat and inert material. The data for the BIOCHAR production are collected at another pilot-scale demonstrator, located in the Auvergne-Rhône-Alpes region, southeast of France.

The goal of the environmental analysis is to find the environmental trade-off between the raw materials and energy needed to perform the process, and the metals and energy that can be recovered. Accordingly, the goal of the economic analysis is to highlight the potential economic drivers representing opportunities or barriers for the future developments of the circular model.

Both LCA and LCC methodologies can be integrated since they share the same life cycle thinking approach, although they are designed to answer different questions: LCA evaluates the environmental performances of a product system, while LCC assesses the cost-effectiveness and economic viability of technologies from the perspective of the economic decisionmakers. When the LCA and LCC share the same scope and system boundaries, the combination of the environmental and economic analyses can complement each other in the decision process (Carlsson Reich, 2005).

Although there are numerous examples and definitions regarding how an economic analysis should be combined with environmental analysis, there is no official standardised procedure on how to combine LCA and LCC. As it is defined by Carlsson Reich (2005) and later by Morel et al. (2018), LCC can be (i) a parallel analysis to an LCA, assessing the same product system using two different keys (financial LCC), or (ii) a weighting method for the LCA, normalising into monetary values the environmental impacts calculated through the LCA (environmental LCC).

For the present study, the financial LCC methodology will be applied, following the framework depicted in Fig. 3. The reasons behind this choice are linked to scientific considerations, thoroughly analysed during several discussions among the CIRMET partners. First, the uncertainty and the lack of consensus on a standardised monetisation method could significantly affect the exploitability of the results. Second, some of the most important environmental impacts related to the system under study, such as carbon emissions and residue landfilling, are already internalised within the economic system.

2.3. Analysed system boundaries and functional unit

An important step in LCA and LCC is to determine the boundaries of the analysed system, which are “the set of criteria specifying which unit processes are part of the investigated product system” (Pe, 2014). The system boundaries for the LCA/LCC must be consistent, and they are set considering the whole recycling process, from the treatment of the metallurgical residues to the recovery of the by-products, as already shown in Fig. 2.

Another fundamental step is the definition of the functional unit of the study. The functional unit is the quantified description of the analysed product system, and it is used as the quantitative reference to which all inputs and outputs of the product system are calculated. In this study, the functional unit for both environmental and economic analyses refer to a one-year treatment capacity of non-ferrous residues. Based on the data collected directly at the pilot plant, the treatment process runs for 22 cycles per year, with 324 h each cycle and 150 kg of

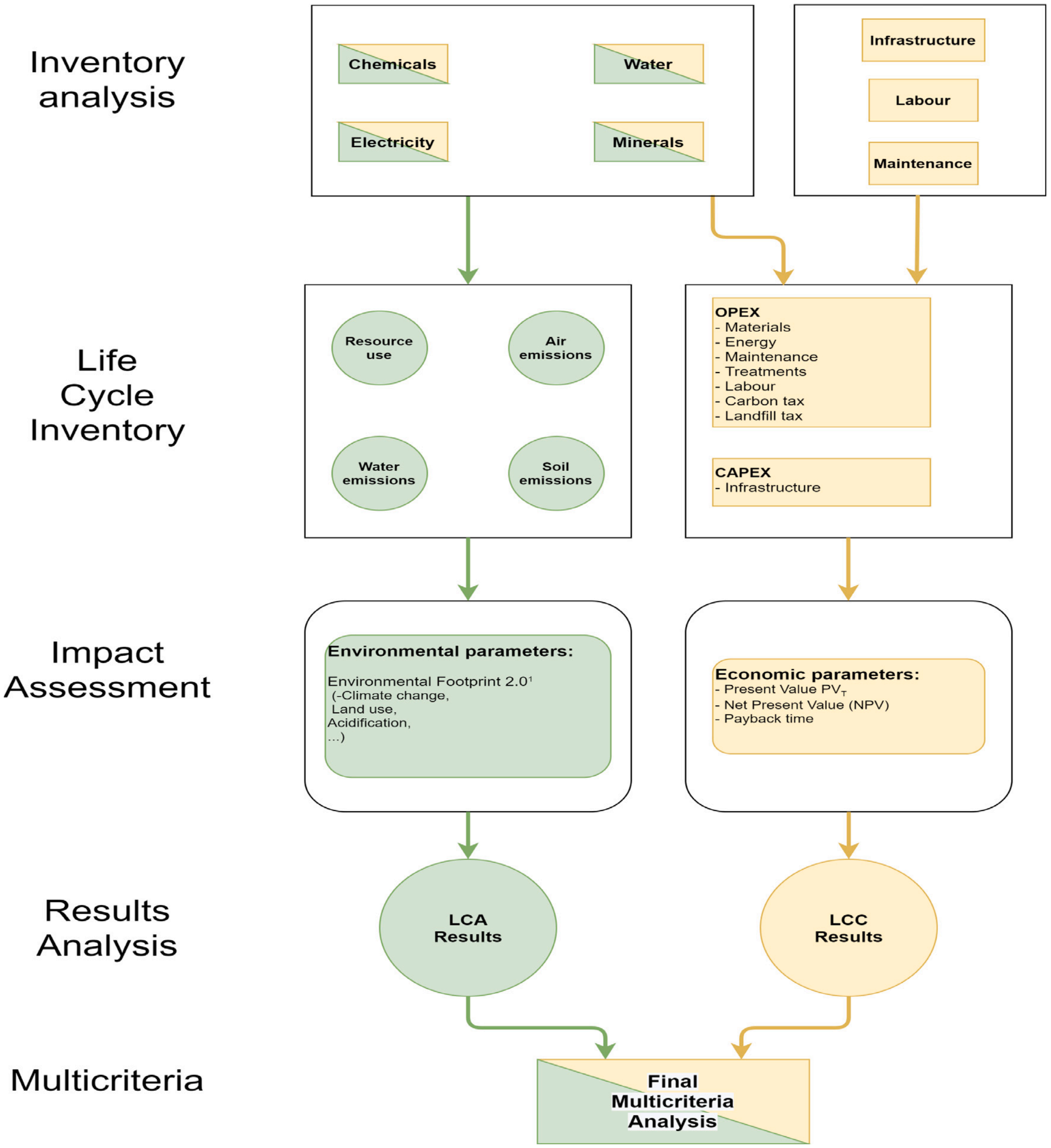

Fig. 3. The methodological framework for the combined environmental and economic calculation. LCA and LCC will be performed independently, and in the end, the results from both analyses will be combined in multicriteria analysis. The green colour represents the environmental path, while the yellow colour represents the economic path.

residues treated per hour. This makes a total of 6804 h of treatment and 1020.6 tonnes of treated residues per year. Additionally, per each cycle, there is a pre-heating phase with 4 h electricity (250 kWh/$t_{residue}$) and 8 h natural gas combustion (50 N m^3/h).

The final recovered products (secondary zinc oxide, molten copper, inert material, and mechanical energy) avoid the production of alternative products from primary resources. A further avoided impact is represented by the avoided landfilling of the non-ferrous metallurgical residues. To assign the credits for the avoided productions, the system expansion method is applied, accounting for the effect of the substitution, i.e. modelling the effect of by the substitution of alternative processes (Schrijvers et al., 2020).

