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Life cycle assessment of ferronickel production in Greece

Georgios Bartzas[a], Kostas Komnitsas[b,*]

[a] National Technical University of Athens, School of Mining and Metallurgical Engineering, 15780 Athens, Greece
[b] Technical University Crete, School of Mineral Resources Engineering, 73100 Chania, Greece

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ABSTRACT

Ferronickel (FeNi) is predominantly produced from nickeliferous laterite ores which are converted into a product with a nickel content of around 20%. With increasing emphasis being put on energy efficiency and global climate change, it is important for the nickel industry to further explore energy saving issues and to evaluate a number of potential opportunities for reducing the greenhouse gas footprint of primary FeNi production. The present study adopted a life cycle assessment (LCA) approach to assess energy consumption and greenhouse gas footprints of the main processing stages of a typical Greek nickel laterite ore for the production of ferronickel. In this context, a detailed life cycle directory was created based on facility-specific data and used for a holistic cradle-to-gate LCA analysis (including mining and the main ore processing routes). The following energy and environmental indicators were assessed: global warming potential (GWP), acidification potential (AP) and primary energy demand (PED). Using current FeNi production as a baseline scenario (BL), two alternative scenarios, namely (i) the green energy (GE) scenario that involves 50% substitution of fossil fuels mix (lignite and coal) with biochar and 50% substitution of lignite with renewable resources for electricity production, and (ii) the waste utilization (WU) scenario that includes 65% utilization of slag in the construction sector, to improve energy and waste utilization, minimize the adverse environmental impacts and therefore achieve more sustainable FeNi production were investigated. Results showed that the best alternative scenario for energy savings and reduction of associated GHG emissions during FeNi production was the GE scenario. With this scenario energy savings and GHG emissions were about 17% and 35% lower compared to BL scenario, respectively. Lower reduction in energy consumption (7%) and GHG emissions (13%) compared to the BL scenario was attained when the WU scenario was considered.

1. Introduction

Ferronickel (FeNi) and ferrochrome are the two main ferroalloys used for the production of stainless steel. It is predominantly produced from nickeliferous laterite ores which are converted via the pyro-metallurgical route into a product with a Ni content of around 20% (Crundwell et al., 2011a,b). Currently, only 42% of world primary Ni production is processed from laterite ores mainly through pyrometallurgical routes, with FeNi holding the highest share (∼72%) among all nickel-based products (Zhou et al., 2015). However, pyrometallurgical laterite ore processing is much more energy intensive compared to sulphide ore processing (Mudd, 2010; Haque and Norgate, 2013) and it results in the production of large volumes of greenhouse gas (GHG) emissions and solid wastes (Norgate et al., 2007; Warner et al., 2006). In its efforts for energy conservation, emission reduction and process sustainability, metal industry has used several approaches to quantify its performance, that include among others ecological risk assessment (ERA), environmental performance and operational indicators, cost benefit analysis (CBA), materials flow analysis (MFA), and life cycle assessment (LCA) (Sorvari et al., 2011).

To date, LCA is considered the best approach for the assessment of sustainability in all industrial sectors (Finnveden et al., 2009). As a result, LCA has become an important tool for the metal industry, which faces a growing public pressure to act responsibly on climate change issues, to evaluate its environmental performance towards an improved sustainability (Eckelman, 2010). In particular, LCA addresses the potential environmental impacts, human health and resource concerns of any product or process over its entire life cycle, from raw material acquisition to manufacturing, use, end-of-life treatment, recycling and/or ultimate disposal (Yellishetty et al., 2011). While some LCA studies are available for the metal industry in general (van Berkel, 2007; Yellishetty et al., 2009; Paraskevas et al., 2015), the number of respective studies to

* Corresponding author.
E-mail address: komni@mred.tuc.gr (K. Komnitsas).

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assess GHG emissions during FeNi production from laterite ores is limited (Eckelman, 2010; Haque and Norgate, 2013) and their results are restricted by certain limitations, including high degree of uncertainty, low robustness and insufficient applicability (Norgate and Jahanshahi, 2011). The main reasons for these constraints are either methodological and/or operational. Methodological constraints mainly include differences in the type of functional unit, source and availability of inventory data, transportation of raw materials, allocation procedures and cut-off rules used. On the other hand, operational constraints involve variations in ore grade, mineralogy and processing, as well as type of electrical energy (fuel grid mix) and thermal energy (solid fuels) used.

A common limitation in most LCA studies is that they include only metal production stages (e.g. smelting and refining) and thus they do not take into account impacts associated with mining. In addition, most studies rely on the use of imported nickel ores for FeNi production and in some cases they do not take into consideration the environmental impacts associated with raw materials transportation to production facilities. As highlighted by Eckelman (2010) and Northey et al. (2014), updated and detailed site-specific data about ore types, geology, topography and hydrology are required to improve reliability of the results in LCA studies.

In this context, the novelty of the present study consists in (i) the use of a complete bottom-up approach which considers up-to-date and site specific facility-process data for the inventory analysis, (ii) the inclusion of the mining sector, (iii) the consideration of environmental impacts associated with transportation of the raw materials and (iv) the analysis of alternative production scenarios that optimize the efficient use of both mineral and renewable energy resources.

The specific objectives of this study, which is the first one carried out for this sector in Greece, were to: (i) evaluate the life cycle of the "cradle-to-gate" FeNi production, (ii) identify the processing stages and hotspots that are energy intensive and cause the most important environmental impacts, (iii) propose two alternative scenarios, namely the green energy and the waste utilization, to minimize impacts and improve sustainability of the sector, and (iv) highlight crucial points for future research.

2. Ferronickel production in Greece

Greece is the only FeNi producer in the European Union, the third largest producer in Europe and one of the seven largest in the world. In 2012, approximately 95,000 t of granulated FeNi with 20% average Ni content was produced by the General Mining and Metallurgical S.A. LARCO from domestic nickeliferous laterite ore deposits. Ferronickel production at LARCO accounts for 32% and 4% of the European and world production, respectively and covers nearly 5% of the European annual market Ni demand (Apostolikas et al., 2009; USGS, 2015). A detailed schematic overview of FeNi production in LARCO is shown in Fig. 1. Further details of the FeNi production route in Greece are given in Supplementary material (S-1).

