



Sustainable processing of Europe's low-grade sulphidic and lateritic nickel/cobalt ores and tailings into battery-grade metals (ENICON)

D5.2

Final report on environmental assessment (through LCA)



Public Deliverable

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1 Executive summary

This deliverable (D5.2) summarises the final Life cycle assessment (LCA) results produced in Task 5.1 for the main state-of-the-art (SOTA) process (high-pressure acid leach-HPAL) and the ENICON processes developed and upscaled within the associated technical WPs 2–4 of ENICON HE project. Task 5.1, entitled Environmental assessment (through LCA), addresses three main research activities: (i) the LCA of the ENICON novel HCl route and its advantages over the HPAL process for each input material, (ii) the carbon-neutral smelting of Ni/Co-sulphide concentrates, and (iii) the assessment of the most promising matrix-valorisation technology among mineral carbonation, alkali activation, and co-calcination investigated / developed in WP4. In this context, Task 5.1 aims to achieve the respective KPI of WP5 related to the best achievable eco-footprint reduction across the 15 environmental impact categories, with particular attention given to CO₂, energy, water, and land-use footprints in comparison to incumbent Ni/Co flowsheets, including HPAL.

Based on the standardized ISO 14040–14044 methodology and a harmonised LCA framework developed within Task 5.1 and aligned with the ENICON objectives, this report integrates several essential components, including contribution analysis, identification of environmental hotspots, comparative evaluations, scope-based emissions analysis, and sensitivity analysis per process. A detailed description of each process is provided following the ENICON LCA framework in terms of goal and scope, system boundaries, functional unit, inventory compilation, allocation and impact-assessment approach. On total 15 impact categories according to CML 2001, EF 3.0 and Recipe 2016 v1.1 using the well-established LCA for experts (LCA FE) software v.10.9 (Sphera) equipped with Professional/ Ecoinvent 3.9-3.12 databases are evaluated.

Firstly, a full cradle-to-gate LCA was carried out for the main prevailing reference production route at global scale, namely HPAL treatment of laterites in Indonesia followed by MHP refining into battery-grade nickel sulphate hexahydrate (NSH, NiSO₄·6H₂O, ≥ 22% Ni) in China. The assessment incorporates site-specific operational data, reagent production, transport distances, and mass allocation for Ni/Co battery grade production. The results show that the HPAL stage constitutes the main environmental hotspot, with approximately 35% of total GWP, followed by the purification stage (25%) and the Chinese refining stage (18%). The scope analysis confirms that Scope 3 emissions dominate the overall footprint because of the carbon intensity of key reagents, grid electricity mixes, and upstream supply-chain activities. Sensitivity analysis indicates that significant reductions are achievable only through cleaner electricity mixes or integrated NSH production, while variations in ore grade or reagent substitution exert minimal influence.

The ENICON next-generation HCl-based route provides substantial environmental advantages for both ferronickel (ENICON023) and limonitic laterite (ENICON017). For ferronickel, the novel HCl-leach route achieves a GWP of 9.2 kg CO₂-eq per kg Ni in NSH, equivalent to a 37% reduction compared with the sulphate-based FeNi leaching routes reported in the literature. Contribution analysis assigns 35% of total impacts to the refining stage, 31% to HCl leaching, 22% to purification, and 12% to re-leaching. Energy inputs represent ~55% of total GWP, while chemical inputs represent 45%. Scope analysis attributes 46% of emissions to indirect emissions Scope 2, 26% to direct emissions released on-site (Scope 1), and 28% to Scope 3 (upstream processes). For limonitic laterite, the route yields a GWP of 29.5 kg CO₂-eq per kg Ni, standing 11–36% lower than published reference values. The leaching and purification stages dominate the profile (31% and 28%), followed by re-leaching (15%) and refining (26%). Chemical inputs account for 63% of total GWP, dominated by hydrochloric acid and hydrated lime, while energy inputs account for 37%. Scope analysis shows that Scope 1 emissions account for 22% of total GWP, representing direct releases from on-site combustion and process reactions. Scope 2 accounts for 36%, reflecting the indirect impacts of purchased electricity used across key hydrometallurgical stages. Scope 3 represents 42%, driven mainly by the upstream production of hydrochloric acid, hydrated lime, extractants, and other reagents that impose a significant GHG burden on the ENICON017 route.



The carbon-neutral smelting route for Ni/Co-sulphide concentrates demonstrates a pronounced reduction in GHG emissions when hydrogen substitutes coke in the Flash Smelting Furnace – Electric furnace (FSF–EF) system. The LCA results indicate 146 kg CO₂-eq per tonne of cleaned slag. Contribution analysis assigns 72% of total GWP to the FSF, with fuel-oil consumption accounting for 73.5 kg CO₂-eq (50%) and oxygen supply adding 30 kg CO₂-eq (21%). The EF process represents 28% of total GWP, with 20 kg CO₂-eq (14%) associated with electricity use and 23–24 kg CO₂-eq (16%) arising from upstream hydrogen production at 20 vol% H₂ content. Scope analysis attributes 50% of total GWP to Scope 1, which reflects the direct emissions released on-site, primarily from fuel-oil combustion in the FSF. Scope 2 accounts for 34%, representing the indirect emissions associated with the electricity demanded by both the FSF and the EF. Scope 3 contributes the remaining 16%, driven by upstream processes such as hydrogen production, oxygen generation, and the manufacturing of ancillary materials and inputs that enter the smelting system.

The environmental performance of the alkali-activation (AA) route for ferronickel slag (ENICON021), which supports ENICON's near-zero-waste strategy, is assessed through LCA for two representative AA-based construction products: a 1 m³ mortar and a block with dimensions of 150 mm × 150 mm × 65 mm. The GWP for 1 m³ of AA mortar equals 286 kg CO₂-eq, while the AA block exhibits a GWP of approximately 0.41 kg CO₂-eq, based on the recent laboratory pilot-scale tests conducted by TUC (WP4). The mixing stage dominates with 191.6 kg CO₂-eq (67%), followed by drying (11%), milling (9%), curing (8%), and casting/demoulding (5%). In this process, scope analysis assigns 85% of total GWP to Scope 3, a result that reflects the dominant influence of upstream production of commercially available activators used, as sodium silicate and sodium hydroxide require substantial fossil-energy inputs during their production. Scope 2 accounts for 12% of total GWP, representing the indirect emissions associated with electricity use across the milling, mixing, drying and curing stages. Scope 1 contributes the remaining 3%, since on-site thermal and mechanical operations generate only minor direct emissions within the alkali-activation process. Despite the burdens associated with activator production, the overall footprint remains favourable, and compressive-strength values above 25 MPa confirm suitability for large-scale construction applications or for the production of binders that may (partially) replace cement in concrete production.

The research activities carried out within Task 5.1 and the obtained LCA results ultimately contribute to meeting the successful fulfilment of the respective KPI of WP5 by M48. This timeline coincides with the completion of Task 5.3, LCA-TEA benchmarking against SOTA and baseline approaches (M37–46), and the submission of D5.4 “Final Report on LCA-TEA Benchmarking against SOTA and Baseline Approaches”. The results presented in this deliverable establish a robust basis for the subsequent confirmation of the anticipated advantages associated with the ENICON Ni/Co processing routes relative to current battery-grade Ni/Co production practices. In this context, this deliverable provides a comprehensive benchmarking framework that enables comparison of all main ENICON-developed processes against both SOTA and baseline industrial routes. It therefore offers a market-relevant reference point for future standardisation, sustainability benchmarking, and broader industrial adoption of the developed technologies.



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3 List of abbreviations

AA	Alkali Activation
ADP	Abiotic Depletion Potential
AP	Acidification Potential
CCD	Counter Current Decantation
CED	Cumulative Energy Demand
CFC-11	Trichlorofluoromethane (ODP reference substance)
CML	Center of Environmental Science of Leiden University
CO ₂ -eq	Carbon Dioxide Equivalent
CRMs	Critical Raw Materials
CSH	Cobalt Sulphate Heptahydrate
Cu-eq	Copper-equivalent (metal depletion reference unit)
DCB	Dichlorobenzene (TETP reference substance)
EF	Electric Furnace
EoL	End of Life
FeNi	Ferronickel
FEP	Freshwater Ecotoxicity Potential
FSF	Flash Smelting Furnace
FU	Functional Unit
FWEP	Freshwater Eutrophication Potential
GHG	Greenhouse Gas
GWP	Global Warming Potential
HPAL	High Pressure Acid Leaching
ISO	International Organization for Standardization
KPI	Key Performance Indicator
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MHP	Mixed Hydroxide Precipitate
MJ	Megajoule
MSP	Mixed Sulphide Precipitate
NSH	Nickel Sulphate Hexahydrate
ODP	Ozone Depletion Potential
OPC	Ordinary Portland Cement
pCAM	Precursor Active Materials
PLS	Pregnant Leach Solution
POCP	Photochemical Ozone Creation Potential
ROM	Run of Mine
Sb-eq	Antimony-equivalent (abiotic depletion reference)
SCF	Slag Cleaning Furnace
SO ₂ -eq	Sulphur Dioxide Equivalent
SOTA	State-of-the-Art
SX	Solvent Extraction
TBP	Tri-n-Butyl Phosphate
TEA	Technoeconomic Assessment
TETP	Terrestrial Ecotoxicity Potential
TSF	Tailings Storage Facility
VOC	Volatile Organic Compounds



4 Introduction

The European Union (EU) has placed the transition to a climate-neutral society by 2050 as a prominent priority in its policy agenda, constituting a fundamental element of the European Green Deal (EC, 2019; Calignano and Trippel, 2020). The European Green Deal recognizes the vital role of resources such as minerals and metals in achieving climate neutrality. These resources are crucial for renewable energy systems, energy storage, electric mobility, and energy-efficient technologies. In this context, the Green Deal Industrial Plan has been very recently introduced by the European Commission to serve as a strategic framework properly designed to increase technological development, boost manufacturing production, and facilitate the widespread adoption of net-zero products and sustainable energy supply in the next decade (EC, 2023). As part of this plan, two important Acts i.e. Critical Raw Materials/CRMs Act and Net-Zero Industry Act are proposed in order to establish a solid foundation for industrial manufacturing of key technologies and products (such as batteries) essential to ensure sufficient access to CRMs as well as achieving the European Union's climate neutrality goals (COM/160, 2023; COM/161, 2023).

Among these CRMs, nickel (Ni) and cobalt (Co), particularly in the form of nickel-cobalt-manganese (NCM) materials, lithium nickel oxide (LNO), lithium cobalt oxide (LCO) and nickel-cobalt-aluminum (NCA) cathode materials, are the cornerstone for the production of high-performance lithium-ion batteries suitable for electric vehicles and renewable energy storage systems (Wang et al., 2020). The International Energy Agency (IEA) predicts that the number of electric vehicles worldwide will reach 145 million by 2030, potentially reducing carbon dioxide emissions by more than one billion metric tons per year and avoiding demand of 5 millions oil barrels per day (IEA, 2021a; 2023). This transition has already increased the demand for key-energy transition metals (ETMs) such as Ni and Co by 70% and 40% between 2017 and 2022, respectively (Gardes-Landolfini, 2023; Komnitsas et al., 2023). The paramount critical and strategic importance of Ni and Co stems from the unique properties of their battery grade end products i.e. nickel sulphate hexahydrate (NSH, $\text{NiSO}_4 \cdot 6\text{H}_2\text{O}$) with $\geq 22\%$ Ni content and cobalt sulphate heptahydrate ($\text{CoSO}_4 \cdot 7\text{H}_2\text{O}$) with $\geq 20.5\%$ Co content. Both high quality products are used for the production of precursor cathode active materials (pCAM) that enable the cathode manufacturing of Li-ion batteries with superior energy storage capabilities and long cycle life (Wang et al., 2020; Abdelbaky et al., 2023).

Battery-grade nickel sulphate is currently produced from high-purity Class I nickel ($> 99.8\%$ Ni) including briquettes, powders, cathodes and oxides as well as from nickel intermediates with lower Ni content (35-70 %) such as mixed hydroxide precipitate (MHP), mixed sulphide precipitate (MSP) and nickel matte (Schmidt et al., 2016; Winjobi et al., 2022). Class I nickel is mostly produced from sulphide ores, while laterite ores are typically used to produce Class II nickel products ($< 99.8\%$ Ni) such as metallic nickel in various product forms, nickel oxides, nickel pig iron and ferronickel that are not suitable to battery market. In 2022, 80% of global nickel mine production originated from laterite deposits, of which Indonesia produced more than 30%. MHP is increasingly emerging as the most preferred nickel intermediate product in battery-grade nickel sulphate production, particularly in Indonesia based on the treatment of limonitic laterites with high-pressure acid leaching (HPAL) technology (Szurlies and Vasters, 2024). Since 2021, four HPAL plants producing MHP especially for the Chinese battery supply market commenced operation in Indonesia, while more than 10 plants are under development or construction (Sangadji, et al., 2023; Heijlen and Duhayon, 2024). It is estimated that about 900 kt MHP will be produced from the Indonesian-based hydrometallurgical plants by 2027, highlighting Indonesia's significant contribution to the global battery grade nickel and cobalt supply chain in the coming years.

However, given the limited Ni/Co medium and high-grade ($> 1.5\%$ Ni) reserves worldwide, several issues are of paramount importance including the complex and resource-intensive extraction and refining processes that are necessary for their processing, geopolitical considerations, ethical/social concerns in several mining regions as well as the security and sustainability of battery grade nickel and cobalt supply (Han et al., 2023).



To ensure the responsible and sustainable production and utilization of battery grade Ni and Co towards a low-carbon and resource-efficient society, it is imperative to conduct comprehensive life cycle assessments (LCAs) to evaluate the environmental impacts associated with nickel and cobalt extraction, processing, and refining (Bartzas et al., 2021; Bai et al., 2022; Das et al., 2024). LCAs provide valuable insights into the entire life cycle of these ETMs, from raw material extraction to final product disposal, enabling informed decision-making and the identification of opportunities for environmental improvement. By quantifying greenhouse gas emissions, energy consumption, water usage, land use occupation/degradation and other environmental indicators, LCAs can enable the development of targeted strategies to minimize the environmental footprint of nickel and cobalt production. They can also explore more sustainable and near zero waste management scenarios in terms of materials, energy and resource-efficiency, decarbonization and waste valorization across the battery grade Ni/Co production industry.

Of particular interest is the approach investigated in the ENICON HE project aiming to produce battery grade Ni and Co from various raw materials and extend the downstream processing of intermediates and secondary sources (Sadeghi, et al., 2023; ENICON HE project, 2024). These include limonite and saprolite laterites, ferronickel, Ni/Co-sulphide concentrates, MHP/MSP from pyrite tailings and carbonated Ni-silicate tailings. For this purpose, a next-generation HCl-based route for Ni/Co recovery is used as an alternative to the conventional processing methods for sulphides (such as smelting) and laterites (such as HPAL). The primary anticipated benefits of this approach include the ease of hydrochloric acid (HCl) regeneration, the elimination of the need for limestone, the reduced input of chemical reagents and water use, and the prevention of gypsum and sodium sulphate (Na_2SO_4) waste generation (Dewulf et al., 2023). Based on these benefits, it is expected that this approach will offer i) a more sustainable and environmentally friendly production route for battery grade Ni and Co, alternative to traditional processing methods and ii) innovate the existing European Ni/Co supply chains.

4.1 Goal of this LCA study and link of this deliverable to ENICON Objectives

The main objective of this research work, i.e. Objective 8 as mentioned in the Grant Agreement (GA), is to perform a metallurgically-sound eco-assessment (through LCA) of the new HCl-based processing route and the modified (EU-based) existing metallurgical processes, and to benchmark these against the existing state-of-the-art (SOTA) processes. Temporally-explicit LCA-TEA is combined with the forensic geometallurgy protocol (WP1), allowing integrated decision-making maximising process & environmental performance, during the process of flowsheet development (rather than *a posteriori*, i.e., when it is already too late).

The LCA work in this deliverable under Task 5.1 is divided into three research activities. It includes the LCA of i) the ENICON novel HCl route, intended to justify its expected advantages over the HPAL process, ii) the carbon-neutral smelting of Ni/Co-sulphide concentrates, and iii) the most promising matrix valorisation technology for each input material, namely mineral carbonation, alkali activation, or co-calcination, developed in close collaboration with the slag and residue producers.

Based on the D2.4 (Dewulf et al., 2024), the three input streams selected (Milestone 11) for conducting the mini-pilot tests under ENICON project were ferronickel (ENICON023 from pyro-processing at Larco, Greece), limonitic laterite (ENICON017 from Evia in Greece, Larco), and saprolitic laterite (ENICON028 from Turkey, Euronickel). These input streams were identified as the most promising due to their high nickel and cobalt recoveries under mild leaching conditions, efficient Fe(III) and HCl removal, and broad availability in Europe. The ferronickel stream showed excellent leaching efficiency and straightforward impurity management, enabling easy purification of Ni/Co-rich solutions. Both limonitic and saprolitic laterites demonstrated strong potential for circular hydrometallurgical processing, allowing simultaneous recovery of HCl and FeCl_3 , enhancing process sustainability. These three streams collectively represent the best balance between



technical feasibility, scalability, and circularity, supporting ENICON's goal of producing battery-grade nickel and cobalt through a sustainable HCl-based hydrometallurgical route and therefore were selected in order to perform a metallurgically-sound eco-assessment (through LCA) according to Task 5.1.

Based on the **Internal Deliverable 5.1** (Karmali et al., 2025), alkali activation (AA) was identified as the most promising matrix valorisation technology (Milestone 12) for further investigation in terms of LCA within WP5. Among the three evaluated matrix valorisation technologies i.e. mineral carbonation, alkali activation, and co-calcination, AA was selected because the results obtained from the experimental work conducted under WP4 were particularly promising in terms of structural integrity, mechanical and thermal performance as well as toxicity levels reduction and metal(loid)s stabilization effectiveness. Additional upscaled tests were scheduled at TUC in June 2025 to further support the LCA activities under Task 5.1. Although all three waste valorization technologies achieved successful results, alkali activation was ultimately chosen due to its technical maturity, demonstrated performance, and scalability potential.

