



**Near-zero-waste recycling of low-grade sulphidic
mining waste for critical-metal, mineral and
construction raw-material production in a
circular economy
(NEMO)**

D6.1

**Environmental assessment report of NEMO
processes**



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Executive Summary

The aim of Deliverable 6.1 is to present the environmental analysis of the NEMO pilots developed in WPs 1-5, in order to indicate the factors driving the environmental performances of the processes. The methodology used for the environmental analysis is the Life Cycle Assessment (LCA). The data for each pilot that has been used in the LCA calculation were collected in collaboration with the pilot managers. Based on these data, an inventory table (a list of all inputs and outputs involved) and a flowsheet have been developed for each pilot. The calculation of the environmental impacts is performed using the “Environmental footprint (EF) 3.0”.

The results of the LCA analysis highlighted the main environmental hotspots for each of the analysed pilots. Although such hotspots can vary depending on the pilot under study, most of the calculated environmental impacts are caused by the electricity consumption and the use of sulphuric acid and other chemicals. These results can provide useful information to the pilot managers to develop efficient optimization strategies to decrease the environmental impacts of the processes.

Finally, the report highlights the relevance of integrating the NEMO pilots into a complete valorisation process, from the mining of sulphidic mine residues to metals and inert fraction valorisation. Such an integrated scheme can be indeed benchmarked with current mining operations for the production of equivalent products from primary sources, highlighting the environmental benefits brought by the technologies developed in NEMO. An example of integrating pilot 2 and pilots 4 showed that the environmental benefits from the valorisation of sulphidic mine residues overcome the environmental costs of the valorisation process.

All the results presented in this report should be considered as a starting point for further discussions and developments of efficient strategies, to reduce the overall environmental impacts of the proposed technologies.



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1 Introduction

Deliverable 6.1 presents an environmental assessment for each of the pilots developed within NEMO. The goal of the deliverable is therefore to highlight the elements, in terms of chemicals, materials or energy, driving the environmental performances of the NEMO pilots.

Performing an environmental assessment already at an early stage of process development can indeed increase the understanding of the design choices on the final environmental performances. Such an understanding throughout the first phases of the technology development can prevent environmentally unsound choices, that can threaten the future environmental performances of the technology. Therefore, the environmental analysis performed in this report should not be seen merely as a stand-alone assessment of the environmental performances of the pilots, but rather as a part of the development process itself, to produce useful information that can steer further research effort toward environmentally sound final solutions.

The process of preparation of deliverable 6.1 involved all pilot managers. Thanks to various exchanges (online calls, face-to-face meetings, email exchanges), the relevant process data for each of the pilots have been collected. These raw data collected by pilot managers were then integrated with data reported in several deliverables, previously published by several NEMO partners involved in the pilots' development. Finally, this information was further processed and elaborated at KU Leuven, and they are the basis of the environmental analysis presented in this report.

In the first part of the report (chapter 3), each pilot is analysed as a stand-alone process, to highlight the main drivers affecting the environmental profile of the unit operations. However, all NEMO pilots must be seen as part of the larger near-zero waste strategy proposed by NEMO, taking into account the whole sulphidic mine tailing valorisation, from mining to the production of secondary metals concentrates, secondary aggregates and binder for constructing material. Therefore, the environmental profiles of the pilots, integrated in these terms, can be benchmarked with the environmental profile of current metals concentrates, primary cement and natural aggregates production processes.

At the moment, data for this full integration of NEMO pilots are not available. In light of the above-mentioned importance of pilots' integration, chapter 4 of this report present a preliminary study on the environmental results of the potential integration between pilot 2 and pilots 4. The whole analysis will be carried out in the coming months, in parallel with task 5.3 on the "*Technology integration into zero-waste recycling concept for sulphidic mine tailings*". Final environmental analysis for the integrated pilots' operations will be reported in deliverable D 5.3 or D 5.4, due by month 54 (October 2022).

2 LCA: description of the methodology

The environmental analysis performed in this report is based on the Life Cycle Assessment (LCA) methodology. LCA is a structured, comprehensive and internationally standardised method to quantify all relevant emissions, the resources consumed and the related potential environmental impacts associated with any products or services [1].

As defined by the ISO 14040, the standardised LCA framework consists of four different steps, represented in figure 1: (i) definition of the goal and scope; (ii) life cycle inventory phase; (iii) life cycle impact assessment; (iv) results interpretation.