3. Methodology

An LCA approach was adopted to investigate the cumulative environmental impacts (energy and emissions) during the production of FeNi in Greece. According to the guidelines and specific requirements of the International Organization for Standardization (ISO) 14040–14044 standard series (ISO, 2006a,b), there are four main steps in an LCA study, namely, the goal and scope definition, the life cycle inventory analysis, the impact assessment and the interpretation as described below in detail.

3.1. Goal and scope definition

The goal of this LCA study was to quantify the energy consumption and greenhouse gas footprint of the existing metallurgical route (BL scenario) and also explore more sustainable and eco-friendly practices (GE and WU scenarios) that can be used in the FeNi production stages. According to ISO standard series (ISO, 2006a,b), the functional unit (FU) is defined as the quantified performance of a product system and is used as a reference unit in an LCA study. In the present study, the FU for each FeNi production scenario was defined as one tonne of produced FeNi with 20% Ni content. This is consistent with the general function of a production chain from the perspective of the major metallurgical companies,

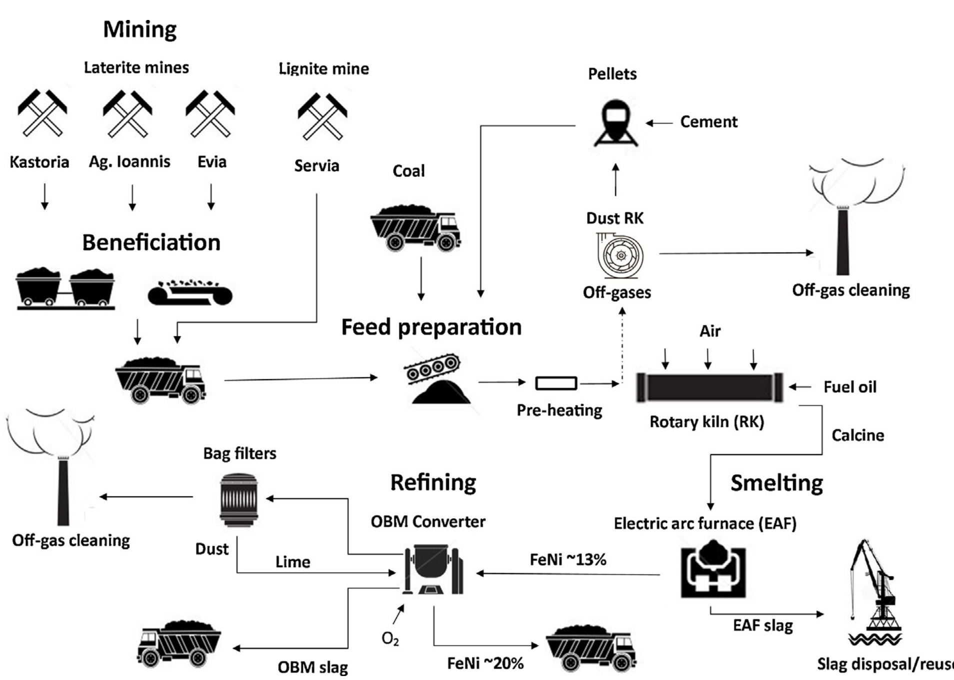

Fig. 1. Detailed schematic overview of FeNi production in LARCO.

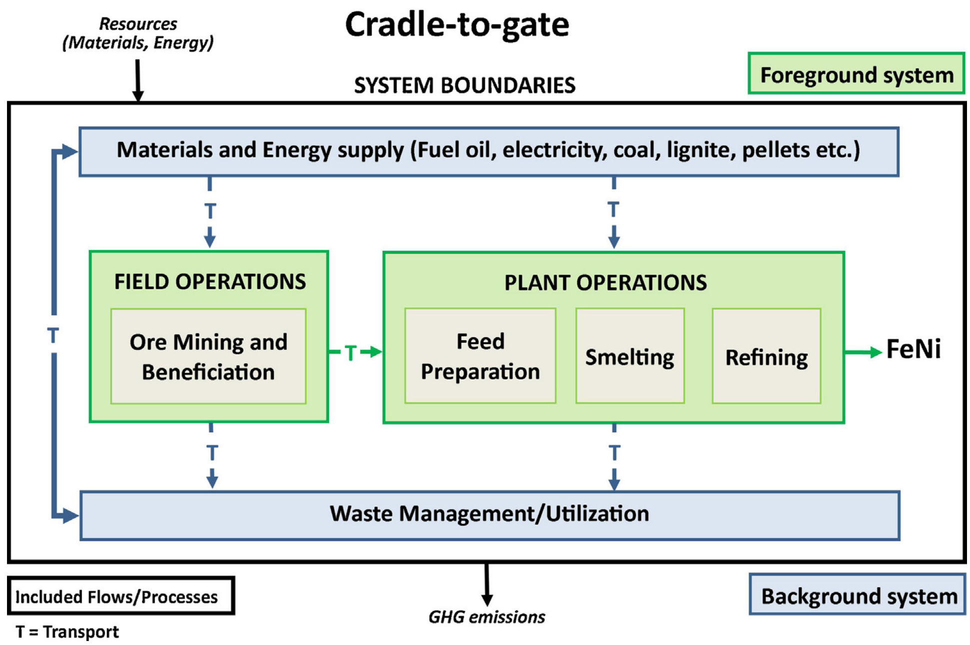

Fig. 2. System boundaries of FeNi production adopted in this study.

and it is also the most commonly used FU in LCA studies (Nickel Institute, 2012; Norgate and Jahanshahi, 2011). All calculated emissions associated with energy consumption, raw materials transport and waste disposal are based on this functional unit.

3.1.1. System boundaries

In the present study, the "cradle-to-gate" approach was used, considering all the production processes involved from raw materials extraction (i.e. the cradle) to the point where the final product (FeNi) is made available to the secondary manufacturing sector e.g. stainless steel producer (i.e. the gate). As a result, the main system flows considered in this study include (Fig. 2): (i) inputs including energy provided from the local grid (electricity) and other sources (diesel, coal, lignite, etc.), (ii) the main processes of the system (mining and beneficiation, feed preparation, smelting and refining), and (iii) the outputs of the FeNi production process stages (by-products, emissions and primary/secondary wastes).