According to the GA, a KPI related to WP5 objective in terms of LCA is to achieve the best possible eco-footprint reduction in most of the ~15 categories, with particular attention for the CO₂/energy/water/land use footprint, compared to the incumbent Ni/Co flowsheets (incl. HPAL). The research activities carried out within Task 5.1 will ultimately contribute to meeting this objective by Month 48 (M48), when the D5.4 "Final Report on LCA-TEA Benchmarking against SOTA and Baseline Approaches" will be submitted. This evaluation will serve as a benchmarking tool to compare all main developed processes against state-of-the-art (SOTA) and baseline routes, providing a market-relevant reference framework for future standardization and benchmarking of the developed technologies. In this context, D5.2 summarizes the final LCA results obtained within Task 5.1 for the main SOTA process (HPAL) and the ENICON processes developed and upscaled so far, in accordance with the GA. Since this deliverable is public, and for confidentiality reasons, more detailed data, scenario analyses, process-specific information along with benchmarking against SOTA and other baseline approaches will be provided in the forthcoming D5.4 (M48).



5 Methodology

5.1 Life cycle assessment (LCA)

5.1.1 Standardized approach

Life Cycle Assessment (LCA) is defined as a method for compiling and evaluating all inputs, outputs and the potential environmental impacts of a production system throughout its life cycle. It enables the user to measure and quantify the environmental impacts of a product (Bartzas et al., 2021). Furthermore, it helps to identify hot spots where the most significant impacts occur, providing the user the opportunity to develop strategies for improving the product's environmental footprint. The use of LCA in environmental management and sustainability has gained considerable attention by researchers and related practitioners in recent years as seen from the steadily increasing number of published research studies.

In respect to metal production industry, LCA is a tool that enables comprehensive evaluation of the environmental impacts associated with all processes, from raw material extraction to end-of-life (EoL) disposal or recycling. LCA allows stakeholders in the metal industry to identify hotspots of environmental burden, such as energy consumption, emissions of greenhouse gases and pollutants, water consumption, land use occupation and resource depletion (Bartzas and Komnitsas, 2015). Through the quantification of these impacts, LCA helps in taking decisions to optimize processes, reduce environmental footprints, and promote sustainable practices throughout the life cycle of metal products. Additionally, LCA can support eco-design initiatives, product labeling, and environmental performance benchmarking, advancing transparency and accountability within the battery grade metal production industry.

The main components for standardized LCA, as outlined in the ISO 14040-14044 series of standards (ISO, 2006a,b), typically include the following four steps: i) Goal and Scope Definition, ii) Inventory analysis, iii) Impact Assessment and iv) Interpretation (Figure 1).

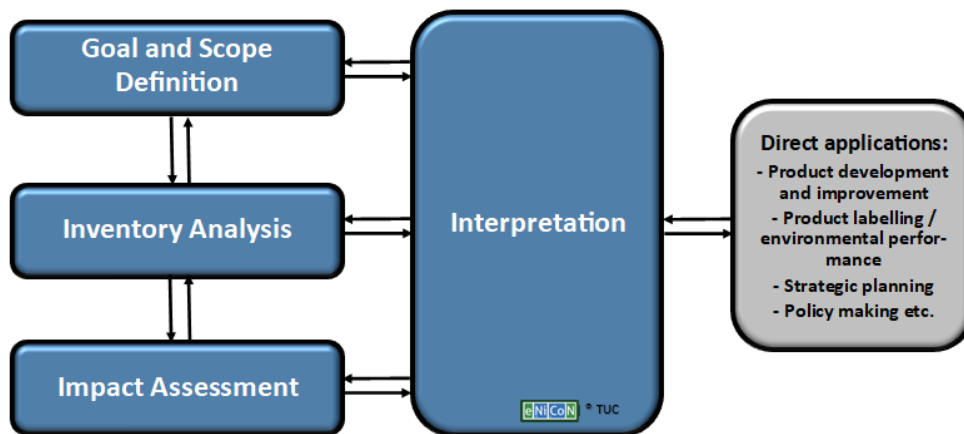


Figure 1. Standardized LCA framework according to ISO 14040-14044 series of standards

5.1.2 ENICON LCA framework

In the context of ENICON project, a detailed LCA framework has been fully defined in accordance with the 14040-14044 standard series, GHG protocol scopes (WRI, WBCSD 2004; WRI, 2011), and project's objectives to enhance the credibility, transparency and comparability of the environmental-based assessment (Figure 2). The framework has been developed with precision, involving each of the four stages of the LCA process. Within this framework, contribution analysis, identification of hot spots, comparative and sensitivity analysis,



and reporting are systematically integrated to ensure a thorough and rigorous assessment of the environmental impacts associated with the metal product under study.

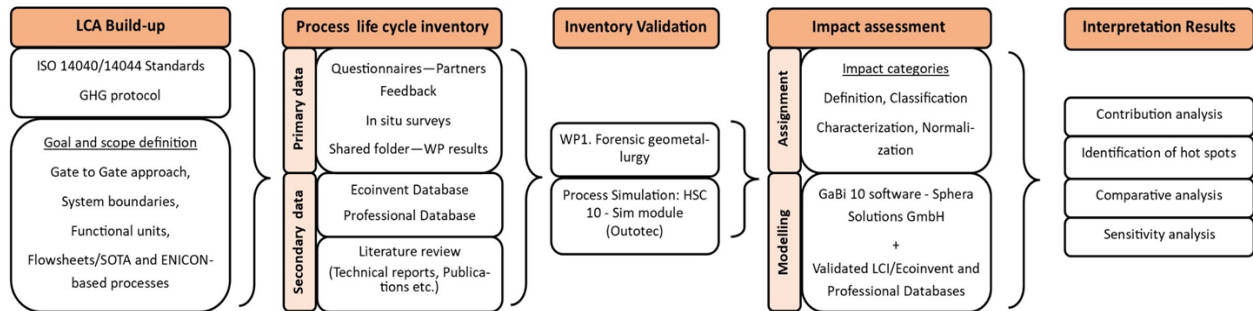


Figure 2. Detailed LCA framework in the context of ENICON project

Prior to the LCA work conducted during the Task 5.1., a comprehensive literature review focusing on recent advancements in the production of nickel (Ni) and cobalt (Co), based on various well-established sources such as Scopus, Google Scholar, Web of Science (WoS), and technical reports, has been conducted. In this context, a holistic overview of the environmental impacts generated from existing Ni/Co production at several projects worldwide has been carried out. The latest developments and critical challenges in Ni/Co production in terms of environmental performance were identified and critically analyzed. In this context, an Excel-based Life Cycle Inventory (LCI) database that includes both existing projects and studies has been created. The primary focus was to conduct a detailed inventory analysis, which is a critical step in order to fully understand and then quantify the environmental performance of the SOTA and ENICON processes, to compile comprehensive data sets.

5.1.2.1 Goal and scope definition

The goal and scope definition is the foundational phase of LCA in metal production, as mandated by ISO 14040 and 14044 standards. This phase establishes the study's objectives, methodological boundaries, and key parameters, ensuring clarity, transparency, and comparability throughout the LCA process. The goal must specify the intended application, reasons for conducting the study, target audience, and whether results will be used for public comparative assertions. Goal and scope definition is critical in metal production LCA as it determines appropriate allocation procedures and modeling approaches (Zevenhoven, 2020). Allocation is the predominant approach to address multifunctionality in metal production LCA, although ISO 14044 identifies it as a last choice (Lai et al., 2021). In most cases, however, allocation is applied as the primary option for solving multifunctionality in metal co-production LCAs. The choice of allocation method significantly influences the estimated impacts of co-produced metals (Santero and Hendry, 2016). Economic allocation is often regarded as more appropriate and consistent than mass allocation in the context of metal production, but its applicability depends on the stability of market prices and the relative economic value of the co-products under consideration. Other key methodological decisions defined under the goal and scope definition include (Bongono et al., 2020; Curran, 2017; Santero and Hendry, 2016): i) system boundary determination, ii) functional unit (FU) definition, iii) data quality and representativeness criteria, and iv) impact assessment method selection.

System boundaries specify which processes are included in the assessment, ranging from cradle-to-grave (entire life cycle) to more limited scopes like cradle-to-gate or gate-to-gate. The choice affects which environmental impacts are captured and can introduce significant variability between studies. Broader



boundaries provide a more comprehensive view but increase complexity and uncertainty, while narrower boundaries may omit important impacts

The FU is a quantified reference that supports the comparison of different systems. Its definition must accurately reflect the function of the product or service under study and remain consistent with the goal and scope of the analysis. An inconsistent or poorly defined FU can hinder comparability and introduce bias into the results. Functional units may be expressed in terms of mass, volume, area, or performance, depending on the product system. Their selection should also take into account system multifunctionality and the relevant market context to ensure meaningful and transparent assessment outcomes.

High-quality, transparent, and representative data are essential for reliable LCA results. Many studies rely on secondary or outdated datasets, with limited assessment of data quality and representativeness. The use of objective data quality criteria and sensitivity analyses is recommended to ensure robustness and transparency. These methods help identify uncertainties, evaluate the influence of key parameters, and maintain consistency and credibility within the LCA framework.

The selection of the most appropriate impact assessment methods and categories (e.g., Global warming, Eutrophication) is essential for the obtained LCA results. The choice should be justified based on the study's objectives and context, and should be consistent with international standards (ISO 14040/44).

5.1.2.2 Inventory analysis

The inventory analysis includes the collection and validation of both primary and secondary data for all relevant process stages. It involves the compilation of input and output flows, such as materials, energy, emissions, and waste, normalized to the defined functional unit. The primary data used in this report were obtained from several sources. These include (i) laboratory and pilot-scale data generated within the experimental Work Packages (WPs 1–4) of the ENICON project, collected on a regular basis, and (ii) technical and production data compiled annually. Secondary data were derived from literature sources, including relevant studies, reports, and scientific publications. Additionally, model validation was performed using SuperPro Designer (Intelligen inc.) through energy and mass balance calculations developed specifically for this LCA study to ensure the accuracy and internal consistency of the dataset across the defined system boundaries. The background data were obtained from established databases available within the LCA FE software, such as Ecoinvent v3.11 and its Professional versions, which are widely applied in LCA studies in the metal industry. These databases provide comprehensive and reliable environmental inventory data for various industrial processes and materials. The integration of background data from such established life LCI databases ensured completeness, coherence, and consistency throughout the LCA model.

5.1.2.3 Impact Assessment

The LCA study has been carried out for the SOTA and ENICON processes using the well-established LCA for experts (LCA FE) software v.10.9 (Sphera) equipped with Professional/ Ecoinvent 3.9-3.11 databases (Sphera, 2023a). LCA FE formerly known as GaBi, is a leading software platform for environmental impact analysis, widely used in industry, research and policy, including by many Fortune 500 companies (Baitz et al., 2023). It offers one of the most comprehensive and continuously updated life cycle inventory (LCI) databases, containing over 20,000 high-quality datasets, and fully supports compliance with ISO 14040/44 standards. Designed for reliability, data transparency, and integration into several processes, LCA FE provides a user-friendly environment for modelling complex industrial systems and assessing the environmental performance of products and technologies across their life cycles. In the metals production sector, LCA FE is especially valuable for modelling complex mining and metallurgical systems and offers industry alignment,



and flexibility for detailed process analysis (Segura-Salazar et al., 2019). Its widespread adoption in metal industry and ability to handle detailed, multi-stage processes make it a top choice for metallurgical LCA applications especially those involving critical metals and batteries. With the collected LCI data, the life cycles of the SOTA and ENICON processes are modeled and analyzed using LCA FE. A representative example of the main SOTA process is illustrated in **Figure 3**.

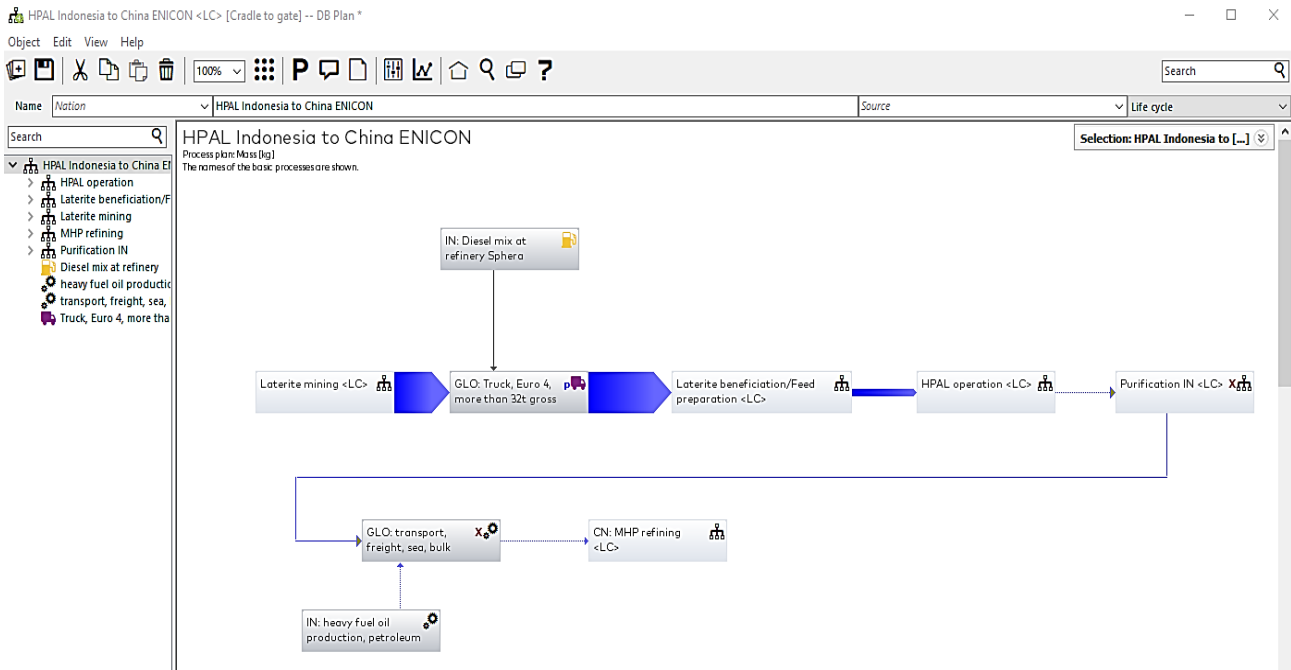


Figure 3. Life cycle model of the SOTA process in LCA For Experts software

On total 15 impact categories according to the guidelines and specific requirements of the International Organization for Standardization (ISO) 14040-14044 standard series and the GHG protocol scopes are evaluated (**Table 1**). More specifically, impact categories have been defined according to CML 2001 (Center of Environmental Science of Leiden University), Environmental Footprint (EF 3.0) and Recipe 2016 v1.1 as recommended by the metal industry at European or global scale (Farjana et al., 2018; Mistry et al., 2016; Strezov et al., 2021). GHG Protocol classifies GHGs into three scopes (WRI, WBCSD 2004; WRI, 2011; Sphera, 2023b): i) Scope 1 includes the direct GHG emissions from sources that are owned by the company, for example, emissions from combustions in boilers and furnaces, ii) Scope 2 includes the indirect GHG emissions from the generation of purchased electricity, steam, heating and cooling consumed by the reporting company, and iii) Scope 3 covers all other indirect emissions from a company's value chain. Scope 1–3 emissions were considered in all cases studied. The current LCA study excludes capital goods such as infrastructure and equipment, in accordance with the requirements of ISO 14040 and ISO 14044 for comparative life-cycle studies, as these elements are not expected to cause significant differences between the alternatives (Tokede and Rouwette, 2024).



Table 1. Impact categories assessed in this LCA study per LCIA methodology selected

Impact Category	LCIA methodology
Acidification potential (AP) [kg SO ₂ -eq·FU ⁻¹]	CML 2001- Aug.2016
Eutrophication potential (EP) [kg PO ₄ -eq·FU ⁻¹]	CML 2001- Aug.2016
Global warming potential (GWP) (100 years) [kg CO ₂ -eq·FU ⁻¹]	CML 2001- Aug.2016
Ozone layer depletion potential (ODP) [kg CFC-11-eq·FU ⁻¹]	CML 2001- Aug.2016
Photochemical ozone creation potential (POCP) [kg C ₂ H ₄ -eq·FU ⁻¹]	CML 2001- Aug.2016
Terrestrial ecotoxicity potential (TETP) [kg DCB-eq·FU ⁻¹]	CML 2001- Aug.2016
Climate change land use and land use change [kg CO ₂ -eq·FU ⁻¹]	Environmental Footprint (EF 3.0)
Climate change, fossil [kg CO ₂ -eq·FU ⁻¹]	Environmental Footprint (EF 3.0)
Abiotic depletion, elements (ADP) [kg Sb-eq·FU ⁻¹]	CML 2001- Aug.2016
Metal depletion (MD) [kg Cu-eq·FU ⁻¹]	Recipe 2016 v1.1
Fossil depletion (FD) [kg oil-eq·FU ⁻¹]	Recipe 2016 v1.1
Fine particulate matter formation (FPMF) [kg PM _{2.5} -eq·FU ⁻¹]	Recipe 2016 v1.1
Freshwater consumption (FWC) [m ³ ·FU ⁻¹]	Recipe 2016 v1.1
Land use (LU) [annual crop eq·FU ⁻¹]	Recipe 2016 v1.1
Cumulative energy demand (CED) [MJ·FU ⁻¹]	-

More detailed information on the ENICON-developed processes and technologies, as well as the LCA framework applied to each process examined in this report, in accordance with the principles and requirements of the ISO 14040 and ISO 14044 standards, is provided in the following section.



6 Description of SOTA and ENICON processes

6.1 Reference / SOTA case study – High Pressure Acid Leach (HPAL)

Goal and scope: Based on the aforementioned framework, an LCA study of SOTA High Pressure Acid Leach (HPAL) for Ni-Co laterite processing has been carried out in order to justify the (anticipated) advantages of the ENICON novel HCl route (Bartzas and Komnitsas, 2024). In this context, energy consumption and greenhouse gas footprint of a typical hydrometallurgical route in Indonesia for the production of Mixed Hydroxide Precipitate (MHP) and further refining in China for the production of battery grade Nickel Sulphate Hexahydrate (NSH) have been assessed. MHP is increasingly emerging as the most preferred nickel intermediate product i) in Indonesia, where currently half of the global nickel supply is accounted for and ii) in China, due to its potential for further refining into high-purity nickel sulphate. China is currently a major player in the Ni battery grade production covering 55% of the world's nickel sulphate market (Sangadji, et al., 2019; IEA, 2021a; Szurlies, M. 2021, 2022; Saegert, et al., 2023, Global Battery Alliance, 2023). Therefore, the production route covered in this case study reflects the main pathway of global nickel supply for batteries dominated by Indonesia and China, at least in the next decade.