The use of non-ferrous metallurgical residues and metals scraps can be considered as closed-loop recycling: a material associated with a product is used again in the same product. For the environmental analysis, the modelling is not straightforward, and an allocation problem arises: what share of the environmental burdens from primary production of these inflows should be allocated to the process/product investigated (Ekvall and Tillman, 1997)? Two approaches are commonly used in LCA to assess the benefits of metals recycling: the "recycled contents" and the "end-of-life".

In the recycling content approach, the recycling system bears the environmental impacts of the collection and recycling process of the waste metal, and the credits are represented by the avoided impacts of final disposal. In the end-of-life approach, based on the substitution method, the system producing the primary metals receives the credits from the recycling process, represented by the avoided burden of primary metals production.

The recycled content approach aims to incentivise waste diversion, and it is most useful as a metric for materials that are normally landfilled or incinerated (Dubreuil et al., 2010). Therefore, the recycled content approach suits well the case of the metallurgical residues, used as the main inputs of the processes. On the other hand, landfilling and incineration are not a common end-of-life fate for the metal scraps used as an inflow in EFFIMELT, since metal scraps present a mature, stable and growing recycling market (Dubreuil et al., 2010). For this reason, the end-of-life approach is strongly endorsed by the metal industry when dealing with metal scraps recycling (Atherton, 2007). For the present study, the end-of-life approach is used for metal scraps, and the credits are assigned to the primary metal's production rather than to the scraps valorisation process. Consequently, the metals scraps are not included within the environmental system boundaries. On the other hand, they are considered within the system boundaries of the economic analysis since they are purchased in the market with a cost.

2.4. Inventory analysis and LCI results

The inventory analysis involves the compilation and quantification of all foreground relevant inputs and outputs for the analysed system. For the environmental inventory analysis, inputs are represented by the materials and energy resources used in the project, while outputs account for all emissions and waste production, in addition to final products. For the economic inventory, the costs and revenues are calculated by multiplying the flows of energy, materials and final products by the respective market prices. The inventory for the BIOCHAR scenario is described in the next session, while the calculation of the inventory data for the carbon emissions from EFFIMELT and the energy recovery in RECUWASTE can be found in supplementary notes 2 and 3.

Table 1 and Table 2 list all the environmental and economic foreground inputs and outputs used in the study. For each of the environmental inputs, the background environmental flows must be assessed (e.g. the resources needed to produce the electricity to be used in EFFIMELT). The background environmental flows are modelled using the ECOINVENT LCI database v3.7. The list of all background and foreground environmental flows represents the final LCI model, which is the base for the environmental impacts calculation.The economic flows have been estimated through personal communication with the pilot managers. It is worth to highlight the high volatility of economic flows over time, because of the ever-changing market conditions. Often, the volatility of economic data is indeed much higher than the variability of environmental flows (Hunkeler et al., 2008). To assess the effects of these potential variations on the final economic results, an economic uncertainty analysis, based on a Monte Carlo simulation, is performed in Section 3.2 of this study.

2.5. Life cycle impact assessment

2.5.1. Environmental impact assessment

The environmental Life Cycle Impact Assessment (LCIA) aims to translate the results of the LCI model into different impacts on the environment, expressed in terms of several environmental impact categories. Many different LCIA methodologies are available in the literature to calculate the environmental impact categories. One of the main distinctions is between midpoint and endpoint methods, which look at different stages in the cause–effect chain. Midpoint-based methodologies focus on the direct causal relation between an elementary flow and its direct consequence on the environment, while endpoint-based methodologies look at the end of the chain, at the final effect that such an environmental impact may have on humans, ecosystems, and natural resources. Commonly, midpoint categories are considered scientifically more robust, since they provide a higher level of details than endpoint categories, which aggregate all indicators into only three endpoint categories. On the other hand, endpoint categories are thought to better convey information to policymakers, thanks to the low number (only three) and their link with easily intuitive detrimental effects (damages to human health, ecosystems, and natural resources). A further discussion on the pros and cons of midpoint vs endpoint goes beyond the purpose of this study, as it has been extensively documented in previous literature (see for instance: (Bare et al., 2000; Bare and Gloria, 2008; Goedkoop et al., 2008; Ismaeel, 2018; JRC, 2011). At an early development stage (lab and pilot scale), a much higher level of detail on the environmental hotspot is required, and midpoint analysis can indeed provide detailed information on the environmental hotspots of the proposed technology. Endpoint analysis, on the other hand, is more useful when going from pilot to industrial scale, at the final stage of development. Owing to the early stage of development of the analysed technologies, only the midpoint categories are investigated in this paper, leaving aside the endpoint analysis.

To quantify the contribution of the elementary flows from the LCI model into midpoint environmental impact categories, each elementary flow E (e.g. emission of CO_2 into the air) is multiplied by its respective characterisation factors *CFs*. The *CFs* quantify the contribution of an elementary flow to a specific impact category (e.g. how the CO_2 emissions contribute to global warming). The contribution of all elementary flows to a specific impact category IC are then summed up resulting in an impact score IS, which determines the result for the environmental impact category, as shown in Eq. (1):

$$IS_{IC} = \Sigma_i (CF_i \cdot E_i) \tag{1}$$

For this study, the characterisation model Footprint 2.0 (EF 2.0) is selected for the environmental impacts calculation (Fazio et al., 2018; JRC, 2019). EF 2.0 contains all the *CF* for each category, allowing to calculate the IS of each flow on each category, as described in Eq. (1). The LCI model, including the background environmental flows from ECOINVENT 3.7, and the impacts calculation through EF 2.0 have been implemented in the software GaBi, version 10.6.0.110.

2.5.2. Economic impact assessment

The goal of the economic impact assessment is to identify all the costs involved within the system boundaries, highlighting the cost drivers and the profitability of the proposed technology. The inputs are expressed in terms of cash flows derived from purchasing, while the outputs are expressed in terms of the cash flows derived from the sales. Different economic metrics were calculated to define results that may contribute to a cost-oriented decision-making process.

The first, and probably most straightforward, calculated economic metric is the present value PV_T, which represents the value generated by the technology over its lifetime, reported to the present value of money. The PV_T is calculated according to Eq. (2), representing the sum of the net yearly economic cash flows $(Revenues)_T - (OPEX)_T$, discounted by the future value of money $1/(1+x)^T$:

$$PV_T = \Sigma_{t=1}^{T} \frac{(Revenues)_T - (OPEX)_T}{(1+x)^T} \tag{2}$$

Where x is the discount rate and T is the expected lifetime of the infrastructure, set at 25 years. The discount factor $(1+x)^T$ measures the present value of future cash flows, that is the future value of one euro received in year t (more details can be found in Brealey et al. (2010). The value of x is usually difficult to estimate since it depends from case to case and should represent the rate of financial assets of equivalent risk (Arnaboldi et al., 2015). Commonly, the discount rate for new developments in metallurgical industries ranges between 6% and 10%, depending on the marketability of the commodity. After internal discussion with the industrial project partners, considering both the evolution of the nominal interest rates during the last decades, and the risk profile of the developed asset, the value of x is set at 7%. Other valuable economic metrics to be assessed to evaluate the economic viability of the proposed solution are the *Net Present Value (NPV)* and the *Payback time*. The combination of different economic parameters is usually applied to verify whether or not investing in a project is finally economically viable (Brealey et al., 2010). In Eq. (3), the NPV is the sum of the yearly discounted cash flows, also considering the initial investments. It equals the present value plus the required initial investments:

$$NPV = CAPEX_{t_0} + \Sigma_{t=1}^{T} \frac{(Revenues)_T - (OPEX)_T}{(1+x)^T} \tag{3}$$

Table 1
Environmental and economic inventories.