In this LCA study energy consumption and emissions from each stage have been quantified, while transport between the different stages has been taken into account where needed. Notably, the transport processes of the principal materials (laterite ore and lignite) were considered while minor material and energy flows accounting for less than 1% of the total were excluded. Therefore, the neglected processes do not exceed 5% of those involved in the entire process based on the system boundaries adopted in this study.

3.1.2. Modelling approach, scenario design and assumptions

In the present study, the LCA analysis was performed using the commercial GaBi 6 software and related databases (PE International, 2014a), taking also into consideration the classification and characterization phases that the norm ISO 14,040, which specifies the general framework, the principles, and the basic needs to perform an LCA study of this kind. During the classification phase, each burden was linked to one or more impact categories, while in the characterization phase the contribution of each burden to each impact category was calculated by multiplying the burdens with a characterization factor (Guinée et al., 2001). Each of the involved production and transport phase was separately modelled using data from the performance of each individual unit with its own mass and energy balance. The demand for energy, production and transport of the raw materials were also estimated based on the collected data.

Scenario analysis is the primary method to project and analyze possible alternative future developments in a product chain in terms of energy conservation, emissions reduction and sustainability (Liu et al., 2015). It is closely related to a sensitivity analysis and has therefore been widely applied to identify potential key factors for further developments in large-scale facilities such as metal industries and improve decision-making by considering outcomes and their feasibility implications. In this LCA study, the following three scenarios were investigated:

1. *Baseline scenario* (*BL*). It includes normal mode of operations for both mining and smelting activities. This scenario was based on the actual current operational and waste/by-product management practices that take place in the FeNi plant and was used as the basis for comparison with the other two hypothetical scenarios that represent alternative optimization options. Table 1 shows the quantities of the main waste/by-products generated in each production stage at the LARCO metallurgical plant and the type of management/utilization that is currently used.

Table 1
Key characteristics concerning waste/by-product generation and utilization at the FeNi plant in Greece.

Stage	Output	Unit	Value	Waste/by-product utilization (%)
Smelting	Dust RK	t/t FeNi	1.89	Reuse (as pellets): 99%
	Slag EAF	t/t FeNi	21.05	Sea disposal: 65%Sandblasting material: 35%
Refining	Slag OBM	t/t FeNi	1.26	Concrete additive: 100%
	Dust OBM	t/t FeNi	0.01	Reuse: 99%

It is obvious that the Greek FeNi industry generates annually considerable amounts of solid waste/by-products (slags and dusts), and although some of them are to a certain extent either reused on site or recycled off site (sold as secondary raw materials), the largest amount of the produced EAF slag is still disposed into the sea.

2. *Green energy scenario* (*GE*): The key advantage of this hypothetical scenario lies in the use of renewable energy instead of conventional fossil fuels and grid-supplied power with the aim to reduce GHG emissions. Therefore, in this scenario 50% of the commonly used fossil fuels (coal and lignite) is replaced by biochar produced from agricultural wastes, while 50% of the electricity used in all production stages is also substituted with equal mix derived from renewable resources: wind-turbine and biomass. It is underlined that biochar has recently gained significant importance for its potential use in the metallurgical industry, instead of fossil fuels, in an effort to reduce the non-renewable greenhouse emissions (Feliciano-Bruzual, 2014; Fidalgo et al., 2015; Norgate and Jahanshahi, 2011). Biochar is an energy resource that can be easily produced from the pyrolysis of biomass from a variety of agricultural wastes and residues (Komnitsas et al., 2015). Due to its low cost, high availability in almost all countries and high carbon content, the use of biochar is considered a potential resource for energy generation. The non-renewable credit of this scenario in terms of reduction of the greenhouse gas emissions in the Greek FeNi industry seems to be significant, by also taking into account the production of electricity from renewable resources such as wind-turbine and biomass. This scenario is considered challenging for the LARCO plant, which is located at the edge of the agricultural plain of Kopais lake (7 km South Eastern) and the wind energy park of Kastro in Viotia (9 km East) with 38 MW total capacity.
3. *Waste utilization scenario* (*WU*). This scenario involves management of the produced EAF slag (2.000 kt/y), as follows: (i) 50% of the slag (FeO: 38%, Fe_2O_3: 3%, SiO_2: 35%, CaO: 3%, Al_2O_3: 9%, MgO: 3%, Cr_2O_3: 2%, Ni: 0.1%) will be utilized as aggregate in asphalt mixtures for anti-skip pavements and as sub-base in road construction, (ii) 15% of the slag will be used as raw material in the cement industry, and (iii) the remaining 35% of the slag will be used as in the BL scenario, for sandblasting. This scenario is considered as optimal, since it increases considerably both the economic profit and the recycling rate of the main waste streams produced at the plant. This scenario also reduces significantly the volume of slag which is disposed into the sea, thus lower expenses are anticipated in terms of energy consumption for materials handling and machinery use. Furthermore, the most significant benefit of this recycling strategy is the potential reduction of the overall environmental burdens of the FeNi plant. Although EAF slag has been typically classified as non-hazardous material according to the European Catalogue for Hazardous Wastes (Lemonis et al., 2015), there is still a need to explore alternative, sustainable and more eco-friendly ways for slag utilization that will help large-scale facilities to reduce energy and the related GHG emissions and also minimize potential adverse effects on various ecosystems (sea water, marine life, landscape). To this extent, promising results have been obtained in the last decade regarding nickel-based EAF slag utilization for the production of construction materials with excellent mechanical properties such as glass ceramics (Wang et al., 2010) and geopolymers (Komnitsas et al., 2013). However, so far most of these efforts have been restricted to laboratory and pilot-scale, and are therefore inadequate for extrapolation in large scale applications.

All scenarios considered in this study were proportional, meaning that each hypothetical scenario was built by substituting part of the system boundaries of the baseline scenario, depending on the type of energy and utilization state of the waste/byproducts that were considered in each case, respectively.