Description of process: The run-of-mine (ROM) nickel-bearing ore undergoes beneficiation as the initial step, resulting in the production of limonite nickel ore slurry, which is then fed into the HPAL process (Figure 4). The ore is pulverized and transformed into a slurry with 38% pulp density, after which the nickel and cobalt are leached using high pressure leaching with sulfuric acid (270 kg/t) in two parallel titanium autoclave units (HPAL). Each autoclave operates at $T=260^{\circ}\text{C}$ and $P=4300\text{ kPa}$ and is equipped with seven compartments for maintaining a total residence time of 60 minutes. In the downstream process steps, hydroxide precipitates containing Ni and Co are re-dissolved during Primary Neutralization using limestone, while impurities such as iron and aluminum are precipitated.

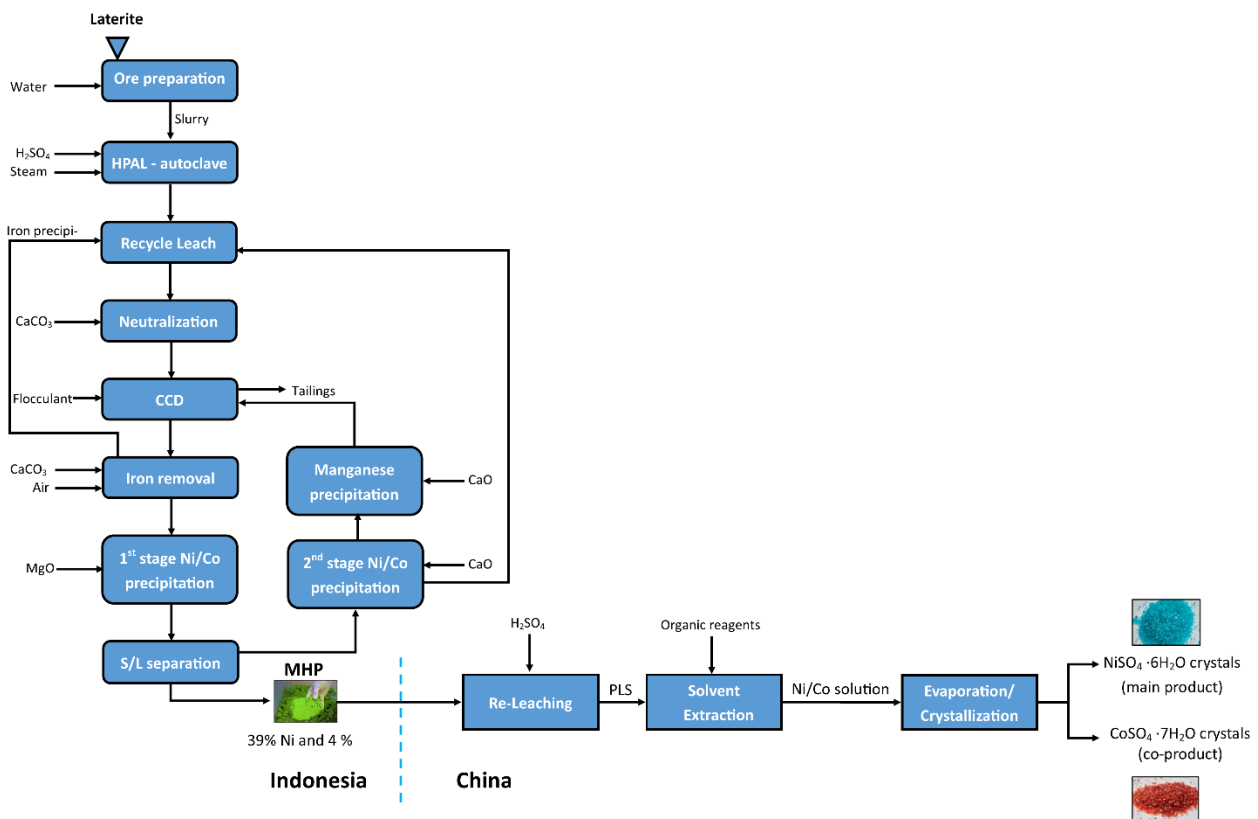


Figure 4. Detailed production stages of the Reference/SOTA case under study



In a six-stage counter current decantation (CCD), circuit continuous separation of solids and liquids is carried out and thus the pregnant solution is recovered. To comply with environmental regulations, the pH of the tailings is adjusted with slaked lime in the final neutralization step prior to disposal in a tailings storage facility (TSF). MHP precipitates with magnesia and quicklime in two stages and is shipped in bulker bags to China with 39% Ni and 4% Co content. Subsequent refining to NSH (in China) involves MHP re-leaching using fresh sulphuric acid on site, two stages of solvent extraction (SX) and two stages of stripping for Fe, Mg, Mn impurity removal and separation of Ni and Co, respectively and separate crystallization for Ni and Co at the last stage.

System boundaries: Based on the “cradle to gate” approach i.e. from ore mining to beneficiation, primary extraction, and refining processes, the LCA study has considered also, apart from Scope 1 and Scope 2, Scope 3 emissions as well as impacts deriving from tailings disposal on land, deforestation and land-use changes commonly occurred in tropical areas (Figure 5).

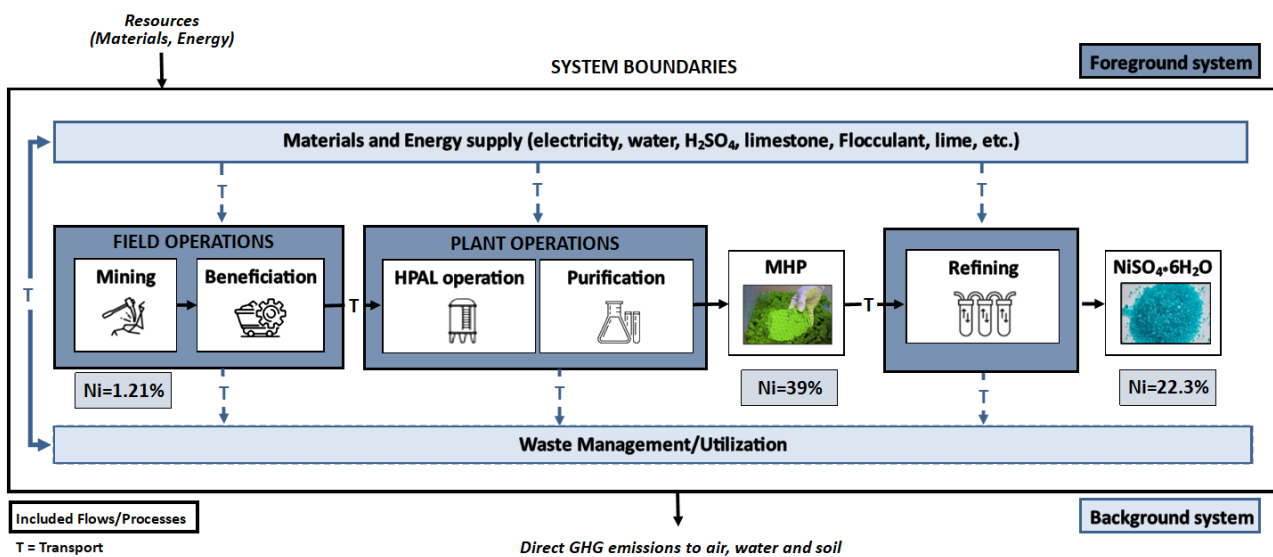


Figure 5. System boundaries adopted for the Reference/SOTA case under study

Functional unit: The functional unit of 1 kg of nickel in Nickel Sulphate Hexahydrate - NSH (NiSO₄·6H₂O) (22.3 wt% Ni content) at the plant gate (China), which enables the system inputs and outputs to be quantified and normalised, is used. The LCA study included impacts associated with the major processing and transportation stages of NSH production (i.e. mining, beneficiation/feed preparation, domestic transportation, HPAL operation, purification, transportation to China and MHP refining). In order to elucidate the importance of the processing and transportation stages that exhibit the highest contribution to impact categories (hot spots) under different input requirements, operating and site-dependent conditions and thus enhance reliability and comparability of the obtained results, a detailed sensitivity analysis is performed for the case under study.

Inventory analysis: An Indonesian laterite mined in an open-pit (strip ratio 1.2:1) on the Halmahera and Obi islands that contains 1.21% Ni and 0.17% Co is considered in this LCA study (Table 2) (Gultom and Sianipar, 2020; Permatasari et al., 2021; Konopka et al., 2022). The mineralogical analysis indicates that the limonite ore is characterized by a high content of iron and low content of Si and Mg.



Table 2. Chemical analysis of the Indonesian laterite used in this study

Oxides/ Elements	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	Cr ₂ O ₃	MnO	MgO	Ni	Co	CaO	CuO	S	ZnO	LOI
% w/w	14.45	7.16	57.56	2.68	1.36	2.86	1.21	0.17	0.05	0.01	0	0.05	12.06

The LCI of this study includes also extraction, production and transportation of raw materials, e.g. flocculants, organic solvents etc., acid production on site via combustion of elemental sulphur as well as energy generation from a lignite-fired power plant (60 MW) and transmission to the plant (**Table 3**).

Table 3. Main LCI data of the SOTA process investigated in this study.

Materials resources inputs	Unit (kg/kg Ni in NSH)***	Value
Diesel		0.8
Explosives		0.52
Sulphuric acid (98% conc.)*		3.1
Sulphur		4.26
Limestone (crushed)		9.8
Quicklime		2.31
Magnesia		0.76
Flocculant		0.01
Organic agents		0.04
Tap water		11.2
Water, unspecified natural origin		103
Energy inputs		
Electricity (coal)	kWh/ kg Ni in NSH	9.9
Electricity (grid mix)	kWh/ kg Ni in NSH	1.5
Steam	MJ/ kg Ni in NSH	38.92
Waste formation		
Tailings	t/t laterite	1.11
Wastewater	m ³ /t laterite	0.16
Marketable Products/Co-products		
MHP**	kg	8.93
NiSO ₄ 6H ₂ O	kg	4.48
CoSO ₄ 7H ₂ O	t	0.73

*Purchased from open market and used in the MHP refining stage, ** Intermediate product, ***unless otherwise stated



A Limestone quarry (15 km away from the plant) operated by the Indonesian company is also considered for covering the supply of limestone. Road transport of the Ni/Co concentrate from the beneficiation plant to the HPAL processing facility (25 km distance) involves the use of >32t diesel lorry trucks. Sea transport of the MHP product from Halmahera island in Indonesia to Jilin province in China is also included (4.700 km) along with road transportation by >32t diesel lorry trucks (300 km) in mainland China. An annual capacity of 11.03 kt of nickel sulphate and 1.34 kt of cobalt sulphate based on 4.6 Mtpa of ROM feed (on dry basis) and intermediate production of 73 ktpa of MHP (on dry basis) is considered.

In this case study the mass allocation method was utilized to distribute the emissions of the final marketable (co)products i.e. battery grade $\text{NiSO}_4 \cdot 6\text{H}_2\text{O}$ and $\text{CoSO}_4 \cdot 7\text{H}_2\text{O}$ on a physical basis. Mass allocation method was applied only to those stages where both metals (Ni and Co) were processed together. In this LCA study, mass allocation factors for $\text{NiSO}_4 \cdot 6\text{H}_2\text{O}$ (main product) and $\text{CoSO}_4 \cdot 7\text{H}_2\text{O}$ (co-product) were 85.6% and 14.4%, respectively. The system expansion approach was used for the on-site production of sulphuric acid from sulphur combustion in Indonesia.

6.2 ENICON processes/flowsheets

The ENICON novel HCl route and the modified (EU-based) existing metallurgical process of the carbon-neutral smelting of Ni/Co-sulphide concentrates along with the most promising mineral-matrix valorisation technology (alkali-activation) upscaled for slags have been carefully compiled on the basis of the developed LCA framework and the requirements of the ENICON project. In this context, primary data (scale up) from the experimental WPs 1-4 and the industrial partners have been retrieved on a frequent basis and incorporated on the assessed processing routes ensuring consistency, transparency, and accuracy in the life cycle assessment outputs. So far, conventional refining has been applied to process the Ni/Co intermediate produced via the next-generation HCl route. The ultra-refining of this intermediate in the existing hydro-process at Nikkelverk, using a Cl_2 -SX/EW process (T3.2), will be incorporated into the respective inventories together with the full life cycle inventory of the saprolitic laterite (ENICON028) once full scale-up data become available from WP3 and WP2, respectively. The respective LCA modelling calculations and obtained results will be presented in D5.4 (May 2026).

6.2.1 Next-generation HCl-based processing route for 3 input streams (ENICON023, ENICON017, ENICON028)

Goal and scope: The goal of this LCA study is to evaluate and document the environmental performance of a next-generation HCl-based processing route for Ni and Co recovery. The processing route converts ferronickel (ENICON023), limonitic laterite (ENICON017), and saprolitic laterite (ENICON028) into battery-grade Ni/Co products. In this content, the scope of this study covers the assessment of material and energy flows, GHG emissions, and resource use associated with the overall process, with the objective of achieving the lowest possible eco-footprint across approximately 15 impact categories according to GA and the related KPI of WP5. Special emphasis is given to the CO_2 , energy, water, and land use footprints, which are compared against the incumbent HPAL-based flowsheet.

Description of process: The next-generation HCl-based processing route initially involves the conversion of ferronickel (ENICON023), limonitic laterite (ENICON017) or saprolitic laterite (ENICON028) into MHP through atmospheric HCl leaching (first stage) (**Figure 6**). This is followed by three subsequent solvent extraction (SX1-3) stages. The resulting Ni/Co raffinate solution is then neutralized with NaOH and treated with magnesium oxide (MgO) to finally precipitate MHP. In the second stage of the process, the MHP is re-leached with



sulphuric acid, and the resulting pregnant leach solution (PLS) is subjected to further purification to enable the recovery of battery-grade nickel and cobalt.

More specifically, the production of MHP from the 3 input streams involves a series of hydrometallurgical processes designed to selectively extract and precipitate Ni and Co while minimizing impurities such as Mg and Ca. Initially, each input stream undergoes 6–8 mol/L (M) hydrochloric acid (HCl) leaching under controlled temperature (95 °C), stirring (500 rpm) and solid-to-liquid ratio (100:1) conditions. A small excess (25 mol% above stoichiometric amount) of H₂O₂ in the case of ferronickel (ENICON023) is added to oxidise Fe(II) to Fe(III), prior to solvent extraction. After leaching, FeCl₃ is firstly removed from the leachate by SX1 using undiluted, water–presaturated Tributyl Phosphate (TBP). The FeCl₃ obtained after SX1 is transformed into hematite (Fe₂O₃) with HCl generation by hydrolytic distillation/stripping. Ca and Mg in the raffinate after SX3 are transformed into CaCO₃ and MgCO₃ by SX-assisted carbonation, with HCl recovery. Subsequent refining to NSH involves MHP re-leaching using sulphuric acid (H₂SO₄), two stages of solvent extraction (SX) and two stages of stripping for Fe, Mg, Mn impurity removal and selective separation of Ni and Co using Cyanex 272, Cyanex 301 and kerosene, respectively and separate crystallization for Ni and Co at the last stage to obtain battery grade NSH and CSH.

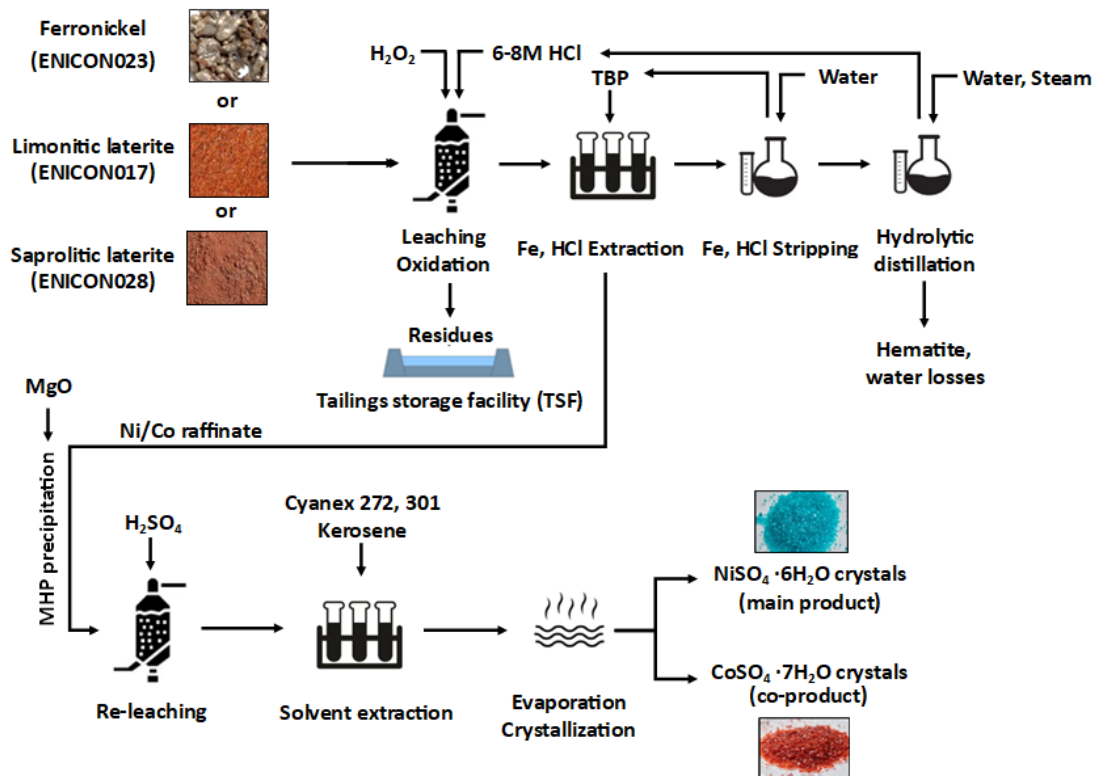


Figure 6. The next-generation HCl-based processing route developed and upscaled in ENICON to produce battery-grade nickel and cobalt from three different input streams

System boundaries: This LCA study follows a gate-to-gate approach, focusing on the environmental impacts associated with the production of battery-grade NSH (**Figure 7**). The processing route converts ferronickel (ENICON023), limonitic laterite (ENICON017), and saprolitic laterite (ENICON028) up to the stage at which the final product i.e. battery-grade NSH. exits the production facility (the gate). The system boundaries cover all upstream and on-site processes required to transform these input materials into battery-grade Ni,



including metallurgical processing, energy use, auxiliary inputs, emissions to air and water, and solid residues generated within the facility.