2.1 Goal and scope

The goal and scope set the context of the LCA study, and it frames the scope defining the system boundaries and the functional unit. The boundaries of the analysed system are “the set of criteria specifying which unit processes are part of a product system” [2]. The functional unit is the quantified description of the analysed product system, and it is used as the quantitative reference to which all inputs and outputs of the product system are calculated.

For the LCA presented in this report, the goal has been already mentioned above, as the identification of the environmental hotspots driving the environmental profile of each of the pilots developed in NEMO. The system boundaries of the study include all inputs of materials and energy, with their production processes. Finally, the functional unit for the study is represented by the treatment of 1t of material for each pilot.

2.2 Inventory

The inventory analysis involves the compilation and quantification of all foregrounds relevant inputs and outputs for the analysed system. For the environmental inventory analysis, inputs are represented by the materials and energy resources used in the project, while outputs account for all emissions and waste production, in addition to final products.

All inputs and outputs used in this report has been collected in cooperation with the pilot managers and integrated with information available in the deliverables previously published within the NEMO project.

2.3 Environmental impact assessment

The environmental Life Cycle Impact Assessment (LCIA) aims to translate the results of the LCI model into different impacts on the environment, expressed in terms of several environmental impact categories. Many different LCIA methodologies are available in the literature to calculate the environmental impact categories. In particular, the so-called “midpoint categories” focus on the direct causal relation between an elementary flow and its direct consequence in terms of impact on the environment, such as global warming, terrestrial and marine acidification, and water use.

To quantify the contribution of the elementary flows from the LCI model into midpoint environmental impact categories, each elementary flow E (e.g. emission of CO₂ into the air) is multiplied by its respective characterisation factors CFs . The CFs quantify the contribution of an elementary flow to a specific impact category (e.g. how the CO₂ emissions contribute to global warming). The contribution of all elementary flows to a specific impact category IC are then summed up resulting in an impact score IS , which determines the result for the environmental impact category:

$$IS_{IC} = \sum_i(CF_i \cdot E_i)$$

Environmental Footprint 3.0 (EF 3.0) is selected as the characterisation model for the calculation [3,4]. The characterisation model contains all the CF for each category, allowing the calculation of the IS of each flow on each category. The model has been implemented in the software OpenLCA v. 1.10.3, using Ecoinvent 3.7 as a database to calculate the environmental impacts of the background processes.

2.4 Results interpretation

The results of the study are interpreted to answer the question(s) posed as part of the goal. The interpretation considers both results of the inventory analysis and the impact assessment elements characterisation and, possibly, normalisation and weighting. The interpretation must be done with the goal



and scope definition in mind and respect the restrictions that the scoping choices impose on a meaningful interpretation of the results, e.g. due to geographical, temporal or technological assumptions [5].

For this report, the results of 16 environmental midpoint categories are presented. Each category (derived from the EF 3.0 methodology) is measured in a different unit. Consequently, in order to put the results for all categories in the same graph, the results are normalised to the total impact for each category. The contribution of the different elements (electricity, chemicals, waste treatment) will be expressed in terms of % contribution to the total impact.

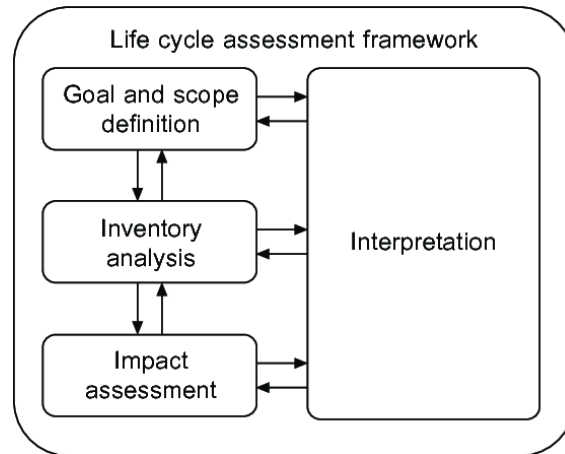


Figure 1: The LCA framework



3 Detailed LCA for each pilot

3.1 Pilot 1a: Enhanced bioleaching operations

The goal of pilot 1a is to enhance the current heap bioleaching operation in Sotkamo through improved kinetics and metals recovery. The leaching process is tested with different types of nutritive solution, under several bioleaching conditions (aeration, pH, etc.).