However, the following assumptions were considered in all scenarios investigated in the present LCA study, to ensure integrity, comparability and consistency of the obtained results:

- Laterite ore used in the smelting plant was extracted from open pits (97.6%) and underground mining (2.4%).
- Strip ratios [tonnes of waste rock per tonne of ore] of 4.5:1 for open-pit mining and 0.1:1 for underground mining were considered (BRGM, 2001; Tuusjärvi, 2013).
- Constant Ni content within and across mines (1.1%).
- Constant feed mixture of laterite ore (per weight), originating from Kastoria (15%), Agios Ioannis (30%) and Evia (55%) respectively, was used in the pyrometallurgical process.
- Land use and infrastructure contributions in each process were excluded due to the lack of detailed information and the fact that their burdens were very small (e.g. large production of FeNi and low land occupation over the entire life time of the smelting plant).
- Electric power station generation efficiency is 35.3% (BL scenario).

Another novel feature of the current LCA study was the consideration of the transportation processes involved in all stages of FeNi production. In this study, all relevant and known facility-specific data regarding transportation of all upstream materials that enter the system boundaries were used, where appropriate. The transport distance of laterite ore was the same for the three scenarios and was determined by the origin of the ore location and the type of the feed mixture used. Since most secondary raw materials were either produced on site (e.g. oxygen and nitrogen) or were available in close proximity (e.g. lime and silica), transport of these materials was excluded from the inventory data. Furthermore, the transportation of recovered/sold by-products was not included, as this exceeds the system boundaries considered in this study.

The complexity of the FeNi industry also reflects the complexity of the allocation rules and the cut-off criteria. As a result, this study has adopted a well-established allocation approach based on mass allocation. This approach, which was used only on the shared by-products and waste, is particularly essential in the metal industry since an output material (slag, dust, etc.) generated by a process stage can by managed by a different option (land or sea disposal, recovery on site or use in other industries) and is therefore treated either as by-product or as waste. It is underlined that according to the methodology used inclusion of at least 95% of mass and energy flows was achieved for all respective flows that were taken into consideration in the inventory data.

3.1.3. Assigned impact categories

In the present study, three impact categories, namely global warming potential (GWP, in t CO_2-eq.) and acidification potential (AP, in t SO_2-eq.), which have been defined according to CML 2001 (Guinée et al., 2001), as well as primary energy demand (PED) as an energy flow indicator, were considered. These impact categories were selected because of their relevance to metal production and related energy processes (Eckelman, 2010; Haque and Norgate, 2013; Norgate et al., 2007). Due to the lack of available reliable data, toxicity categories such as, human toxicity, terrestrial eco-toxicity, and aquatic eco-toxicity were not assessed. Where possible, field emissions in all environmental media (water, soil and air) were estimated using specific models (IPCC, 2006), starting with the primary data that were provided for FeNi production. The primary energy demand, including both non-renewable and renewable energy, was ultimately calculated by considering the net calorific content of the energy commodities. The data for energy use, necessary to calculate the primary energy demand for each unit process, were provided both by LARCO S.A. and the Ecoinvent v.3.1 database of the Swiss Centre for Life Cycle Inventories (Ecoinvent, 2014).

3.2. Life cycle inventory (LCI) analysis

According to ISO 14040–14044 standards, the LCI is an inventory of the input/output data of the system being studied. As a result, all energy, materials usage and the related environmental emissions over the life cycle of the entire FeNi production system, from materials extraction to the gate of the metallurgical plant were identified and fully quantified.

3.2.1. Data acquisition

The use of primary industrial production data in LCA studies is partly limited and inaccurate since their quality varies significantly depending on their completeness, reliability, accuracy, robustness and reproducibility (Liu and Müller, 2012). The input data used in this study obtained from different sources, involving the plant, official authorities and scientific publications, and cross-checked carefully to improve reliability. Within this context, production data were provided primarily from LARCO S.A. (data records, public presentations and company website – www.larco.gr). Secondary data were collected from several scientific repositories including journals, conference proceedings, government and academic publications, technical papers and books. Background data for the inventory list, pertinent to energy flows (electricity and fossil fuels), process equipment and machinery, transportation, and materials of the inventoried FeNi production phase, were obtained from available Gabi software databases (Ecoinvent v.3.1 and Professional database – PE International, 2014b)

3.2.2. Site-specific inventory

The LCI inventory data for FeNi production in Greece is given in Table 2 and is based mainly on site-specific facility data. Table 2 also provides information concerning the origin and the quality of the LCA data used. More details concerning the methodology used for quantifying data quality is provided in Section (S-2) of the Supplementary material. Most of primary data cover the period between 2010 and 2012 and are considered fully reliable and representative. All input data refer to normal operation of the FeNi plant, excluding unexpected events that may cause operating problems. A more detailed description of all LCI phases considered in the present LCA study is also provided in Supplementary material (S-3).

4. Results and discussion

This section outlines the life cycle impact assessment results for the production of FeNi in Greece in terms of PED, GWP and AP based on calculations done with Gabi 6 software.

4.1. Comparative analysis of impact categories for the three different scenarios

The impact assessment results obtained for the different impact categories, considering the three scenarios analyzed, BL, GE and WU are summarized in Table S3 of Supplementary material (S-4). The results represent the absolute values obtained for each scenario and are expressed per functional unit (1 t of FeNi with 20% Ni).

Overall, the results show that for all three different impact categories, the lowest impact was assigned to the GE scenario while the highest to the BL scenario. More specifically, for PED, GWP and AP, the BL scenario provides the highest scores among all scenarios considered. Under the BL scenario, the production of 1 t of FeNi consumes 153.96 GJ and releases 12.60 t CO_2-eq and 0.082 t SO_2-eq, respectively. On the other hand, as anticipated, the alternative scenarios provide more benefits compared to the baseline practice, both in terms of energy conservation and reduction of GHG emissions. In particular, the lowest impacts derive from the GE scenario, wherein the production of 1 t FeNi consumes 127.61 GJ and releases 8.24 t CO_2-eq and 0.064 t SO_2-eq, respectively, thus confirming the benefits anticipated from the higher usage of renewable resources for the production of both electricity and thermal energy.

In the case of the WU scenario, the production of 1 t FeNi consumes 142.68 GJ and releases 10.97 t CO_2-eq and 0.077 t SO_2-eq, respectively. The obtained scores for the WU scenario are slightly lower compared to the BL scenario and are mainly related to the utilization of slag for the construction of asphalt pavements. It is obvious that both alternative scenarios reduce to a lesser degree the global warming and acidification potential when compared to the BL scenario.