REFERENCES						
Residues treated per hour	150 kg					
Treatment cycles per year	21					
Hours per treatment cycle	324 h/cycle					
Pre-heating (with natural gas)	8 h/cycle 50 N m^3/h					
Pre-heating (with electricity)	4 h/cycle 250 kWh/t					
Working hours/year	6804 working hours/year					
Residues treated per year	1020.6 tonnes					
INPUTS						
	Environmental inventory		**Economic inventory**			
Materials						
	Quantities	Unit	€ per unit		€ per year	
Waste	1020.6	t/year	40	€/t	40 824	€/year
Coke oven	122.4	t/year	195	€/t	23 882	€/year
Binder (bentonite)	13.6	t/year	165	€/t	2245	€/year
Metal ingots	10.5	t/year	410	€/t	4305	€/year
Oxygen	840	m^3/year	1.2	€/m^3*	1271	€/year
Graphite	6.04	t/year	1435	€/t	10 251	€/year
Energy						
Natural gas	8400	N m^3 /year	0.0665	€/kWh	5865	€/year
Electricity (pre-heating + treatment)	1786	MWh/year	0.21	€/kWh	375 070	€/year
OUTPUTS						
Copper recovered	81.6	t/year	8806	€/t	718 992	€/year
ZnO Filter dust	612.2	t/year	1361.1	€/t	833 496	€/year
Inert slag	326.5	t/year	10	€/t	3 265	€/year
CO_2 emissions total *	452.8	tCO_2/year	38	€/tCO_2	17 208	€/year
- CO_2 emissions coke	437.6	tCO_2/year				
- CO_2 emissions NG	15.1	tCO_2/year				
Energy released **	957.7	MWh/year				
Avoided electricity (RECUWASTE) **	168.6	MWh/year	0.21	€/kWh	29 522	€/year
BIOCHAR (Alternative scenario)						
biochar	122.4	t/year	150	€/t	18 370	€/year

* Supplementary note 1

** Supplementary note 2.

Table 2
Inventory analysis for biochar production.

Inputs	**Quantities**	**Notes**
Poplar chips	45 kg/h	
Natural gas	1.4 N m^3/h	Calorific value 35 MJ/N m^3
Nitrogen gas	2.4 N m^3/h	
Helium gas	0.15 N m^3/h	
Water	0.011 t/h	
Outputs		
Biochar	15 kg/h	
CO_2 emissions (from biochar production) of which:	18 N m^3/h	Direct emissions measured at the plant. The share between fossil and biogenic carbon is suggested by the pilot plant manager, and it is based on internal mass balances
- 90% from biomass (biogenic)		
- 10% from natural gas (fossil)		
Carbon content	75%	
CO_2 emissions (from biochar combustion in EFFIMELT)	1747 $kgCO_2/t_{biochar}$	Proxy data from CO_2 emission factor for “wood and wood waste” (World Resources Institute, 2015)
Cost	150 €/$t_{biochar}$	Estimation from producer

Where $CAPEX_{t_0}$ is a negative number and represents the initial investment (or cash flow at time zero). In simple words, the calculation of the NPV for a project replicates the process by which the same investment cost would be valued if invested today in the capital market (Brealey et al., 2010). With a simple rule of thumb, when NPV is greater than zero, some values are added to the initial CAPEX at the end of the considered period. A negative NPV represents the opposite situation. Consequently, the situation in which the NPV is equal to zero represents the breakeven point, when the CAPEX equals the PV at the end of the lifetime. Considering that the analysed case study is still in its pilot-scale development, reliable estimations for the value of CAPEX at an industrial scale are not available yet. Therefore, for this study, the economic analysis calculates the breakeven points by assuming an NPV equal to zero (NPV_0) and calculating the correspondent value of $CAPEX_{NPV_0}$. The $CAPEX_{NPV_0}$ represents the maximum amount of money that can be invested to keep the initial investment economically profitable. The calculation of the $CAPEX_{NPV_0}$ allows estimating the payback period, which calculates the number of years after which the cumulative present value equals the CAPEX. $CAPEX_{NPV_0}$ and the Payback period are easily understandable measures, and they represent a simple mean of communicating the financial consequences of an investment.

The calculation of the economic parameters in this study is based on the economic flows presented in Table 1. A series of Excel sheets have been produced to calculate the PV_T and $CAPEX_{NPV_0}$, and shared subsequently with the involved project partners for double-checking.

Finally, in economic analysis, risk and uncertainty are closely linked: assessing uncertainty at the initial phase of analysis can reduce risks at the end (Emblemsvåg, 2003; Ponce-Cruz and Ramírez-Figueroa, 2010). Lofti A. Zadeh, the father of fuzzy logic, expressed this concept in his principle of incompatibility: "As complexity rises, precise statements lose meaning, and meaningful statements lose precision". Therefore, it is fundamental to corroborate the economic results utilising uncertainty analysis of the valuation model (Percoco and Borgonovo, 2012). One of the most common approaches to handle uncertainty in economic models is using statistical methods. A statistical method can simulate the effect on the results of sufficient numbers of potential variations so that the conclusions drawn from the analysis are precise enough to minimise risks. In this regard, Monte Carlo simulation is one of the most used statistical methods to quantify uncertainty in economic analysis. In a Monte Carlo simulation, several probability distributions are specified for uncertain values of the exogenous input parameters, that is assigning random values (within a pre-determined distribution) to each input parameter. Then, a large number of simulations are executed, taking each time a random draw from the distribution for each variable (Van Passel et al., 2013). In the framework of the economic analysis for the circular model, a Monte Carlo simulation is performed to examine how the PV_{25} (present value PV_T after 25 years) varies when the value of each input changes randomly within an interval between +30% and −30% of the quantity indicated in Table 1. The Monte Carlo simulation calculates the probability density of each of the possible outcomes for PV_{25} when inputs vary randomly within the defined interval, as shown in Eq. (4):

$$\Pi_i = \frac{N_i}{N_{tot}} \tag{4}$$

Where Π represents the probability density for each of the possible outcomes i, N_i is the number of counts in which PV_{25} is equal to i, and N_{tot} represents the total number of simulations.

In this study, Python is used to code the model for the Monte Carlo simulation. The complete script of the Python-based Monte Carlo simulation is reported in the supplementary materials.