The primary input material is the sulphidic low-grade heap ore from the secondary heap feed of the Sotkamo mine. The solution is scattered from the top of the heap, and it is progressively enriched with metals while it goes through the heap. The heap is aerated to ensure the ideal conditions for bioleaching. The leachate (the PLS) is collected by a drainage system at the base of the heap and fed to the pond near the irrigation pumping inlet. A simplified flowsheet of pilot 1a is represented in figure 2, while a more detailed description of the pilot can be found in deliverable 1.1.

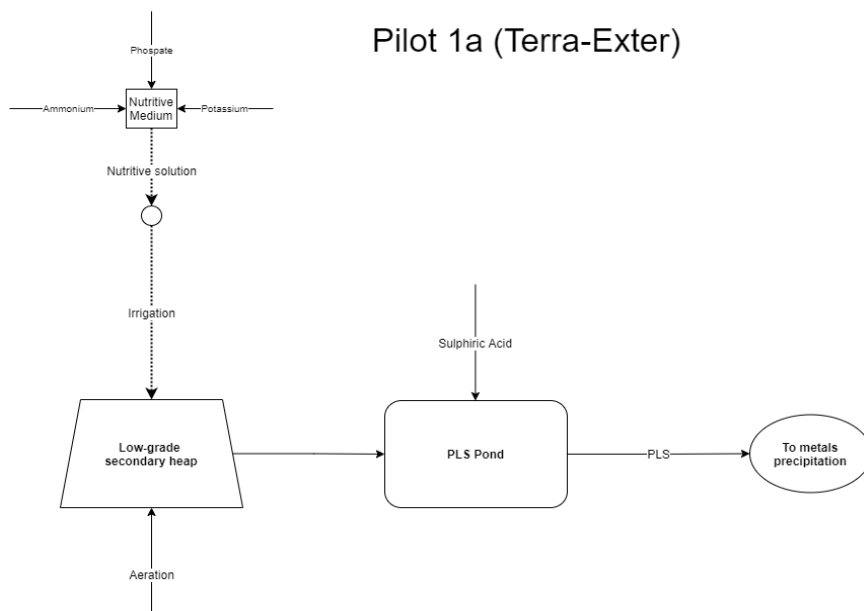


Figure 2: Flowsheet pilot 1a

3.1.1 Pilot 1a: Inventory analysis

The data used in the LCA inventory are collected from one of the last experiments performed by Exeter in February 2022. The inventory analysis for pilot 1a is reported in table 1.

Table 1: inventory table pilot 1a

Pilot 1a- lab test		Upscaling to the treatment of 1 t primary heap residue	
Secondary heap			
Input		1	t
Nutritive solution	0.09 m ³ /t/day	90	1
Ammonium	49.15 mg/l		
via (NH ₄)SO ₄	0.18 g/l	16.2	g



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Phosphate	62.81	mg/l		
Potassium	51.72	mg/l		
	<i>via KH₂PO₄</i>	0.09	g/l	8.1 g
Water	0.09	m ³ /t/day	90	l
Aeration	80	l/t _{ore} /h	80	l/h
Electricity	0.055	kWh/kg	55	kWh
PLS pond				
Sulphuric acid	68.4	kg/t _{ore}	68.4	kg

3.1.2 Pilot 1a: Environmental results

The environmental results for pilot 1a are presented in figure 3. It can be seen how the main contribution to the environmental impact for all categories is shared between the production of electricity and the production of sulphuric acid. More specifically, sulphuric acid production contributes >80% for most of the categories, while electricity production contributes >40% only in the categories of resource use-energy, land use, and ionizing radiation. All other chemicals do not significantly contribute to the final environmental impact, also considering the significantly lower amount required (on the scale of grams, while the requirement of sulphuric acid is at the scale of kilograms).

3.1.3 Pilot 1a: Environmental: Conclusions

The environmental analysis of pilot 1a clearly highlights the major environmental hotspots driving the environmental profile of the process, namely the production of electricity and the production of sulphuric