Sections 4.1.1–4.1.3 identify and highlight in detail the environmental hotspots per energy indicator and impact category.

4.1.1. Primary energy demand

The PED in the three studied scenarios for each FeNi production stage is shown in Fig. 3. As can be seen from this figure, for all scenarios considered, the smelting and refining stages consume most of the primary energy, while ore mining/beneficiation and feed preparation account only for $15 \pm 1.0\%$ and $6.5 \pm 0.5\%$ of PED, respectively. The contribution of smelting and refining is $52.5 \pm 2.0\%$ and $26 \pm 1.5\%$, respectively of the total energy consumption in all scenarios considered.

Smelting has the highest fossil and electricity requirements in the life cycle of FeNi production, since pre-reduction of the nickel–iron oxides and smelting for the separation of metal and slag phases require high temperatures. Furthermore, since laterite ores do not contain any calorific value or sulphur to promote exothermic reactions (Eckelman, 2010), large quantities of fossil fuels (lignite,

Table 2
Main inventory data of the stages investigated in this study.

Stage	Input	Unit	Value	SD_{g95}	Origin/data quality
Mining and beneficiation	Electricity	kWh/t ore	9.8	1.40	LARCO, Ecoinvent v. 3.1, 2014/(3,5,2,3,3,5)
	Diesel	kg/t ore	0.9	1.31	LARCO, Professional database, 2014/(3,4,2,5,3,4)
Feed preparation	Electricity	kWh/t ore	2.1	1.31	LARCO, Ecoinvent v. 3.1, 2014/(3,4,2,5,3,4)
	Diesel	kg/t ore	1.2	1.31	LARCO, Professional database, 2014/(3,4,2,5,3,4)
Smelting and refining	Lignite	t/t FeNi	3.47	1.27	LARCO/(2,4,1,3,3,4)
	Coal	t/t FeNi	1.05	1.33	LARCO/(2,2,4,5,3,2)
	Pet coke	t/t FeNi	0.21	1.33	LARCO, Ecoinvent v. 3.1, 2014/(2,2,4,5,3,2)
	Crude oil	t/t FeNi	0.31	1.45	Professional database, 2014/(4,5,2,3,3,5)
	Carbon electrodes	kg/t FeNi	52	1.27	LARCO, Ecoinvent v. 3.1, 2014/(2,4,1,3,3,4)
	Lime	kg/t FeNi	74	1.45	Ecoinvent v. 3.1, 2014/(4,5,2,3,3,5)
	Oxygen	kg/t FeNi	210	1.45	Ecoinvent v. 3.1, 2014/(4,5,2,3,3,5)
	Electricity	kWh/t FeNi	10,286	1.31	LARCO, Ecoinvent v. 3.1, 2014/(3,4,2,5,3,4)
		kWh/t ore	444		
	Cement	t/t FeNi	0.22	1.33	LARCO/(2,2,4,5,3,2)

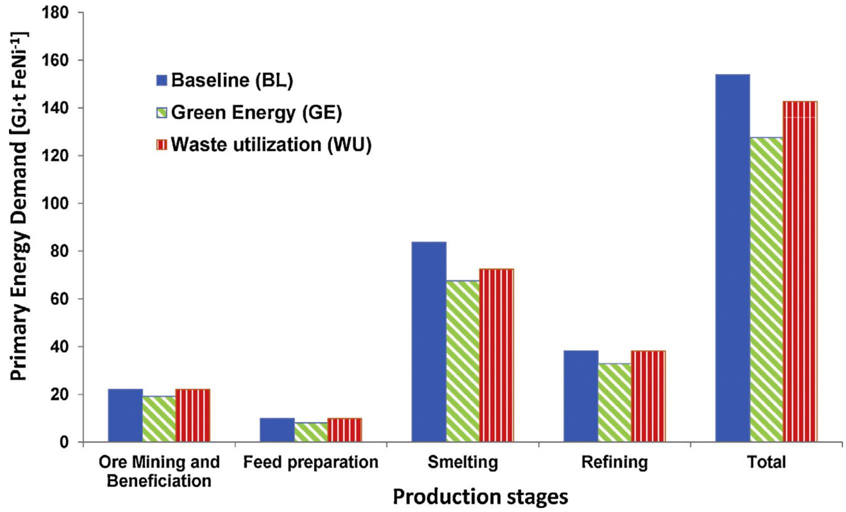

Fig. 3. PED (GJ/t FeNi) in the three studied scenarios for each FeNi production stage.

coal, coke and crude oil) are required during the calcination and smelting phases.

Refining has a significant contribution (~23.5%) to the energy requirements, both under current and alternative scenarios. This is related to its high electrical power requirements, accounting up to 19% of the total input. The electricity consumption for smelting and refining for the BL scenario was estimated at 444 kWh/t ore. This value is comparable to energy requirements of 449 and 470 kWh/t ore estimated by Haque and Norgate (2013) and Norgate et al. (2004) for the treatment of laterite ores from Tasmania (Australia) containing 1.3 and 2.4% Ni, respectively. Ore mining and beneficiation account for 14.4–15.6% of energy use since they require large amounts of electrical energy for processes involving operation of heavy-duty equipment such as those involved in crushing and grinding. The contribution of feed preparation stage was the lowest for all the scenarios considered (share 5–5.5%), mainly due to the transportation of the raw materials by heavy-duty trucks or ships and the associated fossil fuel consumption.

In GE and WU scenarios energy demand was 17.1% and 7.3% lower compared to the current practice. Given this significant savings regarding the total process energy, PED is also presented per energy type for the three different scenarios considered, namely non-renewable fossil fuels (lignite, coal, natural gas and petroleum), renewable fuels (biochar), renewable energy (wind power, hydropower and biomass) and other renewable energy sources (biogas and solar) (Fig. 4).