3. Results and discussion

3.1. Environmental results

The results of the LCA for the midpoint analysis are shown in Fig. 4. Each of the columns represents one of the impact categories reported in the EF 2.0 methodology, while each layered colour represents the contribution of an input/process to a specific impact category. As each midpoint category is measured in a different unit, the contribution for each input/process is normalised as a percentage of the total impact for that category, calculated as the sum of the absolute values of caused and avoided impacts. A list of the units used in Fig. 4 with the corresponding midpoint impact category can be found in Table 3, along with the final results for the total impact, and the sum of all caused and avoided impacts. The detailed results describing the contribution of each input/process to each category can be found in table A in the supplementary tables. The positive part of the graph in Fig. 4 reports the impacts which are caused by the treatments performed, while the negative part of the graph reports the impacts that are avoided thanks to the secondary materials recycling and the avoided landfilling of the residues. Therefore, when a column presents the negative part bigger than the positive part, it means that the environmental benefits of the avoided impacts are higher than the environmental costs of performing the treatments. The normalisation allows representing all environmental categories in the same graph. On the other hand, because of normalisation, the details on the different scales of each impact category are irretrievably lost, and it is misleading to compare the size of the different columns. For instance, in the case of the impact category related to climate change, the column CO_2-equivalent (third column from the left in the upper part of the figure) represents the sum of columns CO_2-equivalent$_{bio}$ (accounting only for biogenic carbon), CO_2-equivalent$_{fossil}$ (accounting only for fossil carbon), and CO_2-equivalent$_{land\ use}$ (accounting for land use-related emissions). Looking at the total in Kg CO_2 -equivalent, reported in Table 3, the CO_2-equivalent$_{fossil}$ accounts for 99.4% of the total CO_2 -equivalent emissions, while the CO_2-equivalent$_{bio}$ and CO_2-equivalent$_{land\ use}$ account only for 0.2% and 0.4% respectively. This result is expected since almost all sources of GHG emissions in the system are sourced from fossil carbon, except a small amount of biogenic carbon coming from the biomass within the Spanish electricity production mix. Therefore, the columns in Fig. 4 must be read as a stand-alone analysis, that cannot be directly compared with the other columns.

As can be seen from the results, it is not possible to detect a consistent path among all categories. Some of the categories reports caused impacts significantly higher than the avoided impacts, as it is the case of global warming potential, while other categories present the opposite results. The higher caused impacts are related to electricity production and the production and CO_2 emissions from coke in EFFIMELT. Depending on the category, the highest avoided impacts are related to the avoided landfilling of the residues, and the avoided production of zinc oxide and copper, except for the category "climate change_land use", where the main avoided impact is related to the avoided production of electricity.

3.1.1. Environmental results for BIOCHAR

Figs. 5 and 6 show the LCA results when BIOCHAR completely substitutes coke as the reductant in EFFIMELT (100% substitution rate BIOCHAR-coke). The complete results for the BIOCHAR scenario can be found in table B in the supplementary tables. The inset graphs in Fig. 5 give details for all climate change categories. Comparing the positive side of the category climate change (first category on the left graph), the BIOCHAR scenario shows a reduction of 528.5 t/year of CO_2-equivalent emission. This significant reduction is due to the combination of two effects: the lower CO_2-equivalent emissions of BIOCHAR production compared to coke production (38.5 tCO_2 vs 106 tCO_2), and the substitution of the fossil CO_2-equivalent emission from coke (437.6 tCO_2) with biogenic CO_2-equivalent emission from BIOCHAR. Looking only at the column for BIOCHAR, the avoided impacts (the negative part) are bigger than the caused impacts (the positive part). This means that the total amount of CO_2-equivalent emissions avoided when using BIOCHAR in EFFIMELT is higher than the quantity of CO_2-equivalent emissions released, with an amount of −83.4 tCO_2-equivalent avoided per year. The two inset graphs on the right allow detecting the different scales of climate change-fossil and climate change-biogenic and -land use. Indeed, the climate change fossil contributes to 99.4% of the total impact of climate change, represented by the first two columns on the left.

Fig. 6 provides a comparison between coke and BIOCHAR production for all other impact categories except climate changes. BIOCHAR production has lower results in all represented categories. The reduction of the impacts between coke and BIOCHAR production is significantly big (>50%) in all categories, except water scarcity and ionising radiation. However, as it can be seen in Fig. 4, coke production represents a very small contribution to the total impacts of the

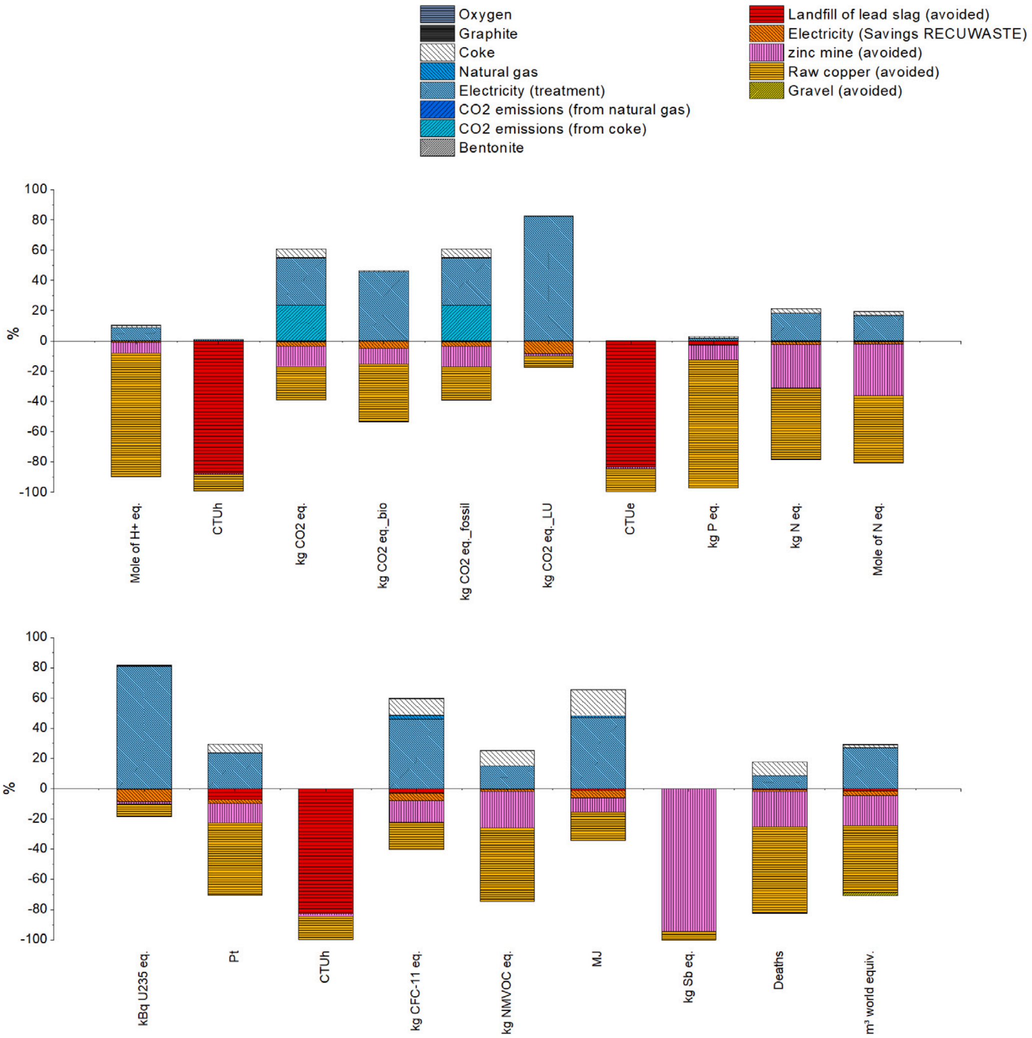

Fig. 4. Midpoint Environmental Footprint 2.0 categories: for each impact category, the positive part represents the caused environmental impacts, while the negative part represents the avoided impacts. The caused impacts are higher than the avoided for the categories of Climate change (total, fossil, land use), Eutrophication terrestrial, Ozone depletion, and Resource use (energy carriers). The avoided impacts are higher than the caused impacts in all other categories.