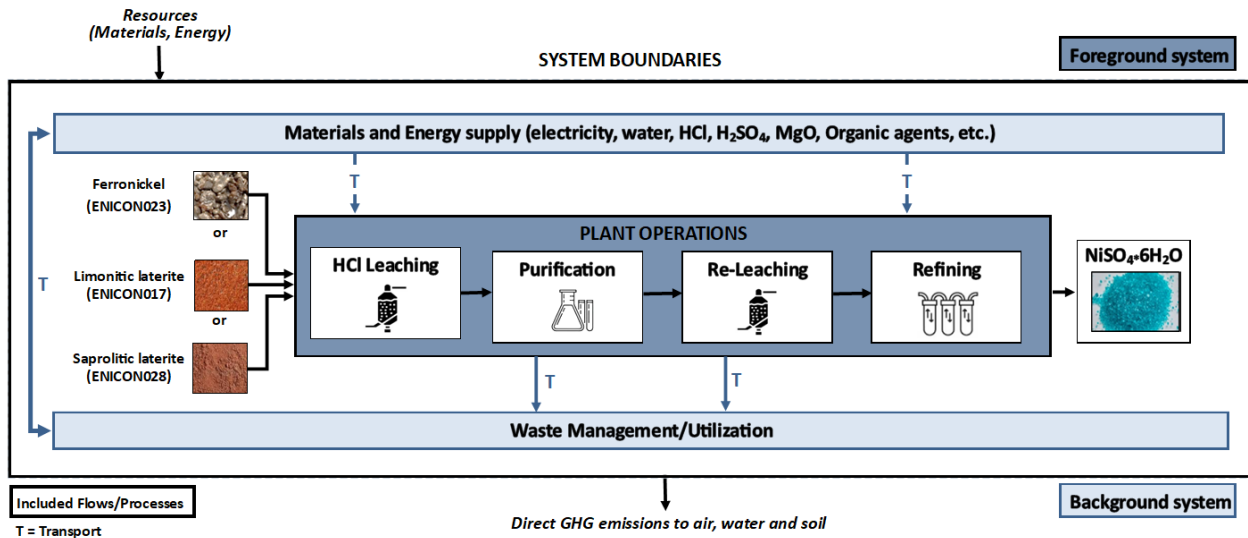


Figure 7. System boundaries adopted for the next-generation HCl-based processing route for the 3 input streams

Functional unit: The functional unit adopted in this study is 1 kg of nickel contained in nickel sulphate hexahydrate ($\text{NiSO}_4 \cdot 6\text{H}_2\text{O}$), equivalent to a nickel content of 22.3 wt%, produced with the use of the new HCl-based route. at the exit of the refining stage from the processing of ENICON023, ENICON017, and ENICON028 This functional unit allows for the quantification and normalization of all system inputs and outputs. The LCA study included impacts associated with the major processing of NSH production namely HCl leaching, purification, re-leaching, and refining, as defined within the previously established system boundaries.

6.2.1.1 Ferronickel (ENICON023)

Inventory analysis: In this LCA study, a medium to large-scale hydrometallurgical plant is evaluated for processing ferronickel (ENICON023) through the new hydrochloric acid (HCl)-based route developed under ENICON to produce MHP, followed by its refinement into battery-grade nickel sulphate hexahydrate (NSH, $\text{NiSO}_4 \cdot 6\text{H}_2\text{O}$) with a nickel content of $\geq 22\%$ and cobalt sulphate heptahydrate ($\text{CoSO}_4 \cdot 7\text{H}_2\text{O}$) with $\geq 20.5\%$ Co content. The chemical analysis of the FeNi obtained from the pyrometallurgical processing of Greek laterite at LARCO S.A is shaped by the ore's complex mineralogy, with nickel mainly in chlorite and hematite. It is characterized by a notable Fe/Ni ratio (~ 4) and low content of Mg, Ca and Si (**Table 4**).

Table 4. Chemical analysis of the FeNi product/alloy (ENICON023) used in this study

Oxides/ Elements	Ni	Co	Fe	MgO	CaO	SiO ₂
% w/w	19.04	0.88	76.4	0.51	0.74	2.4



In this context, the present LCA study assumes an annual production capacity of 91.1 kt of $\text{NiSO}_4 \cdot 6\text{H}_2\text{O}$ and 4.4 kt of $\text{CoSO}_4 \cdot 7\text{H}_2\text{O}$, obtained from 111 ktpa of FeNi feed (on a dry basis), along with an intermediate output of 35.7 ktpa of MHP with 57 Ni% content (on a dry basis). The gate-to-gate LCA approach considers a functional unit of 1 kg of nickel in NSH and allocates impacts at 96.7% for NSH and 3.3% for CSH. The inventory data for ENICON023 processing per functional unit, based on the newly developed hydrochloric acid (HCl) route, are presented in **Table 5**.

Table 5. Main inventory data for the processing of FeNi (ENICON023) per FU, based on the new HCl-based route

Inputs	Unit	Value
Ferronickel (FeNi)	kg	5.46
Processing inputs		
Hydrochloric acid (HCl)	kg	1.73
Sulphuric acid (H_2SO_4)	kg	5.04
Hydrogen peroxide (H_2O_2)	kg	0.44
Organic agents (Cyanex 272, Cyanex 301, Kerosene, TBP)	kg	0.10
Sodium hydroxide (NaOH)	kg	1.97
Water (Fresh water)	kg	1.08
Energy inputs		
Electricity (medium voltage)	kWh	13.38
Natural Gas	kg	2.18
Steam	kg	24.67
Marketable and other Outputs		
Nickel sulphate hexahydrate - NSH	kg	4.48
Cobalt sulphate heptahydrate - CSH	kg	0.22
Hematite (F_2O_3)	kg	5.77
Leaching residues	kg	0.42

FU= 1 kg Ni in nickel sulphate hexahydrate ($\text{NiSO}_4 \cdot 6\text{H}_2\text{O}$)

6.2.1.2 Limonitic laterite (ENICON017)

Inventory analysis: As in the previous case, a medium- to large-scale hydrometallurgical plant is evaluated in terms of LCA for the processing of limonitic laterite (ENICON017) through the hydrochloric acid (HCl)-based route to produce mixed hydroxide precipitate (MHP), which is then refined to battery-grade nickel sulphate hexahydrate (NSH, $\text{NiSO}_4 \cdot 6\text{H}_2\text{O}$) with a Ni content of at least 22%, and cobalt sulphate heptahydrate (CSH, $\text{CoSO}_4 \cdot 7\text{H}_2\text{O}$) with a Co content of at least 20.5%. The chemical analysis of the limonitic laterite obtained from Evia island, Greece, is presented in **Table 6**.



Table 6. Chemical analysis of the limonitic laterite (ENICON017) used in this study

Elements	Ni	Co	Fe	Al ₂ O ₃	Cr ₂ O ₃	MnO	MgO	CaO	SiO ₂
% w/w	0.87	0.04	28.25	3.99	2.05	0.22	3.62	2.11	36.54

In this context, the present LCA study assumes an annual production capacity of 21.1 kt of NiSO₄·6H₂O and 0.9 kt of CoSO₄·7H₂O, obtained from 500 ktpa of limonite laterite feed (on a dry basis), along with an intermediate output of 11.7 ktpa of MHP with 45 Ni% content (on a dry basis). The gate-to-gate LCA approach considers a functional unit of 1 kg of nickel in NSH and allocates impacts at 95.8% for NSH and 4.1% for CSH. The inventory data for ENICON017 processing per functional unit, based on the newly developed hydrochloric acid (HCl) route, are presented in **Table 7**.

Table 7. Main inventory data for the processing of limonitic laterite (ENICON017) per FU, based on the new HCl-based route

Inputs	Unit	Value
Limonitic laterite	kg	106.45
Processing inputs		
Hydrochloric acid (HCl)	kg	10.79
Sulphuric acid (H ₂ SO ₄)	kg	7.35
Organic agents (Cyanex 272, Cyanex 301, Kerosene, TBP)	kg	0.29
Hydrated lime [Ca(OH) ₂]	kg	4.65
Magnesia (MgO)	kg	1.17
Water (Fresh water)	kg	5.33
Energy inputs		
Electricity (medium voltage)	kWh	25.9
Natural Gas	kg	5.74
Steam	kg	50.56
Marketable and other Outputs		
Nickel sulphate hexahydrate - NSH	kg	4.48
Cobalt sulphate heptahydrate - CSH	kg	0.20
Hematite (F ₂ O ₃)	kg	48.28
Leaching residues	kg	51.34

FU= 1 kg Ni in nickel sulphate hexahydrate (NiSO₄·6H₂O)



6.2.2 Carbon-neutral smelting/converting for Ni/Co-sulphide concentrates

Goal and scope: The goal of this LCA study is to evaluate and compare the environmental impacts associated with the production of 1 tonne of slag generated from the smelting/converting process after cleaning ENICON015, where hydrogen is used as the reducing agent. The study assesses the effects of carbon-free reduction of Ni/Co-sulphide concentrates using hydrogen, with the objective of improving overall energy efficiency and reducing Ni/Co losses to the fayalitic smelting/converting slag. The potential environmental benefits of this approach in comparison to the conventional coke-based route, will be further evaluated once pilot-scale data become available (Task 2.2/WP2) and will be presented in D5.4 (May 2026). The current LCA modelling results are based on laboratory-scale reduction tests conducted under Task 2.2 (WP2, IR 2.1) and provide an initial foundation for process optimization and strategic decision-making aimed at the decarbonization and modification of the existing Ni/Co-sulphide pyro-route at Boliden Harjavalta (BOHA), in line with European Union climate objectives.

Description of process: The Direct Outotec Nickel (DON) flash smelting technology, developed by Outokumpu, is one of the prevailing processes for nickel smelting and is employed at BOHA. The DON process is based on flash smelting, which provides an efficient oxidation and separation of sulphide concentrates into a nickel matte and iron–silicate (fayalite) slag under controlled oxygen conditions. (**Figure 8**). The process consists of the Flash Smelting Furnace (FSF) followed by the slag cleaning electric furnace (SCF), which serves as the Electric Furnace (EF) stage for slag reduction and matte recovery.

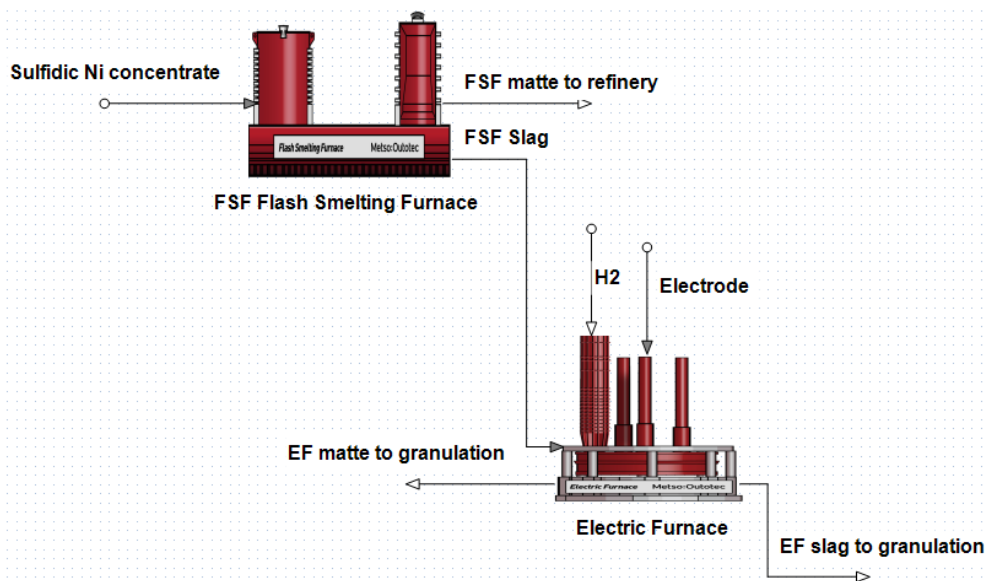


Figure 8. The smelting/converting process of Ni/Co-sulphide concentrates employed at BOHA

In the FSF stage, nickel–copper sulphide concentrates are smelted with fluxes and oxygen-enriched air. This produces two main products separated in the furnace bath: a heavier nickel-rich matte (metal sulphides) at the bottom containing most of the nickel and cobalt, and a lighter fayalite (Fe_2SiO_4) slag at the top that contains mostly iron as well as other oxides from the fluxes used, but it still contains small amounts of valuable metals, typically about 4% Ni and 0.4% Co. The molten matte from the FSF is tapped for further treatment, while the slag is directed to the SCF for metal recovery. The reduction process of Ni slag in the SCF is carried out batchwise and consists of three main stages: slag heating, oxide reduction, and the settling of matte/metal droplets. The SCF at BOHA is a round-shaped furnace equipped with three self-baking



(Söderberg) electrodes, each 1.3 m in diameter, while the total furnace dimensions are approximately 9 m in diameter and 5 m in height. The process in each reduction batch lasts about two hours. During the process, coke is used as a reducing agent to convert nickel and cobalt oxides in the slag into their metallic form, which coalesces as matte droplets that settle at the bottom of the furnace. The typical consumptions per tonne of slag processed are 0.8 kg of electrode, 30 kg of coke, and 172 kWh of electricity. The resulting product (EF/SCF-matte) is iron-rich, containing approximately 50% Ni and 30–40% Fe, and is chemically close to a metallic alloy. It contains more than 6% sulphur and is subsequently granulated before further treatment. The cleaned slag, which typically contains very low amounts of valuable metals (Ni \approx 0.1% and Co \approx 0.06%), is also granulated for disposal or further utilization. The total recovery to the EF/SCF-matte is about 46% of the input with the concentrate. The matte is then treated similarly to the FSF-matte and sold to customers for refining.

The lab scale reduction experiments were conducted in a vertical tube furnace (IR2.1 Hydrogen Report). Samples in silica crucibles were suspended on a Kanthal AF wire and heated to 1350 °C, with temperature monitored by an S-type Pt/Pt–10% Rh thermocouple. The furnace was flushed with N₂ (450 mL/min, 15 min) to remove oxygen, then H₂ (10–20 vol%) was introduced at a total flow of 300 mL/min. Reduction times were 5–60 min. After each test, the gas flow was stopped, and the samples were drop-quenched in ice water under an inert atmosphere to prevent reoxidation. More details about these tests are provided in IR2.1 “Hydrogen Report.”

System boundaries: The system boundary follows a gate-to-gate approach and includes the processing of the nickel sulphide concentrate in the FSF-EF system for the production of 1 tonne of slag at the EF outlet (Figure 9). The upstream system covers extraction and production of raw materials (hydrogen, and fuel oil), electricity generation based on the Finnish grid mix or renewable sources, and oxygen supply. The core system comprises the EF operation, reductant consumption, and the associated energy use required for slag cleaning. The assessment excludes infrastructure and capital goods, consistent with ISO 14040 and ISO 14044 requirements for comparative LCA studies.

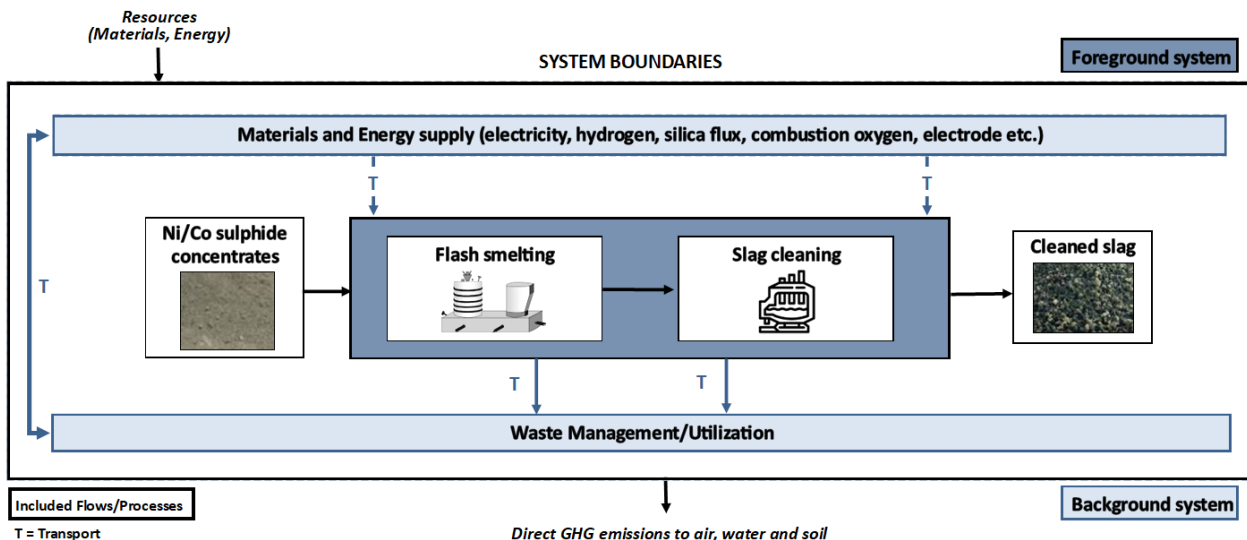


Figure 9. System boundaries adopted in this LCA study for the carbon-neutral smelting process for Ni/Co-sulphide concentrates using H₂ as reducing agent



Functional unit: The functional unit considered in this LCA study is the production of 1 tonne of cleaned waste slag at the EF/SCF exit. This unit ensures a consistent basis for comparison between scenarios using coke and hydrogen as reductants under equivalent output conditions (Ni-Co losses are negligible). The mass allocation factor of the EF cleaned waste slag in the considered system boundaries equals to 0.789 (78.9 % of the total FSF–EF burdens), while the remaining 21.1 % of burdens belong to nickel production (matte and subsequent route). All inputs and emissions are normalized to this reference flow.