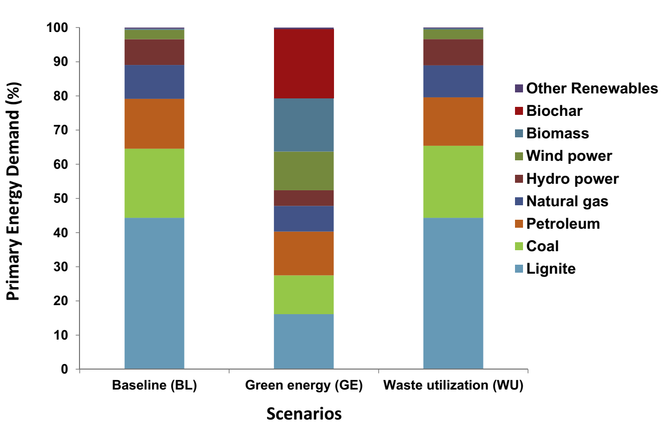

Fig. 4. Contribution (%) of each energy type to PED in the three studied scenarios to FeNi production.

As can be seen in Fig. 4, lignite and coal have by far the largest contributions (44.32% and 20.21%, respectively) in FeNi production under the BL scenario. Both fossil fuels are used for heating and reduction in the smelting stage, while lignite is the main source of the electricity power grid mix in Greece. According to Ecoinvent database, power generation in Greece is dominated by lignite (56.6%), with important contributions of natural gas (18.3%) and hydropower (13.9%) while hard coal contribution is negligible (0.80%). Previous studies have shown that the operation of most Ni smelting plants is dominated by the use of coal (Norgate and Jahanshahi, 2011), while considerable efforts have been made recently towards the use of renewable energy such as hydropower (Eckelman, 2010).

As expected, in the GE scenario the highest contribution derived from biomass and biochar (nearly 36% of the total input), followed by lignite (16%), petroleum (13%), coal (11%) and wind-turbine power (11%). It should be noted that significant reduction in PED is also due to improvement of power station efficiency in the GE compared to the BL scenario (35%). Typical values of electricity generation efficiency adopted in the present study for the GE scenario were 54.2% and 40% for wind-turbine and biomass-based power plants, respectively (Ecoinvent, 2014; Joshi et al., 2010).

4.1.2. *Global warming potential (GWP)*

The contribution of each process stage during the FeNi production to the GWP is shown in Fig. 5 for all studied scenarios.

It is shown that the smelting stage is by far the largest contributor to GWP (56.18% of the total) in the BL scenario, with electricity consumption in this stage to contribute 71% to the total energy requirements. This predominant contribution results from the direct CO_2 emissions from the carbon electrodes and paste consumption in the EAF.

Smelting is followed by the refining stage which contributes 22.90% to total GWP emissions in the BL scenario, mainly due to CO_2 emissions from the generation of electricity using the non-renewable source of lignite in the Greek power grid mix. Mining and beneficiation of the laterite ore is also a considerable lifetime contributor (~15% of the total) to the overall carbon-based emissions, mainly due to the electricity demand for the operation of the heavy-duty beneficiation units.

The contribution of the feed preparation stage is quite small (6% of the total) in the BL scenario compared to the other three stages, thus causing the lowest environmental impacts in terms of GWP during the production of FeNi. The use of equal mix of

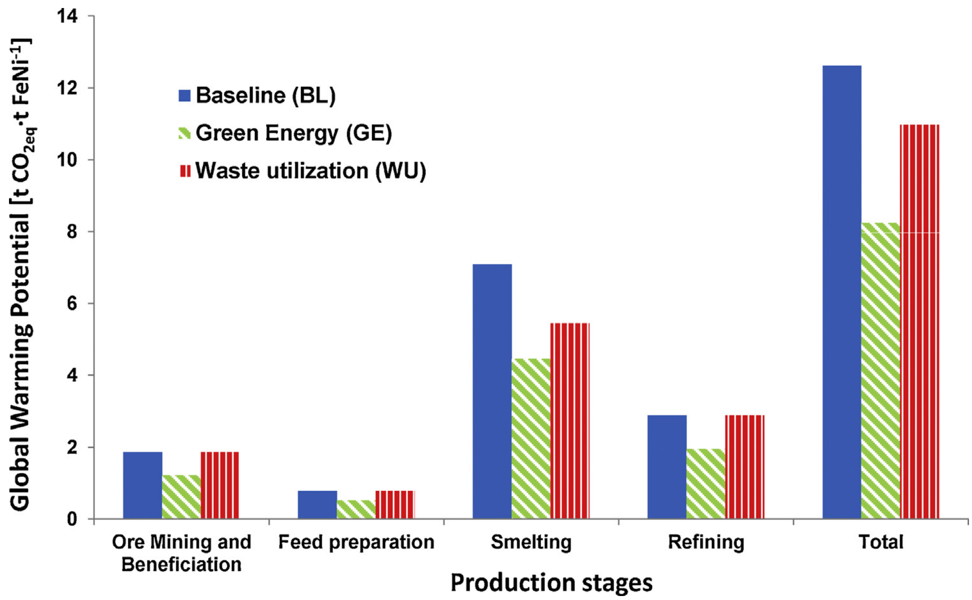

Fig. 5. Contribution of each process stage during FeNi production to GWP (t CO_2-eq/t FeNi) for the three studied scenarios.

Table 3
Key characteristics of power plant electricity generation and thermal energy from different sources as adopted in this study.

Power plant	Net calorific value (MJ/kg)[b]	Sulphur content (%)[c]	Greenhouse gas intensity (gCO_2-eq/kWh)[d]
Lignite[a]	5	0.7	1000–1700 (1025)
Wind-turbine	–	–	8–30 (22)
Biomass/biochar	0.49/18	0.2	35–99 (78)

[a] Values refer to Greek lignite; Reference values for coal (anthracite): 31 MJ/kg and 1.125% S.
[b] UNEP (2013).
[c] García et al. (2015); EURACOAL (2013).
[d] Weisser (2007) (values in parentheses were used in this study).

wind-turbine and biomass derived electricity reduced the GWP for all process stages, as both electricity sources have lower greenhouse gas intensities compared to lignite (Table 3).