Table 3
List of units per impact categories used in Fig. 4, with the correspondent total impact, and the total caused and avoided impacts.

Unit	Impact category (EF 2.0)	Total impact[a]	Total (caused impacts)	Total (avoided impacts)
[Mole of H+ eq.]	Acidification terrestrial and freshwater	62 308.2	6 342	−55 966.2
CTUh	Cancer human health effects	0.55	0.01	−0.54
kg CO2 eq.	Climate Change	1 870 697.6	1 138 627.6	−732 070
kg CO2 eq._bio	Climate Change (biogenic)	3 334.7	1 551.7	−1 783
kg CO2 eq._fossil	Climate Change (fossil)	1 860 964.6	1 131 614.6	−729 350
kg CO2 eq._LU	Climate Change (land use change)	6 367.53	5 256.6	−1 110.93
CTUe	Ecotoxicity freshwater	60 563 931.4	183 644.4	−60 380 287
kg P eq.	Eutrophication freshwater	14 056.3	394.2	−13 662.1
kg N eq.	Eutrophication marine	4 713.9	1 010	−3 703.9
Mole of N eq.	Eutrophication terrestrial	56 569.8	10 907.1	−45 662.7
kBq U235 eq.	Ionising radiation - human health	445 412.4	363 523.4	−81 889
Pt	Land Use	17 608 560	5 210 060	−12 398 500
CTUh	Non-cancer human health effects	33.68	0.04	−33.64
kg CFC-11 eq.	Ozone depletion	0.13	0.1	−0.03
kg NMVOC eq.	Photochemical ozone formation - human health	15 679	3 971.6	−11 707.4
MJ	Resource use. energy carriers	29 885 149	19 634 340	−10 250 809
kg Sb eq.	Resource use. mineral and metals	2 602.2	0.2	−2 602
Deaths	Respiratory inorganics	0.13	0.03	−0.1
m^3 world equiv.	Water scarcity	850 146.9	248 719.8	−601 427.1

[a] Total impact = $|caused\ impacts| + |avoided\ impacts|$.

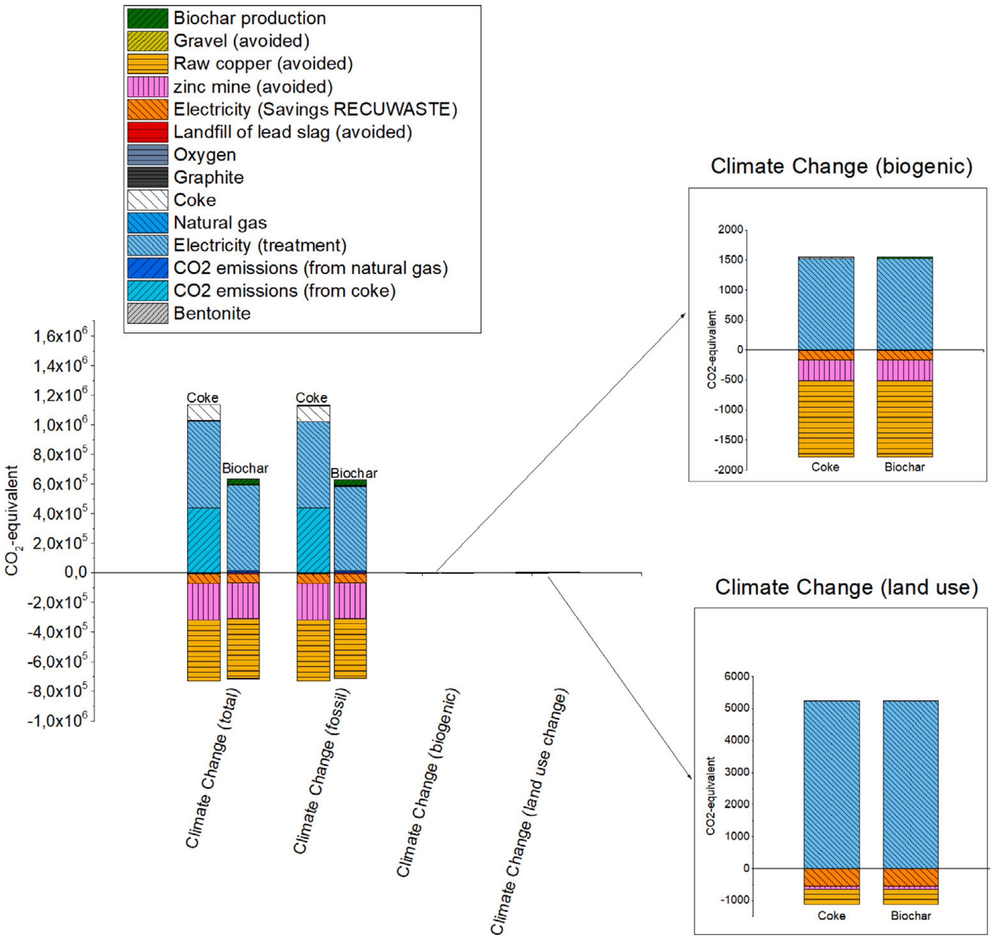

Fig. 5. Comparison between LCA results of CIRMET with coke and CIRMET with BIOCHAR, only for climate change categories. The first two columns on the left represent the total climate change, which results from the sum of fossil, biogenic and land use climate changes. The results highlight the reduction driven by the substitution coke-BIOCHAR, and the different scales of the impacts related to fossil and biogenic + land use climate change.

circular process. Therefore, the reduction driven by the substitution BIOCHAR/coke has a relatively small effect on the total impacts of the circular model, and the most significant effect is given in climate change by the avoided fossil carbon emissions in EFFIMELT.

3.1.2. *Environmental results interpretation*

The results of the LCA analysis allow to highlight the most relevant hotspots of the system, even though the technologies proposed within CIRMET are still in their early stages of development. At this pilot scale, the environmental benefits appear to be evident in many different environmental categories, and they are all related to metals recovery and avoided landfilling of the residues. On the other hand, the high demand for electricity for the furnace and the direct CO_2 emissions represents the main barrier that could hinder the sustainability of the whole process, while the mechanical energy recovered by RECUWASTE does not compensate for the environmental costs of energy consumption. From this analysis, it is straightforward to conclude that higher efficiency in the use of energy, and the substitution of current electricity sources with renewable or secondary resources, would significantly benefit the environmental profile of the proposed circular model. Indeed, the consumption of primary electricity for EFFIMELT could be reduced by recovering heat from other flue gas from other industries (e.g. the cement industry). The results presented in the study confirm the findings from previous LCA studies applied to the various pyrometallurgical processes to treat different residues and to recover metals. As many authors have stated in the past, for novel and emerging technologies it is difficult to compare LCA results from previous studies (Moni et al., 2020). Indeed, only a small number