Inventory analysis: Table 8 presents the inventory data for the carbon-neutral smelting process of Ni/Co-sulphide concentrates in the FSF–EF route for the production of 1 t of cleaned slag using H₂ as a reductant.

Table 8. Main inventory data for the for the carbon-neutral smelting process for Ni/Co-sulphide concentrates

Inputs	Unit	Value
Nickel concentrate	t	1.26
Processing inputs		
Ni silica flux	t	0.20
Fuel oil	kg	23.6
Combustion air	m ³	224
Combustion oxygen	m ³	18.5
Electrode paste	kg	1.18
Hydrogen	m ³	26.1
Energy inputs		
Electricity (medium voltage)	kWh	86.70
Outputs		
Ef slag	t	1
FSF matte	t	0.21
EF matte	t	0.06

FU= 1 t of cleaned slag in the EF/SCF exit



6.2.3 Mineral-matrix valorisation - Alkali-activation of FeNi slag (ENICON021)

Goal and scope: Based on the ENICON LCA framework (see 5.1.2) and the associated objective mentioned in the GA, an LCA study of the most promising mineral-matrix valorisation technology (alkali-activation) has been carried out based on the latest lab pilot data (June 2025) provided by TUC (WP4). In this context, the study assesses the energy consumption and greenhouse gas footprint associated with the synthesis of AAMs produced with Larco slag (ENICON021) as the primary precursor for two representative construction products, namely a 1 m³ mortar and a block with 150 mm × 150 mm × 65 mm dimensions. Benchmarking against 1 m³ of conventional Ordinary Portland Cement (OPC) mortar is underway in Task 5.3 “LCA-TEA benchmarking against SOTA and baseline approaches” and will be presented at the related D5.4 (May 2026) in order to explore the anticipated environmental and energy-related benefits of the most promising mineral-matrix valorisation process developed within ENICON.

Description of process: Pilot data for the LCA study of Alkali-Activation in WP5 were obtained from the outcomes of Task 4.4 (WP4), which focused on the upscaling of selected technology for the alkali activation of slags. Lab pilot tests were carried out at TUC in June 2025 for larger scale production of alkali-activated materials (AAMs) from slags generated during the pyrometallurgical treatment of laterites for ferronickel (FeNi) production (Figure 10). More specifically, the slag (LS/ENICON021) used in these studies is a by-product of FeNi production after the processing of laterites in electric-arc furnaces at the LARCO S.A. plant in Larymna, central Greece. Prior to utilization, 300 kg of LS were dried at 80°C for 24 hours and subsequently pulverized in a Sepor-type rod mill for 2h, resulting in a particle size distribution with d_{90} equal to 103 μm . The activating solution was prepared by dissolving anhydrous NaOH pellets (Sigma Aldrich) in distilled water to obtain a molarity of 8 mol L⁻¹ (M), followed by mixing with a Na₂SiO₃ solution (Na₂O = 7.5–8.5%, SiO₂ = 25.5–28.5%, Merck). The activating solution was allowed to rest overnight before use. The starting mixture in each batch consisted of 16 kg of slag, 2 kg of 8M NaOH solution, and 2 kg of Na₂SiO₃ solution.

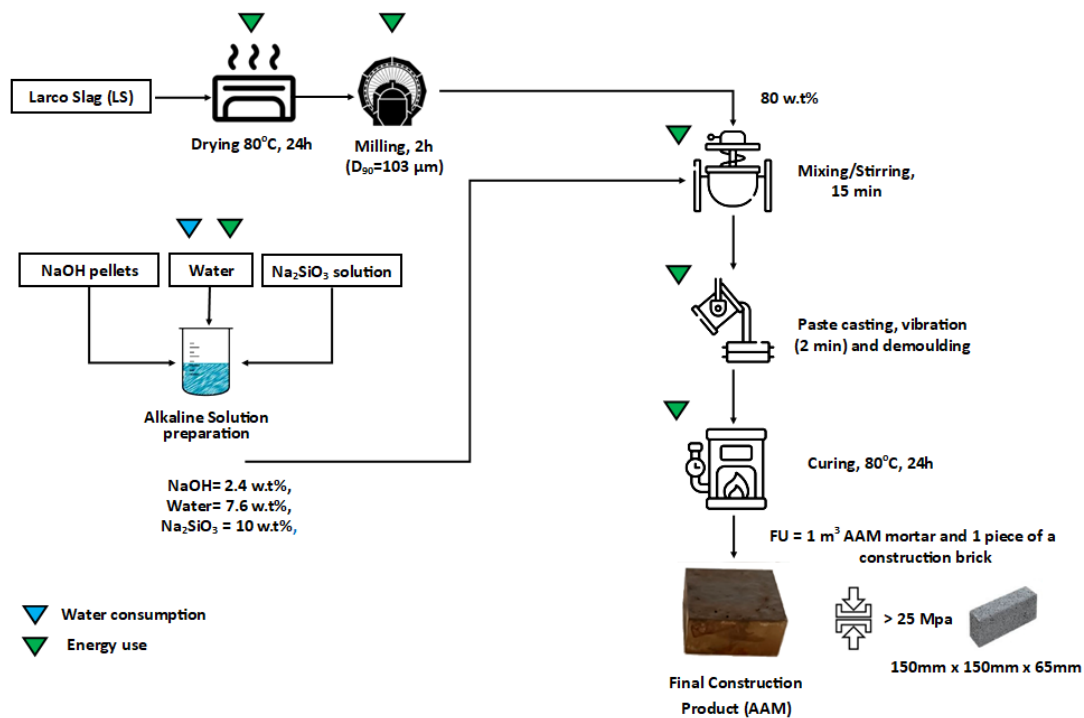


Figure 10. Alkali activation of FeNi slag (ENICON021) for the production of construction elements (mortars, blocks) with >25 MPa compressive strength.



AAM synthesis was performed by the gradual addition of ground LS slag into the activating solution under continuous mechanical mixing for approximately 15 minutes using a Dewalt 1800W DWD241 stirrer. The resulting paste was poured into 3D-printed molds of various dimensions, vibrated for two minutes to remove entrapped air, and subsequently left to harden at ambient temperature for 48 hours. The specimens were then demoulded, sealed in plastic bags to prevent rapid water evaporation, and either stored at room temperature or cured in a laboratory oven at 80°C for 24 hours. Aging took place for either 7 or 28 days. This recipe was selected based on the results of numerous laboratory tests carried out at TUC from the start of ENICON using different slags and tailings. The compressive strength (mainly) as well as other mechanical / physical properties of the final products were then determined.

System boundaries: The system boundaries considered in this LCA study were defined under a gate-to-gate approach, covering the processes from the point where Larco slag was delivered to TUC for the production of AAMs, namely a mortar and a block (**Figure 11**). These boundaries cover all processes associated with slag drying, grinding, alkali activation, mixing, casting and curing. The Larco slag was treated as a by-product of ferronickel production and therefore entered the system without any upstream environmental burden from the metallurgical process, in accordance with by-product allocation principles. In contrast, a cradle-to-gate boundary was applied for the processing inputs, namely sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3), in order to include their full upstream environmental impacts related to raw material extraction, manufacturing, and transport to the production site. This boundary definition ensured a full and more reliable representation of the environmental profile of AAM production while maintaining focus on the processes controlled within the pilot system.

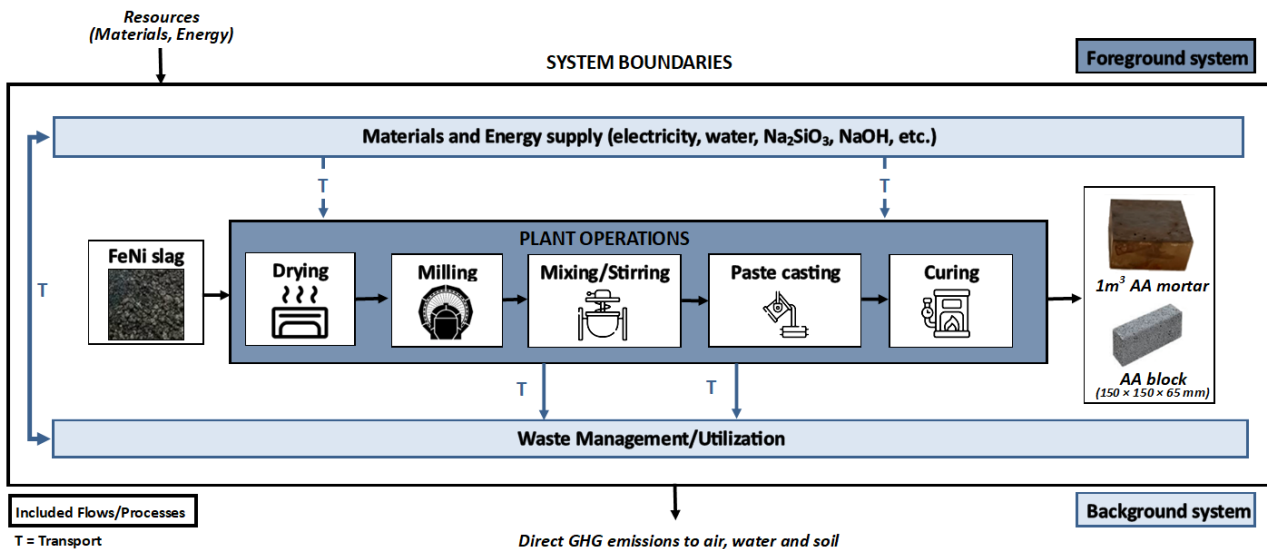


Figure 11. System boundaries adopted in this LCA study for the alkali activation of FeNi slag (ENICON021)

Functional unit: A twofold functional unit was selected for this LCA study, defined as 1 m³ of AA mortar and a single AA block with 150 mm × 150 mm × 65 mm dimensions, produced under the same mix design and curing conditions. This functional unit provides a standardized reference that supports the quantification of resource efficiency and environmental performance throughout the production process (Batuecas et al., 2021; Tang et al., 2021). Furthermore, the adoption of 1 m³ of AAM mortar enables direct benchmarking with OPC systems and permits an objective evaluation of the potential environmental advantages associated with the use of AAMs as alternative binders in construction applications. On the other hand, the inclusion of the



standard-sized AA block provides a practical reference that reflects the product's intended application in masonry and construction sectors. This dual definition establishes a direct link between laboratory-scale data and real-scale building components and allows the assessment results to be interpreted both in terms of material performance and potential market relevance.

Inventory analysis: Table 9 summarises the inputs and outputs (LCI) for the considered functional units, namely 1 m³ of AA mortar and one AA block (150 mm × 150 mm × 65 mm), together with their key characteristics. The transportation of all processing inputs was taken into account, whereas transportation related to Larco slag was excluded in accordance with the gate-to-gate system boundary applied in this study. Both compositions align with the 16:2:2 mass ratio used in the lab pilot mix and, when scaled to 1 m³, corresponds to a dense AA mortar with an estimated bulk density of approximately 2350 kg/m³, which is typical for mortars of similar composition. The AA block produced at the lab pilot facility had a density of 2.52 g/cm³, which reflects a compact and well-consolidated matrix. This high density indicates effective slag activation and low porosity, contributing to the material's mechanical strength and durability. In this context, the determined compressive strength of 27.1 MPa is comparable to, and in some cases higher than, that of commercially available OPC blocks of C20/25 grades and similar dimensions (Lim et al., 2025), confirming the suitability of the developed AAMs for structural and masonry applications.

Table 9. Life cycle inventory for the two representative construction products considered in this LCA study

Parameter	Unit	Construction products	
		1 m ³ AA mortar	Single AA Block
Inputs (Raw materials)		0.8	
Larco slag	kg	1880	0.2946
Processing inputs			
Na ₂ SiO ₃ solution	kg	235	0.368
NaOH pellets	kg	56.2	0.088
Water (distilled)	kg	178.8	0.028
Energy inputs			
Electricity (medium voltage)	kWh	45	0.07
Fossil fuels	kg	75	0.11
Outputs			
AA mortar	m ³	1	-
AA block (150 mm × 150 mm × 65 mm)		-	1
Properties			
Density	g/cm ³	2.35	2.52
Compressive strength	MPa	>25	27.1



7 Results

7.1 Reference/SOTA case study– High Pressure Acid Leach (HPAL)

Table 10 presents the midpoint characterization results of the life cycle impact assessment (LCIA) conducted using the LCA FE software according to the CML 2001, EF 3.0, and Recipe 2016 v1.1 impact evaluation methods. The LCIA results represent the absolute values obtained for the 15 impact categories considered in this study and are expressed per functional unit (1 kg of nickel in Nickel Sulphate Hexahydrate - 22.3% Ni content). **Table 10** also compares the findings of previous LCA studies concerning nickel sulphate production using HPAL technology with the results of this study in terms of the impact categories analyzed (where available).

Benchmarking of the LCIA results obtained from the current case study (laterite HPAL treatment in Indonesia and further MHP refining in China) against limited available literature data, indicates a contribution of about 30% higher than the average reported values for GWP and CED. However, direct comparison of LCAs is often difficult as the methodology followed, the system boundaries, the assumptions made and the scope emissions coverage, among other parameters investigated in an LCA study may vary in several ways (Bartzas and Komnitsas, 2015; Erakca, et al., 2023).

Table 10. Life Cycle Impact Assessment (LCIA) results of the Reference case study per functional unit (FU) – Comparison with available literature

Impact Category	Present study	Range* (other studies)	(Diff. ±%)**
Acidification potential (AP) [kg SO ₂ -eq·FU ⁻¹]	0.998	0.687-1.17 (0.925)	+8
Eutrophication potential (EP) [kg PO ₄ -eq·FU ⁻¹]	0.007	0.006	+17
Global warming potential (GWP) (100 years) [kg CO ₂ -eq·FU ⁻¹]	38.1	17.9-33.3 (28.59)	+33
Ozone layer depletion potential (ODP) [g CFC-11-eq·FU ⁻¹]	0.005	0.003	+67
Photochemical ozone creation potential (POCP) [kg C ₂ H ₄ -eq·FU ⁻¹]	0.013	N.D	-
Terrestrial ecotoxicity potential (TETP) [kg DCB-eq·FU ⁻¹]	7.98	N.D	-
Climate change land use and land use change [kg CO ₂ -eq·FU ⁻¹]	0.14	N.D	-
Climate change, fossil [kg CO ₂ -eq·FU ⁻¹]	0.008	N.D	-
Abiotic depletion, elements (ADP) [g Sb-eq·FU ⁻¹]	0.007	N.D	-
Metal depletion (MD) [kg Cu-eq·FU ⁻¹]	3.89	3.52	+11
Fossil depletion (FD) [kg oil-eq·FU ⁻¹]	2.58	2.20	+17
Fine particulate matter formation (FPMF) [kg PM2.5-eq·FU ⁻¹]	0.31	0.26	+19
Freshwater consumption (FWC) [m ³ ·FU ⁻¹]	0.34	0.25	+36
Land use (LU) [m ² a crop eq·FU ⁻¹]	60.28	46.82	+29
Cumulative energy demand (CED) [MJ·FU ⁻¹]	398	305	+30

* Ali et al., 2023; Tijsseling and Whattoff, 2023; Nickel institute, 2023; The metals company, 2023; In parentheses the average values are given; N.D: Not defined. **Percentage difference with average values



Contribution analysis: The results of the contribution analysis regarding the GWP impact category for the major processing and transportation stages of NSH production (i.e. mining, beneficiation/feed preparation, domestic transportation, HPAL operation, purification, transportation to China and MHP refining) investigated in this case study are shown in **Figure 12**. As can be seen, the HPAL operation stage dominates the entire environmental impact by 35%, followed by the purification stage (25%) and the MHP refining stage in China (18%). This is primarily linked to electricity consumption (41% of the total GWP) and chemical reagents (sulphuric acid, limestone, magnesia and quicklime) used at the aforementioned stages. Electricity consumption accounts for 28% and 42% of the GWP and CED impact categories, respectively. This relatively high contribution of electricity consumption to GWP and CED is mainly caused by the use of lignite in the power plant operated by the company in Indonesia and the high share of fossil fuels in the Chinese grid mix (>60%) (IEA, 2021b). Limestone, sulphuric acid and quicklime are the most GHG intensive chemical reagents used in this case study, accounting for 12.2%, 10.6%, and 13.8% of the total GWP impact category, respectively, all exhibiting also noteworthy contributions to the AP, EP, FD and CED impact categories. The phases of mining and beneficiation/feed preparation exhibited a notable share to the GWP calculated, namely 6% and 15%, respectively, while the contribution of transportation activities to the overall GWP was negligible. To get a better understanding of the scope emissions related to each processing stage of the NSH production, it is important to match them with the specific sources and activities that affect the GWP impact category.