In fact, the GE scenario, which involves electricity generation from renewable sources (equal mix of wind power and biomass) and substitution of 50% lignite/coal from biochar, results in savings of 4.38 t of CO_2-eq per year compared to the BL scenario. In the present study, 50% replacement of the fossil fuels (lignite and coal) used in the smelting stage with biochar resulted in a reduction of 18% of the total GWP emissions (no electricity substitution credits are taken into account), while about 50% reduction of the non-renewable CO_2 energy has been achieved in a previous study with full replacement of coal-based feed (Norgate and Jahanshahi, 2011). Even though the production of biochar requires big volumes of agricultural wastes and its net calorific value (18 MJ/kg) is 42% lower than the one of hard coal/anthracite (31 MJ/kg), its use in metallurgical processes is considered advantageous since it replaces fossil fuels with low net calorific value (5 MJ/kg) such as Greek lignite (Sebastian et al., 2011).

4.1.3. Acidification potential (AP)

The acidification potential impact category is mainly associated with the emission of sulphur oxides (SO_x) and nitrogen oxides (NO_x) during the production of electrical energy, which is used for equipment and machinery operation during their entire life cycle. Other sources of AP that introduce or release hydrogen ions into the environment (air, water, soil) include heat production and transportation. The AP for each stage of FeNi production and each studied scenario is depicted in Fig. 6.

Based on the LCA results, it was estimated that the acidification potential of FeNi production under the BL scenario was 0.082 t SO_2-eq per tonne of FeNi. This value shows that the main share of AP derives from smelting (~49%) and is followed by refining (~26%). The main contributors to acidification in the smelting stage are the fugitive emissions exiting the gas treatment units and emissions from the use of crude oil. The sulphur-based burdens in the refining stage are mainly associated with electricity demand (80%) and to a lesser extent with SO_2 releases from the OBM converters (~5%). Ore mining and beneficiation contributes about 22% to acidification, mainly due to the emissions from the unit processes of ore crushing and grinding as well as from the consumption of fossil fuels for on-site transport operations. Feed preparation does not have a substantial impact on cumulative results, with its maximum AP value reaching 4% of the total.

Fig. 6 shows that 0.018 and 0.004 tonnes of SO_2-eq per t FeNi produced can be saved during FeNi production if scenarios GE and WU are considered, respectively, compared to the BL scenario. Lignite and coal have the highest content of sulphur (0.7 and 1.125%, respectively), and this explains why the highest AP values derive from the BL scenario. On the other hand, biomass has low sulphur content (0.2%) and thus is characterized by lower acidification potential. Overall, due to the high influence of the non-renewable electrical energy and thermal mix on this impact category, investigations pertinent to the production of energy from renewable sources in terms of purchase price, production cost, availability as well as type of technology used for the conversion of biomass (including potential drying) into biochar have to been taken into account.

4.2. Comparison with other LCA studies

In literature, only few LCA studies regarding the production of FeNi from laterite ores via pyrometallurgical processing are available, as shown in Table 4. A brief description of the main findings in previous studies is also provided in Table S4 of the Supplementary material (S-5). As mentioned earlier, comparison of LCAs for metal/alloy production such as FeNi is difficult due to the need of elucidation of several influencing factors including lack of

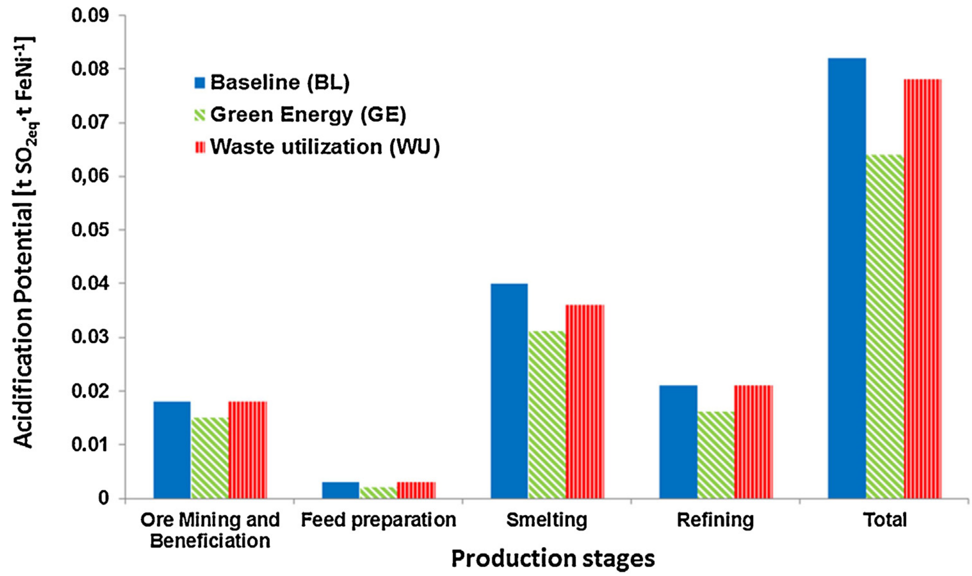

Fig. 6. Contribution of each process stage during FeNi production to AP (t SO_2-eq/t FeNi) for the three studied scenarios.

in-depth information provided in previous studies, differences in LCA methodology including assumptions, system boundaries and calculation methods used for the quantification of GHG emissions and other operational constraints (type of ore, final product Ni content, processing route and co-product handling).

However, comparisons of results show good agreement with previous studies and verify the validity of the inventory data considered in the present study. The primary energy demand of about 154 GJ/t FeNi for the BL scenario is comparable with 140 and 147 GJ/t FeNi reported by Eckelman (2010) and the Nickel Institute (2012), respectively. However, it is significantly higher compared to 102 and 110 GJ/t FeNi reported by Mudd (2010) and Norgate et al. (2004) for the Cerro Matoso nickel project and a hypothetical FeNi product (23% Ni), respectively, even though the refining stage was not included at both those system boundaries. Some of the differences with other studies can be explained by considering the way energy consumption was calculated, as in the study of Haque and Norgate (2013) or if results refer to global scale (Nickel Institute, 2012), and hence average plant data were taken into consideration.