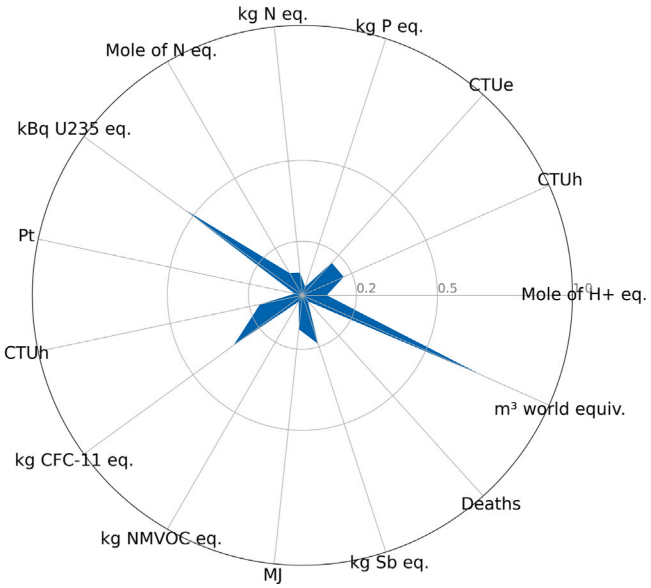

Fig. 6. Comparison of coke-BIOCHAR productions for all categories other than climate changes. The external perimeter represents the LCA results for each category for coke production, while the blue interior polygon represents the results for BIOCHAR production. BIOCHAR production presents lower impacts for all categories compared to coke production. The reduction achieved is higher than 80% in all categories, except water scarcity (≃27%), ionising radiation (≃45%) and ozone depletion (≃68%).

of LCA studies have been reported in the scientific literature on the use of pyrometallurgical processes to recover metals from residues, and these vary significantly in the type of process analysed, metals recovered, modelling assumptions, or in the kind of residues treated. For instance, Rajaeifar et al. (2021) assessed the results in the category climate change for recovering different metals concentrates from spent lithium-ion batteries using different pyrometallurgical processes. The result from this analysis confirms that the benefits in terms of climate change savings, arising from the recovery of metals concentrates, can be balanced out by the high energy requirement in the furnace. Li et al. (2019) assessed the environmental performances of pyrometallurgical technology to recover copper and precious metals from e-waste, confirming that the main impacts in the pyrometallurgical process derive from the electricity demand and the CO_2 emitted directly from the furnace. Zhang et al. (2021) performed an LCA of copper recovery from copper-based scraps through a smelting process, including also zinc, gold and silver recovery as by-products The study found out that the smelter caused the highest impact in 10 out of 16 environmental indicators, although no comparison with the avoided impact deriving from the recovery of secondary copper, zinc, gold and silver concentrates was reported. Finally, Di Maria and Van Acker (2018) reported an LCA of a plasma fuming process of goethite slag from zinc production, confirming the predominant role of the pyrometallurgical process along the whole chain of the slag valorisation process. Considering the LCA results reported by the environmental analysis of the CIRMET model, and in the light of the LCA results of previous studies, the substitution of coke with BIOCHAR represents a potentially valuable solution in the framework of the decarbonisation of the metallurgical industry. The use of BIOCHAR in EFFIMELT significantly lowers the climate change effect related to fossil carbon, which represents 99.4% of the total climate change effect, and it allows reducing the total CO_2-equivalent emissions by 528.5 tonnes per year. According to the LCA analysis, thanks to the use of BIOCHAR, the fossil carbon footprint of the proposed solution becomes negative, with a quantity of 83.4 tonnes of CO_2-equivalent emissions avoided every year. In the comparison with coke production, the BIOCHAR production resulted to have much lower impacts also in all others analysed categories, although the effects of BIOCHAR/coke substitution for categories other than global warming did not have a significant effect on the overall impact of the circular model

3.2. Economic results

The results of the present value PV_{25} for each cash flow are presented in Fig. 7. The sum of the PV_{25} for the revenues is higher than the sum of PV_{25} of the OPEX. Electricity and labour are the highest cost among the OPEX, while the copper and zinc oxide recovery provide the highest revenues. Therefore, from Fig. 7 and according to Eq. (3), it can be concluded that the total value generated by the circular process in 25 years is equal to 7 200 992 €, considering a treatment capacity of ≃1020 t/year. The PV_{25} for BIOCHAR is also shown in the bottom part of Fig. 7, and it is accounted as an alternative to the PV_{25} for coke. If BIOCHAR is used, the PV_{25} for BIOCHAR (214 085 €) replaces the one for coke (278 311€), and the carbon tax due to the CO_2 emissions from coke in EFFIMELT is avoided (−200 537 €). This leads to a total reduction of the final PV_{25} for OPEX of 264 762 €, which represents 2.2%. of the total PV_{25} for OPEX.

Fig. 8 shows the evolution of payback time vs CAPEX during the lifetime of the infrastructures, calculated by assuming NPV=0. The green curve in Fig. 8 represents the maximum CAPEX that can be invested if aiming for a specific payback time, in the case of a pilot plant able to treat 150 kg/h or 1020 t/year of metallurgical residues (the case described so far). Usually, an interesting payback time for industries lays around 5 years, therefore a realistic value for CAPEX that could be invested for such a pilot plant is around 2 533 597 €. It is also interesting to see how the potential upscaling of the technology could trigger economies of scale and optimisation processes, significantly increasing the economic desirability of the technologies. Therefore, a potential upscaling scenario has been assumed, in which treatment capacity increases from 150 kg/h to 750 kg/h, for a total of 5103 t of metallurgical residues treated per year. Data for this potential upscaling scenario have been provided by the plant manager, as a result of calculations performed on the digital model of the process. A complete list of the data used in the upscaling scenario is reported in table C in the supplementary tables. The most relevant assumption is represented by a reduction of 47% in the use of electricity per ton of residues in EFFIMELT, while important cost factors, such as labour cost, stay equal. The blue curve in Fig. 8 represents the variation of CAPEX vs payback time for the upscaling scenario. As it could be expected, the blue curve presents a more upright shape compared to the green curve, which is rather flat. Moreover, the available CAPEX for a 5-year payback time increases by a 9.2 factor compared to the pilot plant (from 2 533 597 € to 23 309 306 €), although the treatment capacity increases only by a factor of 5. Although these numbers must be taken with high caution, as they are calculated from assumptions and digital modelling, they already indicate a trend of the significant economies of scale that could be triggered if upscaling the technologies.

Finally, the Monte Carlo simulation in Fig. 9 shows the probability distribution of possible outcomes for PV_{25}, calculated through 100'000 simulations in which all economic parameters vary between −30% and +30%. The blue bars represent the distribution of the probability function, that is the probability that PV_{25} would have the correspondent outcome in the x-axis. The probability density bars show a normal distribution around a mean value $\mu = 7\,228\,704$ € and a standard deviation of $\sigma = 854\,109$ €. The distribution of the bars approximates the shape of a normal distribution, identified by the probability density distribution (PDF) curve, calculated with the same mean μ and standard deviation σ. Because of one of the properties of normal distributions, the so-called empirical rule, the area under the curve laying within 1σ is approximately 68%, within 2 σ is around 95%, and within 3 σ around 99.7%. Practically speaking, this means that the final value of PV_{25} has a 68.2% probability to fall between 6 374 594 € and 8 082 813 €, the 95.4% between 5 520 486 € and 8 936 922 €, and the 97.7% between 4 666 377 € and 9 791 031 €.

3.2.1. Economic results interpretation

The economic analysis has shown that, under the assumptions undertaken in the study, the PV after 25 years and the payback time seem to be desirable. A potential upscaling scenario also showed the potential economies of scale that could increase the economic desirability of the technologies. Metal recovery plays a key role in the economic profitability of the whole process, accounting together for ≃96% of the total PV_{25}, while a much lower contribution to PV_{25} is given by the avoided landfilling. Also, the analysis of a potential upscaling scenario showed how energy consumption optimisation significantly increases the economic desirability of the technology.