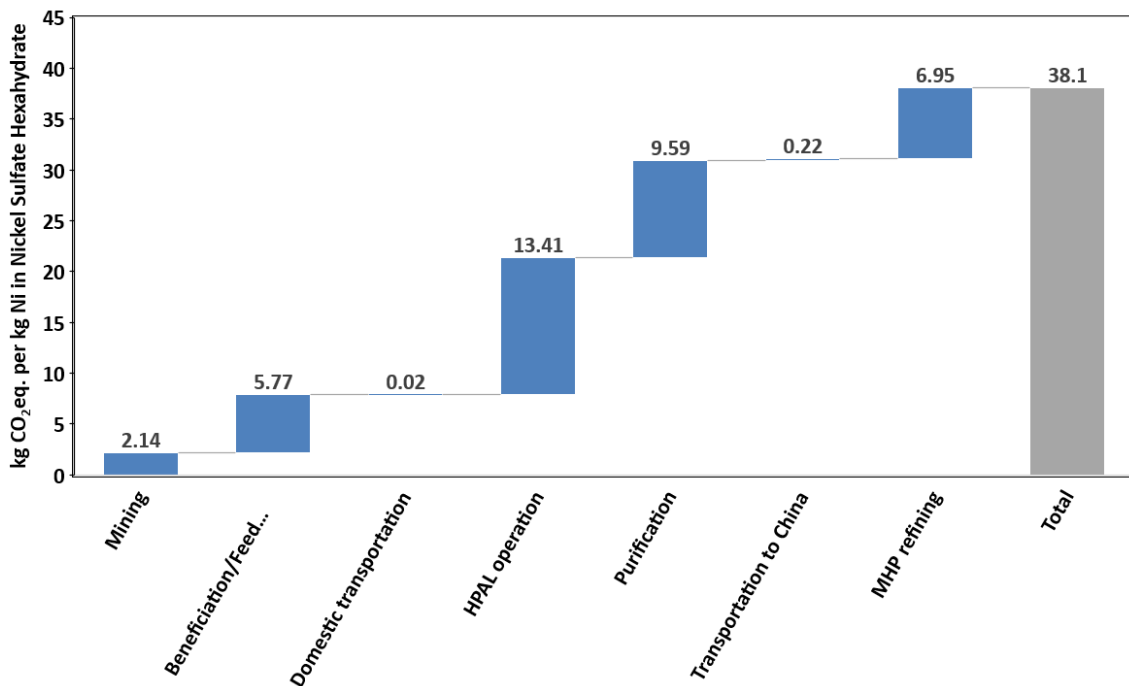


Figure 12. Contribution of each processing/transportation stage during NSH production to the total GWP impact category



Scope analysis: The results of the scope analysis in accordance with the GHG Protocol (Scope 1, 2 and 3) for the GWP impact category are presented in **Figure 13**. Scope 1 emissions account for the largest share (61.4%) of the total CO₂ eq per kg of nickel in NiSO₄·6H₂O, stemming mostly from the lignite-fired electricity generation and associated thermal energy, the limestone quarrying and the on site production of sulphuric acid from sulphur in Indonesia. Scope 2 emissions account for only 8.1% due to the contribution of the Chinese electricity grid mix in the MHP refining stage and Scope 3 emissions account for the remaining 30.5% of the CO₂ emissions. Most Scope 3 emissions are associated with purchased raw materials such as quicklime and magnesia used in the purification stage in Indonesia.

Sensitivity analysis: Based on the research results of GWP contribution obtained for the NSH production and the identification of the associated hot spots, four scenarios were taken into account and further analyzed to quantify the subsequent changes in the results compared to the base case study (laterite HPAL treatment in Indonesia and further MHP refining in China; results shown in previous section) in terms of altering the impact of five different categories i.e. GWP, CED, LU, EP and AP.

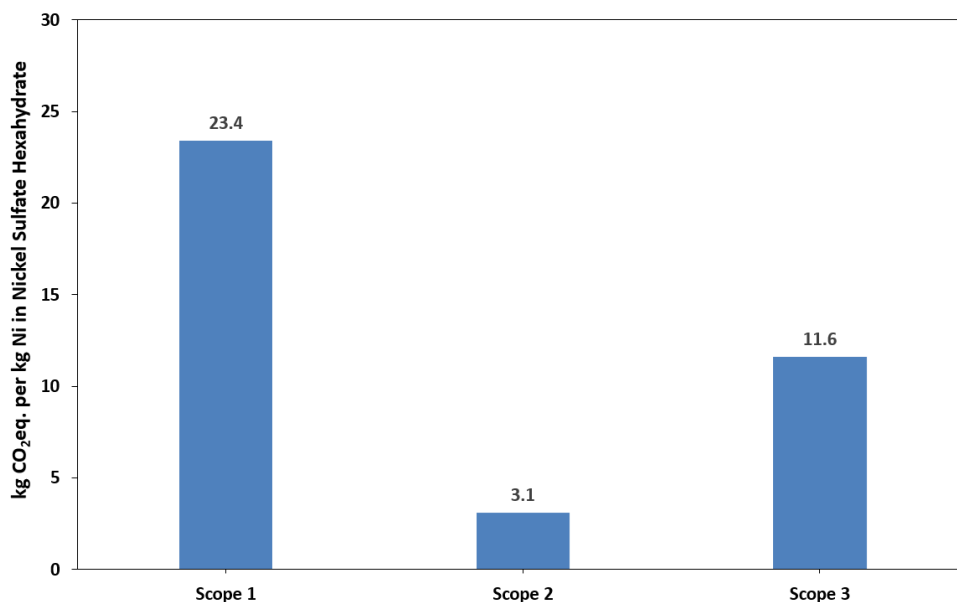


Figure 13. Scope analysis of the NSH production for the GWP impact category according to the GHG protocol

- The first scenario (“Greener energy”) assumes the use of an electricity grid mix with low climate impact (GHG emissions) such as the Finnish one in the MHP refining stage (100% replacement). The Finnish electricity mix (high voltage) has been selected because it has one of the lowest CO₂-eq (0.198 kg CO₂-eq/kWh) in Ecoinvent 3.9 database and is currently used by the majority of the nickel sulphate producers in Europe. On the other hand, the Chinese electricity mix (high voltage in the North-East China Grid) has one of the highest CO₂-eq (1.386 kg CO₂-eq/kWh) in Ecoinvent 3.9 database.
- In the second scenario (“Ore grade decline”), a limonite laterite with 10% lower Ni content i.e. 1.1% is assumed. This scenario is considered likely to occur in the near future based on the fact that the existing high-grade nickel reserves in Indonesia are estimated to last until 2035 (www.mining.com, 2024) and therefore more reserves of lower grade nickel ores are steadily processed over time.
- The third scenario (“Reagent substitution”) explores the possibility of using sodium hydroxide/caustic soda (NaOH) for pH adjustment in the first stage of Ni/Co recovery/precipitation stage instead of magnesia (MgO) to improve selectivity for Ni over Mn and decrease the magnesium content (due to unreacted magnesia) of the MHP product, thus reaching a higher quality intermediate product for



shipment to China. The production and market delivery of caustic soda has lower GWP impact value i.e. 1.42 kg CO₂-eq/kg in Ecoinvent 3.9 database compared to magnesia (2.067 kg CO₂-eq/kg); however, caustic soda is more expensive by two to three times, compared to magnesia, depending on its quality.

- The last (fourth) scenario “MHP refining location” investigates the possibility of MHP refining in Indonesia. This scenario is considered possible in the near future because more Chinese-funded enterprises are currently showing interest or even investing in Indonesia by including the refining process in existing (expansion) or planned HPAL plants (Sangadji, et al., 2019; Saegert, et al., 2023, Global Battery Alliance, 2023). This integrated option offers several advantages including: less use of reagents (i.e. lime and sulphuric acid), no transportation for the intermediate product, less land use requirements and energy availability from one source.

Table 11 presents the obtained results for the four scenarios adopted in the sensitivity analysis in comparison with the base case study of the NSH production. Results are given as percentage variation values for the impacts categories (GWP, CED, LU, EP and AP) compared to absolute values for the base case scenario.

Table 11. Percentage variation of the impact categories (GWP, CED, LU, EP and AP) for the four scenarios adopted in the sensitivity analysis in comparison with the base case study of the NSH production.

Impact Category	Scenarios*				
	Base case	Greener energy	Ore grade decline	Reagent substitution	MHP refining location
Acidification potential (AP) [kg SO ₂ -eq·FU ⁻¹]	0.998	-2.6%	+4.2%	+1.8%	-4.8%
Eutrophication potential (EP) [kg PO ₄ -eq·FU ⁻¹]	0.007	-2.1%	+3.9%	+1.2%	-3.9%
Global warming potential (GWP) (100 years) [kg CO ₂ -eq·FU ⁻¹]	38.1	-2.3%	+5.6%	-1.4%	-5.2%
Land use (LU) [m ² a crop eq·FU ⁻¹]	60.28	+0.4%	+4.9%	+0.3%	-3.6%
Cumulative energy demand (CED) [MJ·FU ⁻¹]	398	0%	+5.9%	+0.9%	-4.8%

*Impact is higher (+) or lower (-) than the base case scenario.

From an overall environmental perspective, the most favorite scenario for the NSH production is the “MHP refining location” followed by the “Greener energy” scenario. In the case of the MHP refining in Indonesia, the percentage variations decrease by 3.6-5.2% for the 5 impacts categories assessed. Similarly, sensitivity analysis indicates that the implementation of the “Greener energy” scenario in the MHP refining stage may slightly reduce AP by 2.6%, GWP by 2.3%, and EP by 2.1%. On the other hand, although the complete substitution of the MgO with the NaOH in the first stage of Ni/Co recovery/precipitation stage shows some promising results in terms of GWP contribution i.e. 1.4% lower impact compared to the base case scenario, it fails to improve the remaining impact categories. This is attributed to the type of the NaOH production (chlor-alkali electrolysis) and the associated impacts available in the Ecoinvent 3.9 database in terms of the AP, EP and CED categories. Finally, among the scenarios investigated, the “Ore grade decline” scenario exhibits the highest percentage variation results (+ 3.9-5.9%) in all the impact categories assessed compared to the base case study. The extraction and processing of lower nickel ore grade requires more energy and land occupation, hence, more GHG emissions and waste generation occur to obtain the same amount of



battery grade nickel product. To conclude, integrated NSH production, followed by the use of greener energy, should be the priority to minimize the potential environmental burdens related to battery grade Ni/Co production. Improvement of the availability and integration of raw material resources, together with the introduction of clean energy sources, constitutes an essential measure that is necessary not only to mitigate climate change but also to enhance the operational efficiency, resilience, and competitiveness of the Ni/Co metal industry.

7.2 Next-generation HCl-based processing route

7.2.1 Ferronickel (ENICON023)

Table 12 presents the LCIA results of the novel HCl-based route for processing FeNi (ENICON 023). The midpoint characterization results refer to the absolute values obtained for the 15 impact categories considered in this study and are expressed per functional unit (1 kg of nickel in Nickel Sulphate Hexahydrate - 22.3% Ni content).

Table 12. LCIA results of the novel HCl-based route for processing FeNi (ENICON 023) per FU

Impact Category	Value
Acidification potential (AP) [kg SO ₂ -eq·FU ⁻¹]	0.15
Eutrophication potential (EP) [kg PO ₄ -eq·FU ⁻¹]	0.002
Global warming potential (GWP) (100 years) [kg CO ₂ -eq·FU ⁻¹]	9.2
Ozone layer depletion potential (ODP) [g CFC-11-eq·FU ⁻¹]	0.001
Photochemical ozone creation potential (POCP) [kg C ₂ H ₄ -eq·FU ⁻¹]	0.002
Terrestrial ecotoxicity potential (TETP) [kg DCB-eq·FU ⁻¹]	2.14
Climate change land use and land use change [kg CO ₂ -eq·FU ⁻¹]	0.02
Climate change, fossil [kg CO ₂ -eq]	0.001
Abiotic depletion, elements (ADP) [kg Sb-eq·FU ⁻¹]	0.002
Metal depletion (MD) [kg Cu-eq·FU ⁻¹]	0.75
Fossil depletion (FD) [kg oil-eq·FU ⁻¹]	0.64
Fine particulate matter formation (FPMF) [kg PM2.5-eq·FU ⁻¹]	0.07
Freshwater consumption (FWC) [m ³ ·FU ⁻¹]	0.06
Land use (LU) [m ² a crop eq·FU ⁻¹]	10.6
Cumulative energy demand (CED) [MJ·FU ⁻¹]	76

FU= 1 kg Ni in nickel sulphate hexahydrate (NiSO₄·6H₂O)

Very limited literature data exists on the environmental performance of battery-grade NSH production from ferronickel, with only one directly comparable study available (Dry et al., 2019). The novel ENICON HCl-based route results in a GWP of 9.2 kg CO₂-eq per kg Ni, whereas the FeNi leaching circuit using H₂SO₄ reported by Dry et al. (2019) presents 14.5 kg CO₂-eq per kg Ni, which indicates a 37% reduction in GWP impact in favour



of the present LCA study. The higher GWP in [Dry et al. 2019](#) arises from very high electricity demand (40.1 kWh per kg Ni) and a large limestone requirement (6.1 kg per kg Ni). In contrast, the ENICON route uses significantly lower electricity (2.81 kWh per kg Ni) and lower amounts of neutralization agents (2 kg per kg Ni produces). In addition, the integrated HCl recovery via SX reduces upstream burdens and supports the significantly lower overall GWP.

Contribution analysis: The contribution analysis for the GWP impact category for the major processing stages (HCl reaching, purification, re-leaching and refining) indicates that the production of 1 kg of Ni in NSH is dominated by the downstream hydrometallurgical stages. (**Figure 14**). The leaching stage is the second main hotspot with 31% contribution, largely due to the upstream production of HCl, NaOH and H₂O₂. Based on the latest Ecoinvent database (version 3.12), the European-based production of HCl via the reaction of H₂ with Cl₂ generates 1.17 kg CO₂-eq per kg, caustic soda contributes 0.99 kg CO₂-eq per kg, and H₂O₂ via autooxidation contributes 1.75 kg CO₂-eq per kg. The purification stage (SX, hydrolytic distillation, Fe removal and MHP precipitation) contributes about 22% of total GWP. This share results from steam demand in SX (27% of total steam), additional steam and natural gas use in Fe recovery, and caustic soda consumption in MHP precipitation. Upstream GHG emissions originate mainly from natural-gas combustion (96.9% of total gas), steam and NaOH consumption. The re-leaching stage shares 12% on the total GWP, mainly from sulphuric acid production and electricity requirements. The refining stage, which involves impurity removal, Ni/Co separation and crystallization, forms the largest share of total electricity demand and accounts for 35% of total GWP. This high contribution reflects the very large electricity load of the NSH evaporation–crystallisation circuit, equal to 81% of total electricity consumption at the plant. Overall, leaching and refining account for 76% of the total GWP impact category, which identifies these stages as the main phases for GHG reduction (hot spots).

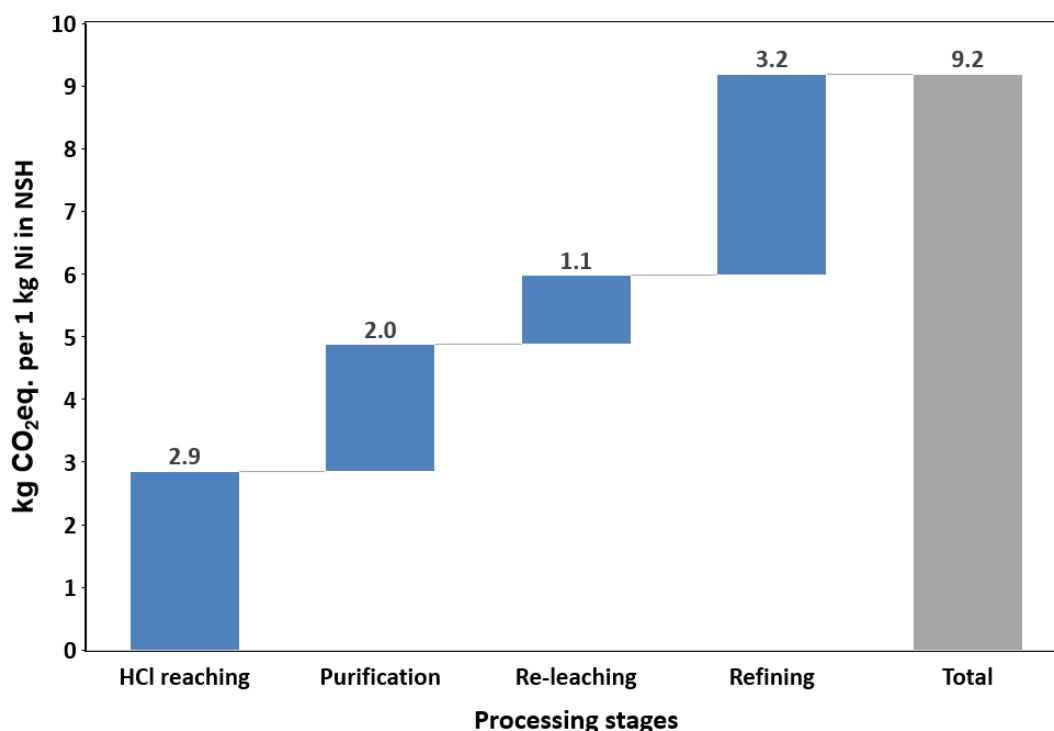


Figure 14. Contribution of major processing stages to the total GWP for the production of 1 kg of Ni in NSH via the novel HCl-based route for FeNi (ENICON023)



A more detailed contribution analysis per input material and energy source shows that energy inputs account for the majority of the GWP, with electricity and natural gas as the largest contributors. Electricity use contributes an additional 29%, based on the carbon intensity of the medium-voltage electricity mix of Finland (0.199 kg CO₂ per kWh). Natural gas accounts for 16% of total GWP, while steam generation adds about 0.9 kg CO₂-eq (10%), which reflects the high heat demand of the atmospheric HCl leaching and the subsequent purification stages. Overall, energy-related emissions account for ~55% of total GWP. Chemical inputs represent the second most important contributor (45%) to the total GWP impact category. Hydrochloric acid production contributes about 2 kg CO₂-eq (22%), sulphuric acid contributes approximately 0.6 kg CO₂-eq (7%), and hydrogen peroxide contributes around 0.7 kg CO₂-eq (8%). Organic extractants (Cyanex 272, Cyanex 301, TBP, kerosene) contribute less in absolute terms, with 5%, though they have greater influence on toxicity-related categories. All remaining contributions, including on-site leaching residues management (belt filtration and storage), represent less than 3% of the total GWP.

Scope analysis: The results of the scope analysis for the GWP impact category are shown in **Figure 15**. Scope 1 emissions account for approximately 26% of the total CO₂-eq per kg of nickel in NiSO₄·6H₂O and arise from on-site natural-gas use for process heat and from the operation of the sulphuric-acid plant. Scope 2 emissions account for about 46% of total GWP and result from the use of purchased electricity throughout the hydrometallurgical stages. Finally, Scope 3 emissions represent the remaining 28% and originate from upstream production of hydrochloric acid, hydrogen peroxide, organic extractants and other auxiliary materials required.