Benchmarking of the results obtained from the BL scenario of the current study against previous ones in terms of GHG emissions, indicate that they fall in the upper range (7.7–13.9 t CO_2-eq/t FeNi) and (0.004–0.090 t SO_2-eq/t FeNi) of the reported values for GWP and AP, respectively. Nickel Institute (2012) reported the lowest GWP value and Haque and Norgate (2013) the highest in the above-mentioned range even though the latter GHG results were based mainly on the use of hydro-electricity. On the other hand, Mudd (2010) reported both the highest and lowest AP values available in literature for FeNi production from laterite ores. This is because the calculations were based on data taken from sustainability reports rather than from on site-specific analysis, therefore crucial factors such as composition of electricity grid power mix were not considered. Generally, the impacts reported in most studies show high variability even for the same type of laterite ore and Ni content of the final product. It is evident that various technological factors may also justify the observed discrepancies, aside from inherent differences in the methodological approach used (system boundaries, allocation and cut-off rules).

Nevertheless, the higher values for GWP and AP for the Greek FeNi plant in the BL scenario, compared to others, can be attributed to the fact that electricity, which is one of the biggest contributors of greenhouse gas emissions, is mainly produced from the combustion of the low reactive and GHG intensive lignite (56% of the total). This non-renewable resource is used in the Greek FeNi plant in several production stages including drying, calcining and smelting/refining. In fact, the production of the electricity consumed in all FeNi production stages contributes about 23% to GWP and 29% to AP of the total environmental impacts in all upstream flows. If the electricity grid mix was close to the average levels of European Member States (EU-27 production mix), then the electricity would contribute only 16% to GWP and 22% to AP. This shows that the Greek FeNi industry is highly dependent on the use of GHG-intensive energy compared to other European countries (Ciacci et al., 2014; Paramonova et al., 2015), but there is still room for improvement.

In fact, instead of only focusing on the conclusion that the fossil feedstock for electricity generation should turn into renewable as recent studies proposed (Eckelman, 2010; Mudd, 2010), the GE scenario considered in this study showed that considerable GHG reduction (18% of the total) can be realized by the 50%

Table 4
Quantification of impacts in other FeNi production LCA studies.

Laterite ore type (Ni %)	Product Ni content (%)	PED (GJ/t FeNi)	GWP (t CO_2-eq/t FeNi)	AP (t SO_2-eq/t FeNi)	Reference [pyro-processing route]
N.R	–	140	–	–	Eckelman (2010) [M–B–S–R]
N.R	29	147	9.3	0.049	Nickel Institute (2012) [M–B–S]
N.R	–	325[a]	13.9	–	Haque and Norgate (2013) [M–B–S–R]
(2.4%)	23	110	9.3	0.075	Norgate et al. (2004) [M–B–S]
Cerro Matoso project (~2.3%)	35	102	10.5	0.004	Mudd (2010) [M–B–S]
Doniambo project (2.0%)	25	-	7.7	0.090	Mudd (2010) [M–B–S]
LARCO S.A. project (1.10%)	20	154	12.6	0.082	This study – BL scenario [M–B–S–R]

[a] Embodied energy, N.R: not reported, M–B–S–R: mining, beneficiation, smelting, refining.

substitution of fossil carbon feedstocks (lignite and coal) with biochar in the smelting stage. By intensifying research efforts to improve efficiency of biomass-based energy and enhance the calorific content of renewable feedstock, biochar seems to have a noticeable potential for on-site savings in primary energy and reduction of GHG emissions.

In literature, energy savings and reduction of environmental impacts in the FeNi industry were mainly linked with the use of renewable energy. The incorporation of waste utilization in the processing route allows for the creation of a better environmental profile (nearly 13% and 6% less GWP and AP, respectively compared to the BL scenario). This option also allows for higher degrees of freedom in the selection of the option of waste management scenario used and the level of the economic profit gained.

Recently, significant research efforts have been focused on the assessment of technical, economic and environmental risks associated with the FeNi industry at global scale (Eckelman, 2010; Mudd, 2010; Nickel Institute, 2012) and how critical these may be for decision- and policy-makers at facility and national level, respectively. To this context, actions to improve sustainability of the FeNi industry should be promoted on the basis of current legislation and regulatory frameworks concerning energy use and waste utilization.

5. Conclusions

Ferronickel production is an extremely energy-intensive metallurgical operation that results in the generation of large volumes of greenhouse gas (GHG) emissions and solid wastes. The implementation of a detailed LCA study for the Greek FeNi industry enabled the identification of the so-called hotspots throughout the entire production chain, from mining to the final product.

In the present study, a BL scenario representing the current operation and two alternative ones (GE and WU scenarios) towards energy conservation, emissions reduction and sustainability improvement were investigated. It has been demonstrated that the environmental impacts associated with the production of FeNi from Greek laterite ores via pyrometallurgical processing are mainly due to the use of non-renewable and highly GHG-intensive fossil fuels (lignite and coal) for electricity and thermal energy generation.

The stages of smelting and refining were responsible for the largest share of energy consumption and the associated GHG emissions, followed by the stages of ore mining-beneficiation and feed preparation. According to the LCA results, the production of FeNi using the GE scenario exhibited the best overall environmental performance, with lower GHG contributions in all production stages compared to the baseline scenario. Considering, however, that the reserves of fossil fuels are limited and non-renewable and that large amounts of bio-waste are available from several rather unexploited resources so far (agricultural waste, wood, etc.), the green energy scenario offers considerable benefits at facility level. Significant environmental earnings were also achieved in the WU scenario for the entire FeNi production when optimum recycling rate of the main waste streams produced at the plant was considered.

Despite the effort to conduct an accurate LCA analysis of FeNi production in Greece, this study presents some limitations that should be taken into account in future studies in order to improve the robustness of the obtained results. Therefore, it would be desirable for the scenarios studied as well as the inventory used in this LCA study to (i) also include other sustainable aspects than environmental, namely economic and social, (ii) improve the efficiency of the rotary kiln, the electric furnace and the OBM converter and (iii) generate reliable data in terms of mineral resources depletion and eco-toxicity (aquatic, terrestrial and human). To this context, further research needs to be carried out to quantify additional environmental impacts, namely, eutrophication potential (EP) and abiotic depletion potential (ADP). The results obtained from this study will be benchmarked along with a cost benefit analysis (CBA) for an entire assessment of the process in terms of economic viability and eco-efficiency.

Finally, the results obtained from this study are of significant importance for the Ni sector, given the fact that the calculation of environmental burdens for FeNi production are likely to become more crucial in the future for the global Ni industry, due to the progressive shift from sulphide to laterite ore processing.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.resconrec.2015.10.016.

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