The potential positive economic outcome by recovering zinc from metallurgical residues has been confirmed also by some previous studies. For instance, Ng et al. (2016) calculated that the recovery of zinc from steelmaking dust could generate between 381–21 740 million €/year, assuming a high dust-production scenario. Also, Phiri et al. (2021, 2022) have shown that the recovery of valuable metals from copper slag through pyrometallurgical processes is undoubtedly one of the most economically promising options for sustainable management of this residue. However, the cost of recycling can be extremely variable, due to the volatility of prices, and also because the recycling method and its efficiency is site-specific and depends on the type of metallurgical residue. To tackle this uncertainty, the Monte Carlo simulation proved to be a useful tool, providing consistent estimates on the potential effects of prices variations on the final revenues. This can help the metallurgical industry in making a more informed decision about the possibilities of recovering zinc and other metals from metallurgical residues.

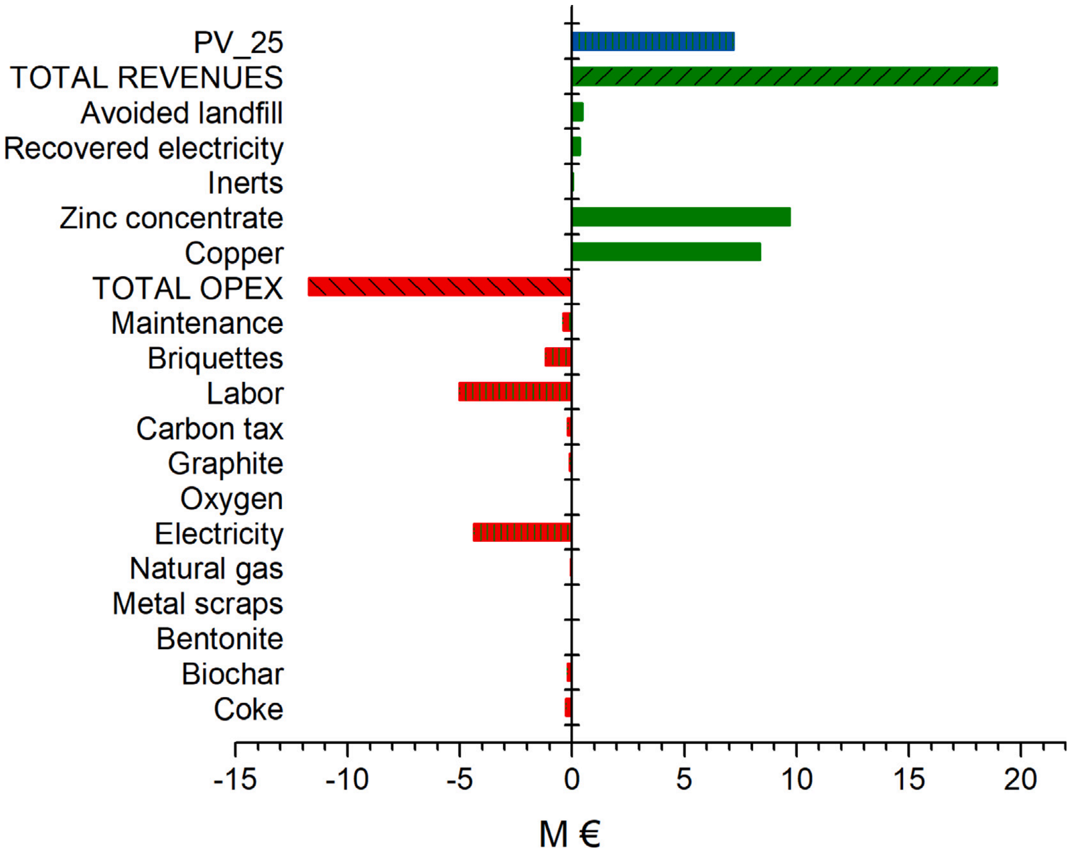

Fig. 7. Results of the economic analysis. Each column represents the PV_{25} for each cash flow. The negative PV_{25} represent the OPEX, while the positive PV_{25} represent the revenues. The sum of the PV_{25} for the revenues is higher than the PV_{25} for the OPEX, meaning that the total PV_{25} for the CIRMET solution has a gain of 7 200 992 €.

Finally, the versatility of the system, as discussed in the Methods section, allows for an efficient adaptation of the process parameters, depending on the characteristics of the residues being treated. Therefore, such versatility allows to theoretically extend the conclusion of the economic analysis also to the valorisation of other types of metallurgical residues. On the other hand, it must be considered that the main economic viability of the process derives from the value of recovered metals. Therefore, independently of the adapted process parameters, the metallurgical residues treated must ensure a sufficient quantity and marketability of the recovered metals.

Some of the identified key parameters are common for both environmental and economic analysis. The energy consumption needed for EFFIMELT (both electricity consumption and natural gas) gives the highest impact in all environmental categories, and among the highest contributions to the OPEX. Some other parameters play a fundamental role in one of the analyses, but resulted to be less crucial in the other, also highlighting the different nature of environmental and economic analysis. For instance, the use of BIOCHAR leads to a significant reduction of the environmental impacts for some categories, but the reduced CO_2 emissions did not influence significantly the economic profile of the process. Also, the recycling of metal scraps to produce copper represents a burden-free opportunity to increase the environmental performance of the system, due to the allocation rule applied to the LCA system boundaries. On the other hand, it represents a significant cost in the economic model, accounting for 14% of the total cost. Moreover, some of the elements that are very relevant in the economic analysis have no place in the environmental results, such as labour and maintenance.

4. Conclusions

An environmental and economic analysis based on Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) has been performed on a pilot-scale plant, testing an innovative circular process to recover materials and energy from metallurgical residues. The proposed circular process, developed within the framework of the H2020 European project CIRMET, consists of the development of 4 modular and integrated technologies: a furnace for metals fuming and recovery (EFFIMELT), a heat-recovery unit (RECUWASTE), a digital platform for processes control (AFF40), and a biobased material (Biochar) to substitute fossil-based coke as the reductant in EFFIMELT. The pilot plant has been tested on metallurgical residues from non-ferrous metals production, for the recovery of zinc oxide, secondary copper, mechanical energy from waste heat and inert materials.