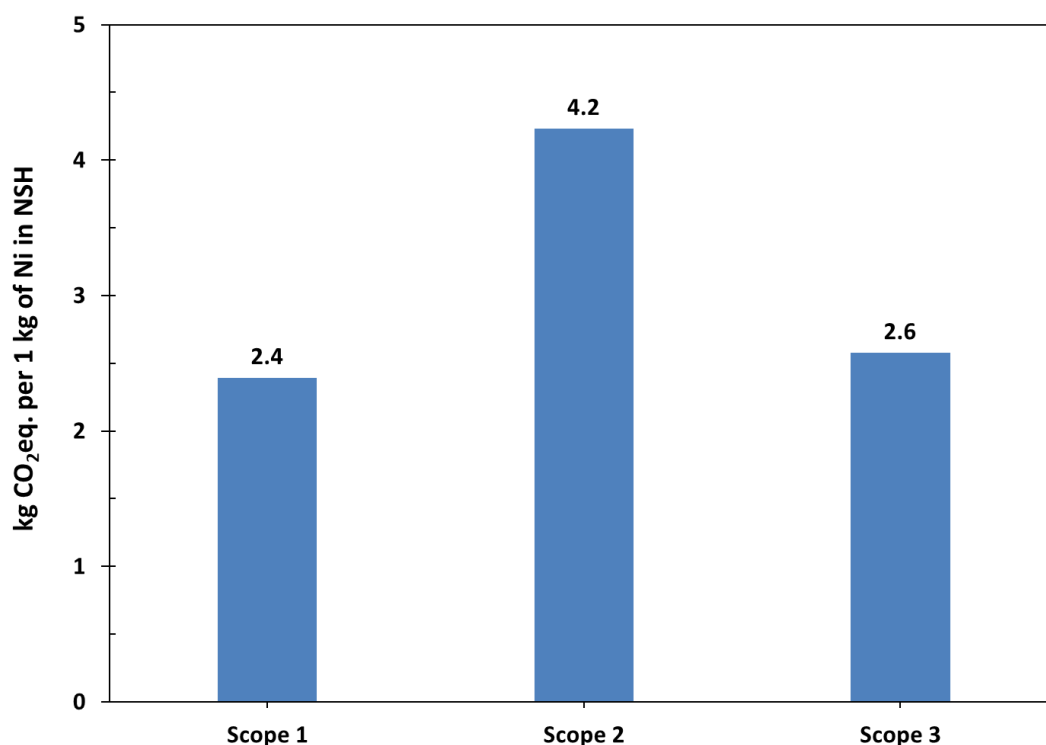


Figure 15. Scope analysis of GWP for the production of 1 kg of Ni in NSH via the novel HCl-based HCl route for FeNi (ENICON023)

Overall, the environmental footprint of the HCl-based route for processing FeNi (ENICON023) is driven mainly by purchased electricity and steam reported under Scope 2, while upstream reagent production accounted for in Scope 3 adds a significant share to the total GWP. Scope 1 contributes a smaller share because on-site



fuel combustion is limited to process heating and sulphuric acid-plant operation. The scope analysis shows that the most effective decarbonization opportunities exist in reducing electricity and steam requirements as well as in lowering the carbon intensity of upstream chemical supply chains.

7.2.2 Limonitic laterite (ENICON017)

The LCIA results of the novel HCl-based route for processing limonitic laterite (ENICON017) are presented in **Table 13**. In this LCA study, the midpoint characterization results reflect the absolute values calculated for all 15 impact categories, expressed relative to the functional unit of 1 kg of Ni contained in nickel sulphate hexahydrate (22.3% Ni).

Table 13. LCIA results of the novel HCl-based route for processing limonitic laterite (ENICON017) per FU

Impact Category	Value
Acidification potential (AP) [kg SO ₂ -eq·FU ⁻¹]	0.814
Eutrophication potential (EP) [kg PO ₄ -eq·FU ⁻¹]	0.006
Global warming potential (GWP) (100 years) [kg CO ₂ -eq·FU ⁻¹]	29.5
Ozone layer depletion potential (ODP) [g CFC-11-eq·FU ⁻¹]	0.004
Photochemical ozone creation potential (POCP) [kg C ₂ H ₄ -eq·FU ⁻¹]	0.009
Terrestrial ecotoxicity potential (TETP) [kg DCB-eq·FU ⁻¹]	3.09
Climate change land use and land use change [kg CO ₂ -eq·FU ⁻¹]	0.09
Climate change, fossil [kg CO ₂ -eq]	0.006
Abiotic depletion, elements (ADP) [kg Sb-eq·FU ⁻¹]	0.006
Metal depletion (MD) [kg Cu-eq·FU ⁻¹]	3.13
Fossil depletion (FD) [kg oil-eq·FU ⁻¹]	2.04
Fine particulate matter formation (FPMF) [kg PM _{2.5} -eq·FU ⁻¹]	0.26
Freshwater consumption (FWC) [m ³ ·FU ⁻¹]	0.28
Land use (LU) [m ² a crop eq·FU ⁻¹]	18.7
Cumulative energy demand (CED) [MJ·FU ⁻¹]	303

FU= 1 kg Ni in nickel sulphate hexahydrate (NiSO₄·6H₂O)

The LCIA profile of the novel HCl-based limonitic laterite route (ENICON017) shows clear differences when compared with the limited set of available cradle-to-gate studies and datasets ([The Metals Company, 2023](#); [Tijsseling, and Whattoff, 2023](#); [Nickel Institute, 2023](#); [Roy et al., 2025](#)). These differences arise from the gate-to-gate scope of this LCA study, which excludes mining. ENICON017 reports a GWP of 29.5 kg CO₂-eq per kg Ni in NiSO₄·6H₂O, a value 11% lower than the 33.3 kg CO₂-eq reported in [Tijsseling and Whattoff \(2023\)](#) and 20% lower than the 36.8 kg CO₂-eq in the hydrometallurgical case of the [Nickel Institute \(2023\)](#). The ENICON017 value also is 36% lower than the 46.82 kg CO₂-eq footprint reported by [Tijsseling, and Whattoff, \(2023\)](#). Acidification potential in this LCA study (0.814 kg SO₂-eq) remains 16% higher than the 0.687 kg SO₂-eq in [The Metals Company \(2023\)](#), while the eutrophication potential (0.006 kg PO₄-eq) remains 25% lower



than the 0.008 kg PO₄-eq reported in the [Nickel Institute \(2023\)](#). The land-use value of ENICON017 (18.7 m²·a) is significantly lower (60%) than the 46.82 m² obtained in [The Metals Company \(2023\)](#). In terms of CED, ENICON017 also remains slightly lower (~1%) than the 305 MJ reported by the [Nickel Institute \(2023\)](#). Overall, the LCA results obtained for the limonitic laterite (ENICON017) route using the novel HCl-based process indicate a favourable process-stage profile but full comparability with previous limited available literature requires alignment of system boundaries.

Contribution analysis: The contribution analysis for the GWP impact category for the major processing stages (HCl leaching, purification, re-leaching and refining) shows that the production of 1 kg of Ni in NSH (FU) from limonitic laterite is dominated by the early hydrometallurgical stages (**Figure 16**). In this context, the HCl leaching stage which accounts for 31% of total GWP followed by the purification stage (28%) The notable share of the HCl leaching stage arises from the large consumption of hydrochloric acid (10.79 kg per FU) and the associated electricity requirements (10% of total electricity demand) linked to the treatment of low-grade limonite ore and the management of the obtained tailings after leaching. The contribution (28%) of the purification stage (SX, hydrolytic distillation, Fe removal and MHP precipitation) to the total GWP impact results from steam use for hydrolytic distillation (50.56 kg per FU), the demand for organic extractants (Cyanex 272, Cyanex 301, TBP, kerosene), and the substantial requirement for hydrated lime (4.65 kg per FU) and natural gas (5.74 kg per FU). The re-leaching stage accounts for 15% of the total GWP, driven by upstream emissions from sulphuric acid and electricity use in dissolving the MHP intermediate. The refining stage, which involves impurity removal, Ni/Co separation and crystallization, accounts for 26% of total GWP. This contribution reflects the large electricity load of the NSH evaporation–crystallisation circuit, equal to 69% of total electricity consumption at the plant. Overall, the leaching and purification stages account for 59% of total GWP and form the key hotspots for GHG reduction in the limonite-based route.

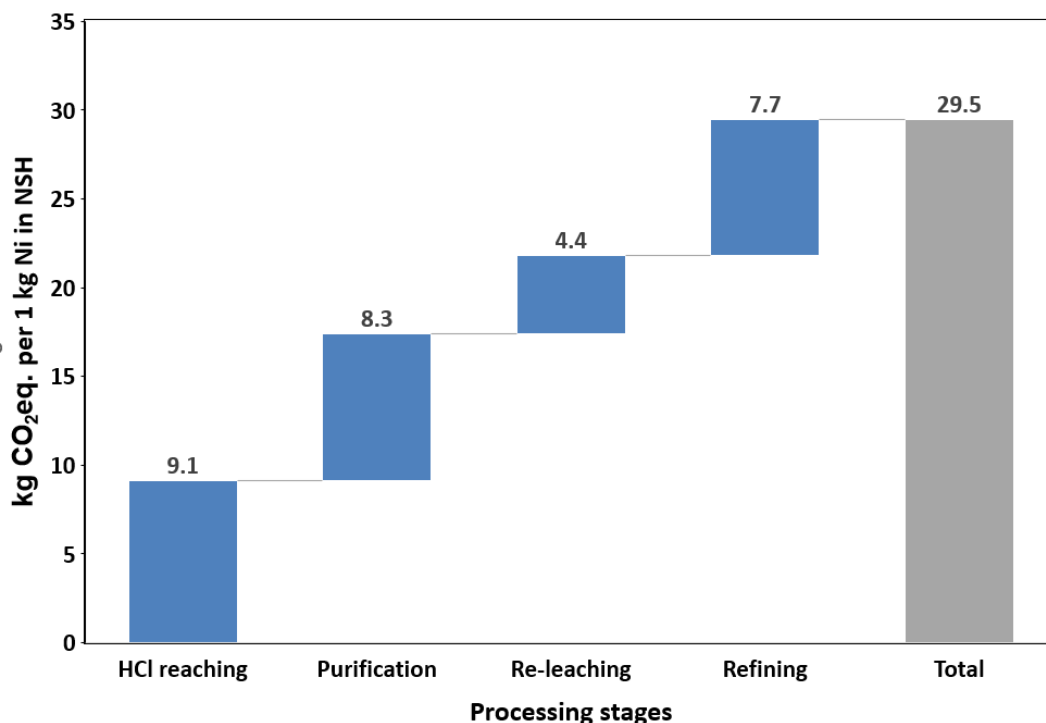


Figure 16. Contribution of major processing stages to the total GWP for the production of 1 kg of Ni in NSH via the novel HCl-based route for limonitic laterite (ENICON017)



In contrast to ferronickel, a more detailed contribution analysis by input material for the production of 1 kg of nickel in NSH via the novel HCl-based route for limonitic laterite (ENICON017) shows that chemical inputs dominate the total GWP with hydrochloric acid, hydrated lime and sulphuric acid contributing for 42%, for 13% and for 3%, respectively. Organic extractants, magnesia, water and other minor reagents account for less than 5% of the total. The second largest share is attributed to the energy inputs, with natural gas and steam supply together account for about 20% of total GWP. Electricity use (25.9 kWh per FU), based on the Finnish medium-voltage grid factor (0.199 kg CO₂ per kWh), accounts for 17%. In summary, energy-related emissions account for about 37% of total GWP, while chemical inputs account for about 63%.

Scope analysis: The scope analysis for the GWP impact category related to NSH production from limonitic laterite (ENICON017 via the novel HCl-based HCl route) is shown in **Figure 17**. Scope 1 emissions account for approximately 22% of the total CO₂-eq per kilogram of nickel in NiSO₄·6H₂O and arise from on-site natural-gas use for process heat together with emissions from the on-site sulphuric-acid plant. Scope 2 emissions account for about 36% of total GWP and result from the use of purchased electricity and externally supplied steam required in the leaching, purification and refining stages. Scope 3 emissions represent the remaining 42% and originate from upstream production of hydrochloric acid, hydrated lime, organic extractants and other auxiliary inputs used in the limonite-based HCl route.

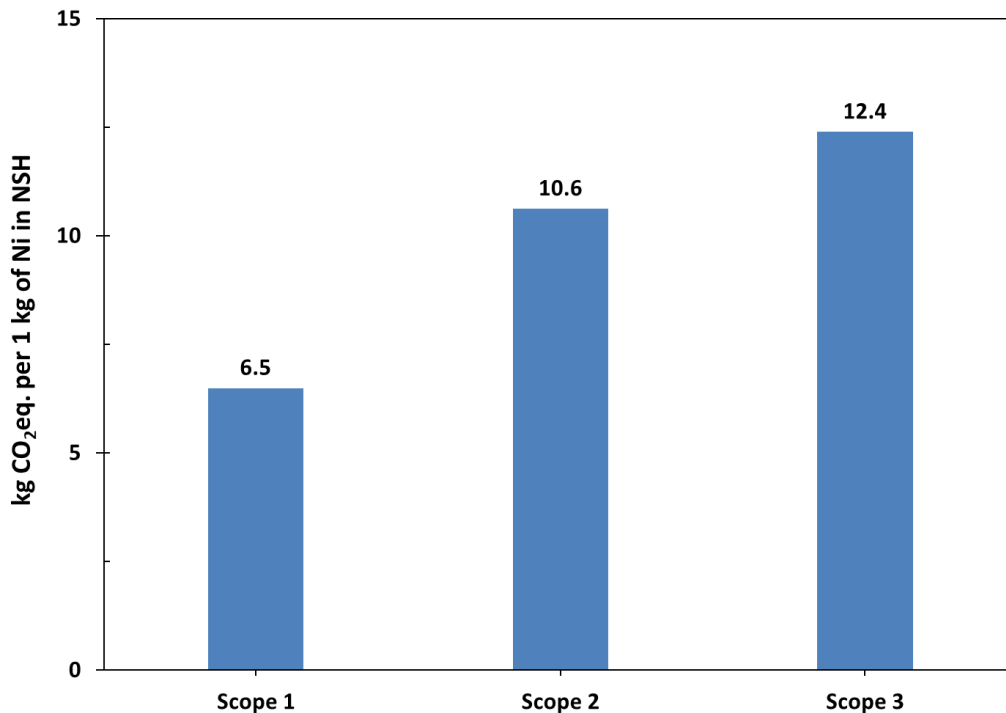


Figure 17. Scope analysis of GWP for the production of 1 kg of Ni in NSH via the novel HCl-based HCl route for limonitic laterite (ENICON017)

Overall, the LCA results show that the most effective decarbonisation measures lie in a reduction of process heat and steam demand and in a decrease of the carbon intensity of upstream chemical supply chains.



7.3 Carbon neutral smelting/convertng for Ni/Co-sulphide concentrates

The environmental performance of the smelting/convertng process for Ni/Co-sulphide concentrates, based on hydrogen reduction (H₂, 20 vol%) under laboratory test conditions (IR2.1 Hydrogen Report), was assessed using a gate-to-gate LCA approach. In this study, the existing FSF–EF operation for processing 373 ktpa of nickel concentrate (12% Ni) and producing approximately 89 ktpa of nickel matte and 296 ktpa of cleaned waste slag is considered. **Table 14** presents the LCA results of the carbon-neutral smelting/convertng process for Ni/Co-sulphide concentrates in the FSF–EF route, expressed per functional unit of 1 tonne of cleaned slag produced using hydrogen as the reductant. On total, 15 impact categories are according to the LCA methodology followed in ENICON (see 5.1.2), are evaluated

Table 14. LCIA results of the carbon-neutral smelting/convertng process for Ni/Co-sulphide concentrates in the FSF–EF route per FU

Impact Category	Value
Acidification potential (AP) [kg SO ₂ -eq·FU ⁻¹]	0.638
Eutrophication potential (EP) [kg PO ₄ -eq·FU ⁻¹]	0.059
Global warming potential (GWP) (100 years) [kg CO ₂ -eq·FU ⁻¹]	146
Ozone layer depletion potential (ODP) [g CFC-11-eq·FU ⁻¹]	2.8E-03
Photochemical ozone creation potential (POCP) [kg C ₂ H ₄ -eq·FU ⁻¹]	0.009
Terrestrial ecotoxicity potential (TETP) [kg DCB-eq·FU ⁻¹]	3.09
Climate change land use and land use change [kg CO ₂ -eq·FU ⁻¹]	13.8
Climate change, fossil [kg CO ₂ -eq]	0.32
Abiotic depletion, elements (ADP) [kg Sb-eq·FU ⁻¹]	5.26E-05
Metal depletion (MD) [kg Cu-eq·FU ⁻¹]	2.36
Fossil depletion (FD) [kg oil-eq·FU ⁻¹]	3.23
Fine particulate matter formation (FPMF) [kg PM _{2.5} -eq·FU ⁻¹]	0.45
Freshwater consumption (FWC) [m ³ ·FU ⁻¹]	0.65
Land use (LU) [m ² a crop eq·FU ⁻¹]	1.2
Cumulative energy demand (CED) [MJ·FU ⁻¹]	2768

FU= 1 t of cleaned slag in the EF/SCF exit

Contribution analysis: A detailed contribution analysis was carried out to identify the main sources of GWP in the hydrogen-based FSF–EF smelting route for Ni/Co-sulphide concentrates. The total impact amounts to 146 kg CO₂-eq per tonne of cleaned slag, and the FSF emerges as the dominant contributor. Approximately 72% of total GWP arises from the FSF. The largest single source is fuel-oil combustion in the FSF, which releases 73.5 kg CO₂-eq, equal to 50% of the total burden. The demand for technical oxygen in the FSF also adds a substantial share through electricity use in the air-separation unit; this requirement results in 30 kg CO₂-eq, or 21% of the overall impact. Minor contributions (less than 2%) arise from FSF off-gas handling and thermal losses. The Electric Furnace for slag cleaning accounts for the remaining 28% of GWP. Approximately



14% (around 20 kg CO₂-eq) originates from EF electricity demand, while 16% (around 23–24 kg CO₂-eq) originates from upstream hydrogen production supplied at 20 vol%. Electrode-paste use and EF off-gas release contribute less than 1%.