The results of the environmental analysis have clearly shown the potential environmental benefits of the proposed solution, especially due to the avoided landfilling of the residues and the recovered metals. On the other hand, energy consumption, from both electricity and natural gas, represents the environmental hotspots that may hinder the environmental profile of the whole process, especially in the environmental impact category of climate change. In this regard, one of the most efficient strategies can be the recovery of energy from alternative energy sources, for instance by coupling the EFFIMELT furnace with other high-temperature industries (e.g. cement manufacturing) for the recovering of waste heat. Also, the substitution of metallurgical coke with biochar can significantly lower the total amount of CO_2-equivalent emissions from EFFIMELT (528.5 t/year), since it replaces the fossil carbon emissions from coke with biogenic carbon emissions from biomass. Moreover, thanks to the use of biochar, the fossil carbon footprint of the whole process become negative (−83.4 t/y). The economic analysis shows the potential opportunities of the CIRMET solution, with a present value at the end of the lifetime of the units (25 years) of over 7 million euros. Assuming a payback time of 5 years, the maximum amount of CAPEX that could be invested to ensure an economic breakeven is 2 533 597 € for small size pilot plant

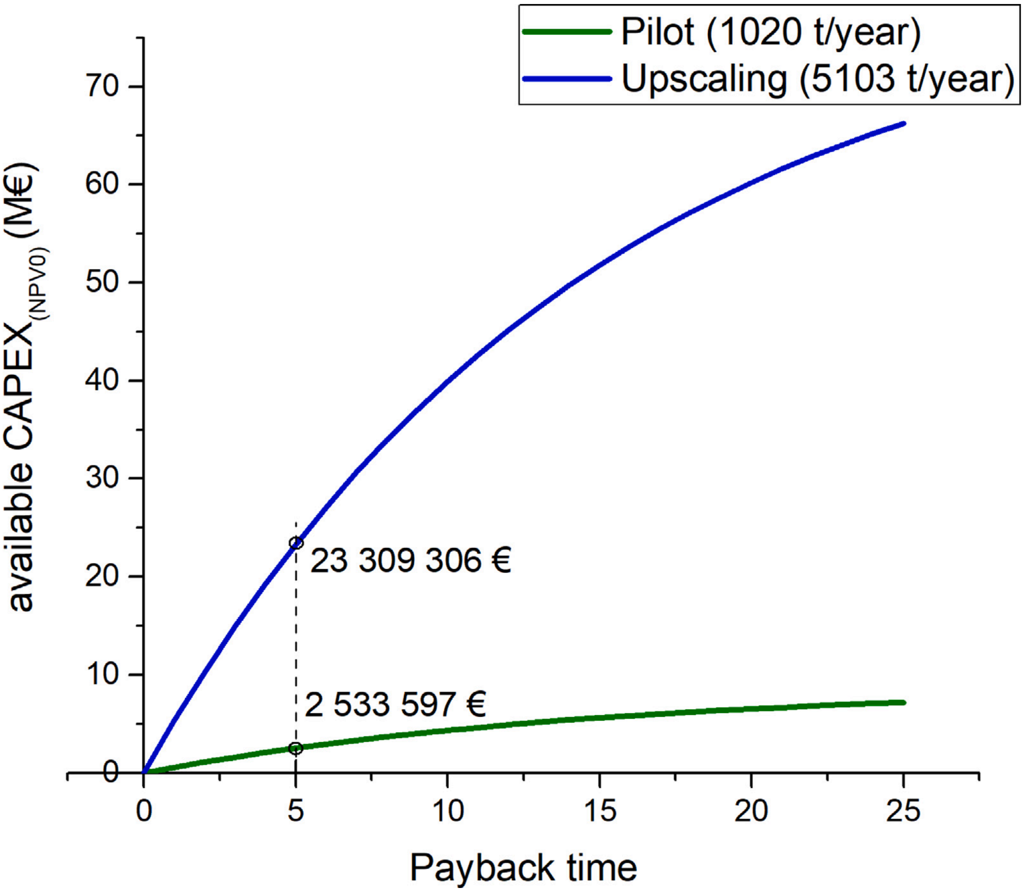

Fig. 8. 25 years of evolution of CAPEX calculated with NPV=0 for a pilot (the case analysed so far) and a potential upscaling scenario, in which the treatment capacity increased by a factor of 5. Aiming for a 5-years payback time, the available CAPEX increases by 9.2 times for the upscaling scenario, indicating the potential effect of economies of scale.

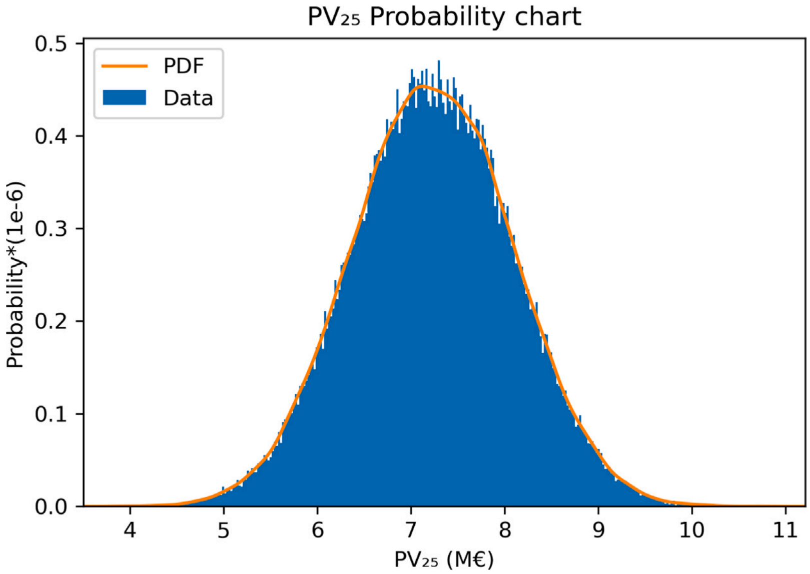

Fig. 9. Monte Carlo uncertainty analysis for 100’000 simulations, in which OPEX and Revenues are randomly distributed between +30% and −30% of their values: The figure shows that the calculated probability density approximates the shape of a normal distribution identified by the probability density distribution (PDF).

able to treat 1026 t/y. The consistency of the economic results has also been tested through an uncertainty analysis run by Monte Carlo simulation.

While the study is performed for a small scale pilot testing plant (1026 t/year), a potential upscaling scenario to 5106 t/year has indicated several mechanisms of resource optimisations and economies of scale, that could increase the overall economic desirability of the technologies up to 9 times. Although it is not straightforward to compare the findings of the study with previous results reported in the literature, both environmental and economic analyses seem to confirm that the recovering of metals from metallurgical residues fits perfectly within the circular economy model, as it provides environmental benefits while also generating economic values

Finally, rather than a conclusive answer, the results from the LCA and the LCC must be considered as an iterative exercise to highlight the potential opportunities represented by the implementation of a circular model to treat metallurgical non-ferrous residues, and also to identify potential drawbacks during the initial development phase, allowing a more efficient design of the technology towards increased environmental and economic sustainability.

CRediT authorship contribution statement

Andrea Di Maria: Conceptualization, Methodology, Data treatment, Investigation, Analysis, Writing – original draft. **Mikel Merchán:** Conceptualization, Data collection, Validation, Project administration, Writing – review & editing. **Muriel Marchand:** Data collection, Validation, Writing – review & editing. **David Eguizabal:** Data collection, Validation, Writing – review & editing. **Maider García De Cortázar:** Validation, Project administration, Writing – review & editing. **Karel Van Acker:** Supervision, Writing – review & editing.

Declaration of competing interest

One or more of the authors of this paper have disclosed potential or pertinent conflicts of interest, which may include receipt of payment, either direct or indirect, institutional support, or association with an entity in the biomedical field which may be perceived to have potential conflict of interest with this work. For full disclosure statements refer to https://doi.org/10.1016/j.jclepro.2022.131790.

TECNALIA and DIGIMET collaborated in the development of the EFFIMELT technology and hold intellectual property on metallurgical developments with circular economy focus. CEA has developed the torrefaction technology and holds intellectual property on the Biochar production process. KU LEUVEN is an independent partner of the consortium for the CIRMET H2020 project, together with TECNALIA, DIGIMET and CEA. KU LEUVEN has worked independently on the development of the analytical models, based on the data provided by the other partners.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.jclepro.2022.131790.

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