Scope analysis: In scope terms, Scope 1 direct emissions account for 50%, Scope 2 electricity use accounts for 34%, and Scope 3 upstream processes account for 16% of the total GWP. These results indicate that major reductions in GWP require lower fossil-fuel use in the FSF and a cleaner electricity supply for both furnaces.

7.4 Alkali activation of FeNi slag (ENICON021)

7.4.1 Production of Alkali Activated Materials (AAMs) from FeNi slag

The environmental performance of AAM production, based on Larco slag and optimized synthesis conditions, was assessed using a gate-to-gate LCA approach. The study considered two functional units: (i) 1 m³ of alkali-activated mortar and (ii) a single AA block with dimensions of 150 mm × 150 mm × 65 mm and compressive strength exceeding 25 MPa. Based on an annual input of 110,000 tonnes of Larco slag (ENICON 021) on a dry basis, this matrix valorization process can produce approximately 60,440 m³ of AA mortar and about 373 million AA blocks on an annual basis, corresponding to ~547,000 m³ of final product. Based on the methodology described in Section 5.1.2, **Table 15** presents the LCA results for the production of AA mortar and a single AA block using ENICON 021 Larco slag as the primary precursor.

Table 15. LCA results of the alkali-activated mortar production from the ENICON 021 slag per FU

Impact Category*	Construction products	
	1 m ³ AA mortar	Single AA Block
Acidification potential (AP) [kg SO ₂ -eq·FU ⁻¹]	1.08	0.0017
Eutrophication potential (EP) [kg PO ₄ -eq·FU ⁻¹]	0.49	0.00077
Global warming potential (GWP) (100 years) [kg CO ₂ -eq·FU ⁻¹]	286	0.448
Ozone layer depletion potential (ODP) [g CFC-11-eq·FU ⁻¹]	1.26E-06	1.97E-09
Photochemical ozone creation potential (POCP) [kg C ₂ H ₄ -eq·FU ⁻¹]	0.136	0.00021
Terrestrial ecotoxicity potential (TETP) [kg DCB-eq·FU ⁻¹]	1.18	0.0018
Climate change land use and land use change [kg CO ₂ -eq·FU ⁻¹]	0.21	0.00033
Climate change, fossil [kg CO ₂ -eq·FU ⁻¹]	0.00118	1.85E-06
Abiotic depletion, elements (ADP) [kg Sb-eq·FU ⁻¹]	0.0016	2.51E-06
Metal depletion (MD) [kg Cu-eq·FU ⁻¹]	8.95	0.0140
Fossil depletion (FD) [kg oil-eq·FU ⁻¹]	49.25	0.0772
Fine particulate matter formation (FPMF) [kg PM _{2.5} -eq·FU ⁻¹]	0.43	0.00067
Freshwater consumption (FWC) [m ³ ·FU ⁻¹]	1.68	0.0026
Land use (LU) [annual crop eq·FU ⁻¹]	14.98	0.0235
Cumulative energy demand (CED) [MJ·FU ⁻¹]	2458	3.85

*FU= 1 m³ AA mortar and AA block weight 2350 kg and 3683 g, respectively



Table 15 shows that the GWP for 1 m³ of AA mortar amounts to 389 kg CO₂-eq, while for a single AA block, it equals approximately 0.61 kg CO₂-eq, which corresponds to the significantly smaller mass of the individual unit. Similar proportional reductions are observed for all other impact categories, as the single block represents only a small fraction (about 0.16%) of the 1 m³ reference system. The GWP of AA mortars typically ranges between 150 and 500 kg CO₂-eq m⁻³, depending on the type of precursor, activator composition, curing regime, and the adopted system boundaries. Mixes based on industrial by-products such as ground granulated blast furnace slag (GGBS) or fly ash generally exhibit substantially lower carbon footprints than OPC systems because the energy-intensive clinker production stage is avoided. Reported cradle-to-gate GWP values for OPC mortars and concretes usually range from 350 to 900 kg CO₂-eq m⁻³, while AA counterparts demonstrate reductions of 40–80 %, with typical values of 180–400 kg CO₂-eq m⁻³ for slag-based systems (Esparham et al., 2023; Habert et al., 2011; Komkova and Habert, 2023; Oyebisi et al., 2022; Turner and Collins, 2013) The GWP value obtained in this study 286 kg CO₂-eq m⁻³ for the Larco-slag-based AAM, falls within the low to middle range, confirming that the optimized alkali activation process developed under the ENICON has favorable environmental performance.

The CED of 2458 MJ m⁻³ and FD of 49.25 kg oil-eq m⁻³ emerge as the dominant categories in the present LCA study for the 1 m³ AA mortar. Similar values are observed across the literature, though with considerable variation depending on precursor and activator type. Mir et al. (2022) reported substantially higher CED values (8700–11,900 MJ m⁻³) for AAMs derived from recycled brick and ceramic waste, largely due to the intensive production of sodium silicate and sodium hydroxide. In contrast, Gopalakrishna and Dinakar (2025) documented up to 40 % reductions in CED compared with OPC reference systems, demonstrating that optimized activator dosages and precursor reactivity can drastically lower energy use. These comparisons indicate that the energy demand of the present mortar lies within the mid-range of reported values, higher than that of optimized fly-ash systems but substantially lower than CDW-based mixes.

The AP (1.08 kg SO₂-eq m⁻³) and TETP (1.18 kg DCB-eq m⁻³) also represent notable contributors to the total impact. As shown in previous studies, these categories are strongly influenced by the use of alkali activators, particularly NaOH and Na₂SiO₃ (Esparham et al., 2023; Habert et al., 2011; Komkova and Habert, 2023). Mir et al. (2022) reported higher AP values (3.7–4.9 kg SO₂-eq m⁻³) for ceramic-based AAMs, again attributed to the large quantities of activators required. The values obtained for ODP (1.26×10⁻⁶ g CFC-11-eq m⁻³) and ADP (0.0016 kg Sb-eq m⁻³) are negligible, which is consistent with published ODP values reported around 10⁻¹⁰ g CFC-11-eq m⁻³ (Mir et al., 2022). These categories remain consistently low across all alkali-activated systems, regardless of precursor or activator type.

Contribution analysis: The contribution analysis for the GWP impact category for the major processing stages of 1 m³ AA mortar production shows that the total climate burden equals 286 kg CO₂-eq, with most of this value arising from the upstream supply of alkali activators rather than from energy use from the grid mix (**Figure 18**). The processing stage with the highest contribution is the mixing stage, which includes the addition of alkali activators and accounts for 191.6 kg CO₂-eq, corresponding to about 67% of the total GWP. This outcome reflects the dominant influence of sodium silicate and sodium hydroxide supply on the overall footprint. The drying stage contributes 31.5 kg CO₂-eq (11% of the total), while milling adds 25.7 kg CO₂-eq (9%). The curing stage accounts for 22.9 kg CO₂-eq, representing 8% of the overall impact. The combined contribution of paste casting, vibration and demoulding remains comparatively low, at 14.3 kg CO₂-eq, or about 5% of the total. This distribution confirms that the majority of climate impacts arise during the activator-related mixing stage, whereas the thermal and mechanical operations at plant level account for a smaller, yet non-negligible, share of the total GWP.



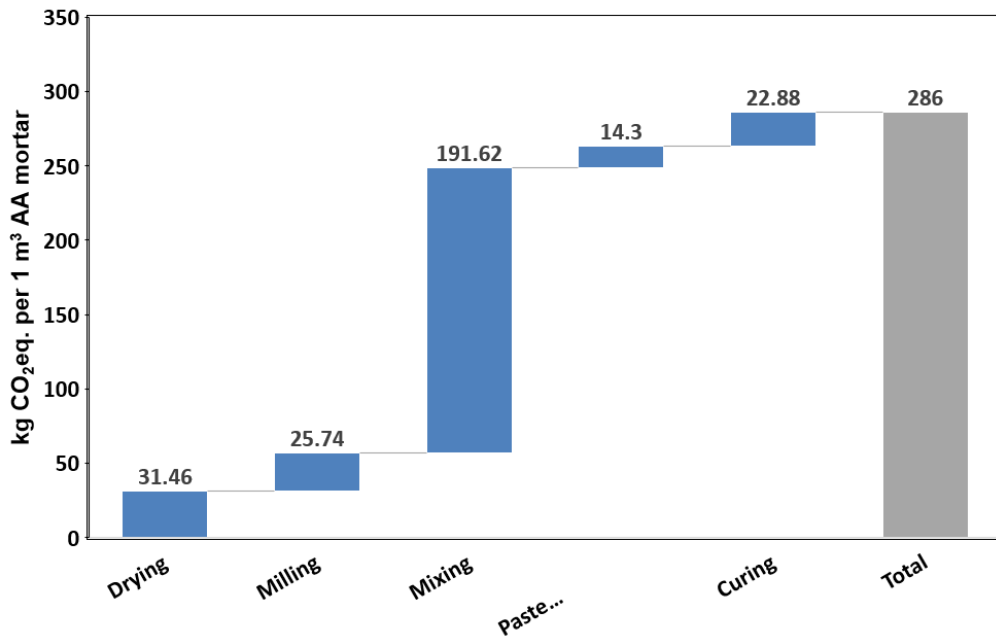


Figure 18. Contribution of each processing stage during the 1 m³ AA mortar production to the total GWP impact category

Scope analysis: The results of the scope analysis conducted in this study in accordance with the GHG Protocol (Scope 1, 2 and 3) for the GWP impact category are presented in **Figure 19**. Scope 1 emissions account for approximately 3% of total GWP, representing the direct on-site emissions associated with material processing operations such as drying and curing.

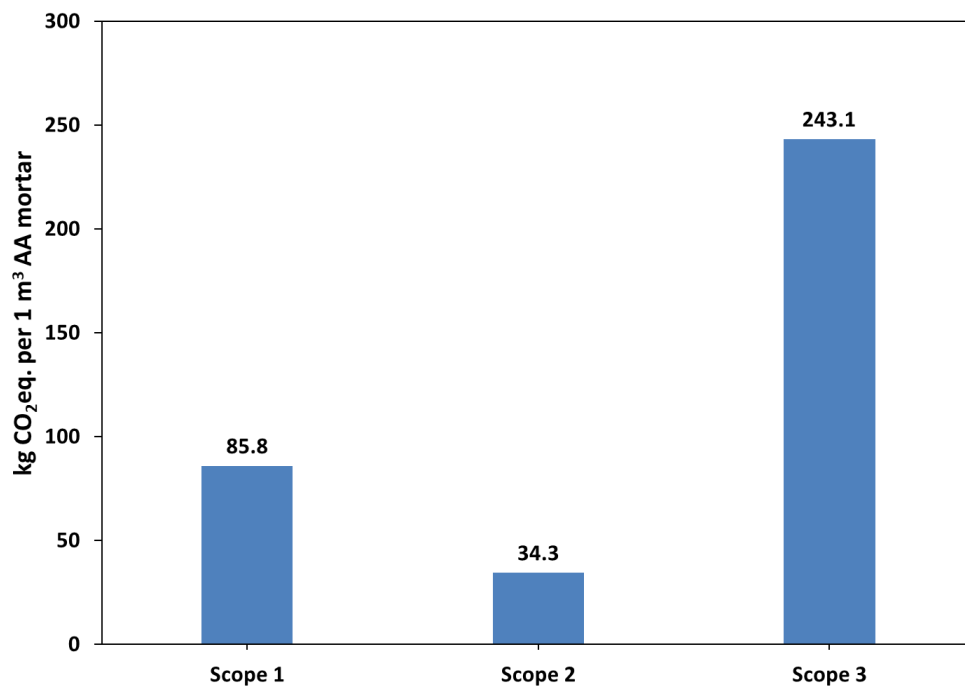


Figure 19. Scope analysis of the 1 m³ AA mortar production for the GWP impact category according to the GHG protocol



Scope 2 emissions account for about 12% and refer to indirect emissions from purchased electricity used for grinding, mixing, and thermal treatment. Scope 3 emissions account for nearly 85% of total GWP, with the largest share due to the upstream production of alkali activators (NaOH and Na₂SiO₃) and all related supply-chain activities. This distribution aligns with previous LCA studies on alkali-activated and geopolymer systems, which identify Scope 3 emissions as the dominant contributor due to the carbon-intensive nature of the production of the activators used (Komkova and Habert, 2023; Mishra et al., 2024; Tang et al., 2021). The latest European-based inventory from Ecoinvent 3.12 reports GWP values for sodium silicate and sodium hydroxide of 0.715 kg CO₂-eq per kg and 0.915 kg CO₂-eq per kg, respectively, with fossil energy requirements equal to 8,200 MJ per tonne for Na₂SiO₃ and 18,300 MJ per tonne for NaOH.

Overall, the LCA results show that, under optimized synthesis and curing conditions, the production of AAMs using Larco slag (ENICON021) has a favorable environmental profile, with performance values expected to compare positively with those of conventional OPC systems once benchmarking is presented (D5.4). The environmental intensity per single AA block remains very low, which demonstrates the potential scalability and practical feasibility of this valorization route for large-scale construction applications.

8 Conclusions

D5.2 presents a comprehensive environmental assessment of both current industrial nickel–cobalt production routes and the innovative processes developed within the ENICON project. Based on the standardized ISO 14040–14044 methodology and the project’s harmonised LCA framework, this report integrates several crucial components including contribution analysis, identification of environmental hotspots, comparative evaluations, scope emissions analysis, and sensitivity analysis. This ensures that all the results obtained within Task 5.1. “Environmental assessment (through LCA)” are methodologically consistent and suitable for benchmarking in the forthcoming D5.4 “Final Report on LCA-TEA Benchmarking against SOTA and Baseline Approaches” that will be submitted at the end of the project. In line with the objectives of ENICON related to WP5, a list with the most important conclusions for each process are given below:

- A full cradle-to-gate LCA was performed for the dominant global reference route: HPAL processing of laterites in Indonesia, followed by MHP refining into battery-grade NSH in China. The assessment incorporates detailed site-specific operational data, reagent production, transport distances, and mass allocation for Ni-Co co-production. Results show that the HPAL operation is the principal contributor to environmental impacts, accounting for approximately 35% of total GWP, followed by the purification stage (25%) and the Chinese refining stage (18%). Scope analysis indicates that Scope 3 emissions dominate the entire route due to the carbon intensity of reagents, electricity mixes, and supply-chain activities. Sensitivity analyses demonstrate that significant reductions are achievable through cleaner electricity mixes or integrated NSH production, while changes in ore grade or reagent substitution have limited influence.
- The ENICON next-generation HCl-based route demonstrates substantial environmental advantages for both ferronickel (ENICON023) and limonitic laterite (ENICON017). For ferronickel, the route delivers a GWP of 9.2 kg CO₂-eq per kg Ni in NSH, equal to a 37% reduction compared with the sulphate-based FeNi leaching process reported in the literature. Contribution analysis assigns 35% of total impacts to the refining stage, mainly due to the high electricity demand of the NSH crystallisation unit. The HCl leaching stage accounts for 31%, the purification stage for 22%, and the re-leaching stage for 12%. Energy inputs represent ~55% of total GWP, while chemical inputs account for the remaining 45%. Scope analysis attributes 46% of emissions to Scope 2, 26% to Scope 1, and 28% to Scope 3. For limonitic laterite (ENICON017), the route results in a GWP of 29.5 kg CO₂-eq per kg Ni, which stands 11–36% lower than published reference values for comparable laterite-



processing routes. The leaching and purification stages dominate the environmental profile, with 31% and 28%, respectively, while re-leaching and refining contribute 15% and 26%. Chemical inputs account for 63% of total GWP, dominated by hydrochloric acid and hydrated lime, while energy-related emissions represent 37%. Scope 1, Scope 2, and Scope 3 emissions account for 22%, 36%, and 42%, respectively, underscoring the influence of upstream reagent production.

- The carbon-neutral smelting route for Ni/Co-sulphide concentrates demonstrates a substantial reduction in GHG emissions when hydrogen substitutes coke in the FSF–EF system. Based on current LCA results, the hydrogen-based route yields a GWP of 146 kg CO₂-eq per tonne of cleaned slag. The contribution analysis assigns 72% of total GWP to the FSF. Fuel-oil use in the FSF releases 73.5 kg CO₂-eq, equal to 50% of total emissions, while oxygen supply adds 30 kg CO₂-eq (21%) because of the electricity demand of air-separation. The EF/SCF accounts for 28%, with 20 kg CO₂-eq (14%) generated through electricity demand and 23–24 kg CO₂-eq (16%) linked to upstream hydrogen production at 20 vol% H₂ content. Scope analysis attributes 50% of total GWP to Scope 1 through on-site fuel-oil combustion, 34% to Scope 2 due to electricity consumption in both furnaces, and 16% to Scope 3, dominated by upstream hydrogen and oxygen production
- The alkali-activation route for FeNi slag (ENICON021) supports ENICON’s near-zero-waste strategy and delivers environmentally and financially competitive construction materials or binders for the replacement of cement in concrete production. The GWP for 1 m³ of alkali-activated mortar equals 286 kg CO₂-eq, with the mixing stage as the dominant source at 191.6 kg CO₂-eq (67%), due to the upstream burdens of sodium silicate and sodium hydroxide. The drying stage adds 31.5 kg CO₂-eq (11%), milling adds 25.7 kg (9%), and curing adds 22.9 kg (8%), while casting and demoulding account for 14.3 kg (5%). Despite the burdens of the activators used, the overall footprint remains favourable, and the achieved compressive strength values above 25 MPa confirm suitability for large-scale construction applications.

Overall, the results confirm that ENICON’s technologies offer significant reductions in GHG emissions, energy use, and resource depletion while enabling residue valorisation and supporting EU climate and circular-economy objectives. These findings provide the environmental evidence base required for final benchmarking in D5.4 and for strategic adoption by industry and policymakers. The results presented here form the basis to justify the anticipated advantages of the Ni/Co processing routes developed and studied in the framework of the ENICON project over the current battery grade Ni/Co production practices. These results will be utilized by several end-users across various sectors and industries including battery manufacturers, mining and metallurgical companies and policy makers.



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