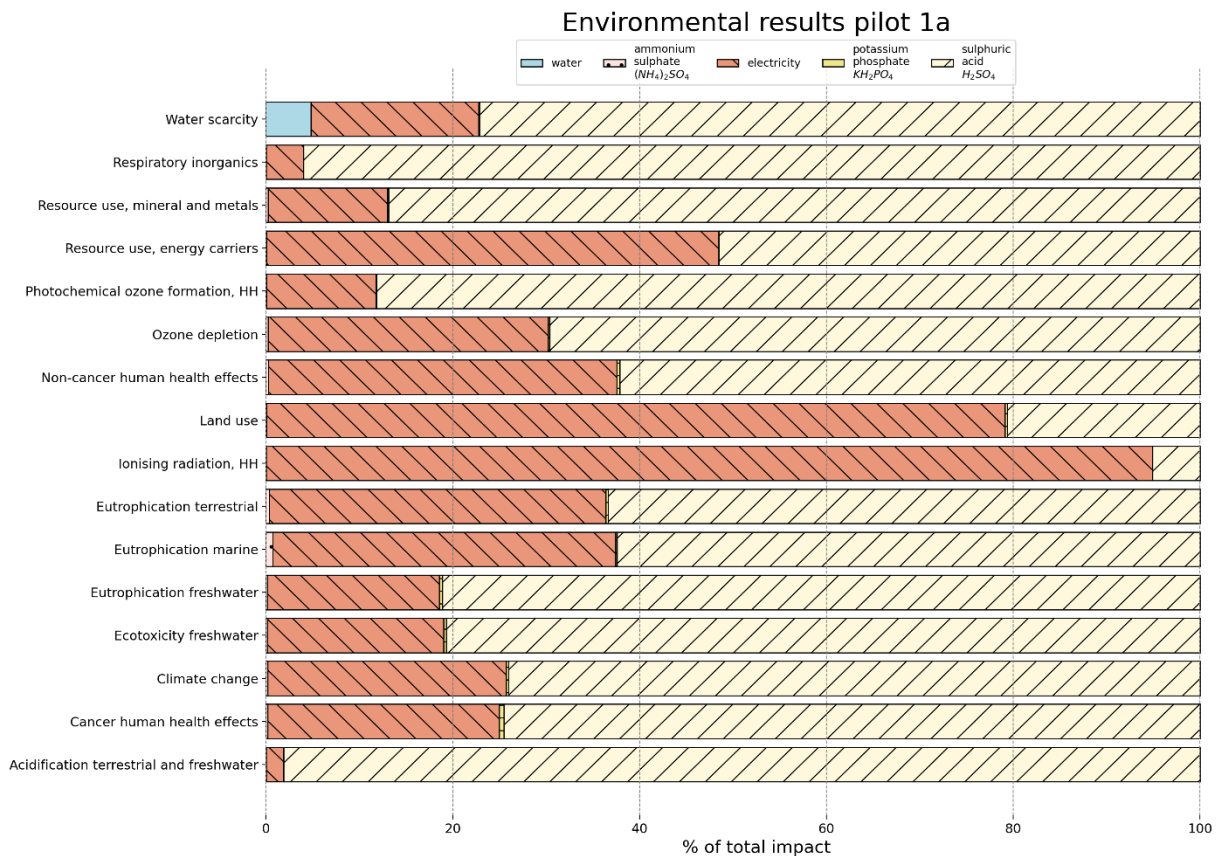


Figure 3: LCA results pilot 1a



acid. From the mass balance, it can be noticed the low concentrations of nutritive elements required by the process. Therefore, further comparison with the current secondary heap leaching process in Sotkamo can be valuable to put the presented environmental results into a wider perspective. Moreover, it could be useful to compare the current metals recovery rate with the recovery rate that can be achieved through pilot 1a operations. A more thorough discussion about future analysis on potential integration between pilots is presented in chapter 4 of this deliverable.

3.2 Pilot 1b: Bioleaching pond

The goal of pilot 1b is to develop and optimize bioleaching operations using the “bioleaching pond” option. The “bioleaching pond” concept has been developed as an in-between pathway compared to conventional heap or stirred tank leaching. This technology enables to perform bioleaching developed as an in-between pathway, compared to conventional heap or stirred tank leaching. It consists in using floating agitators to inject gases as well as to suspend solids in the solution. This technology enables to perform bioleaching (1) in ponds instead of costly tanks, (2) at higher solid load than in conventional stirred tank bioreactor."

The optimization activities performed in BRGM followed a progressive upscaling from lab-scale operation in a 2L stirred tank reactor (STR) in batch mode, up to pilot scale in 20-100L continuous stirred tank reactor (CSTR). The objective of the optimization was to select the optimal microbial consortium and operating conditions for further demonstration of the bioleaching process.

The experiments were performed using primary leaching residue from Terrafame mine in Sotkamo. This residue is currently feeding the secondary bioleaching heap in Sotkamo. Therefore, pilot 1b is proposed as an alternative option to the current secondary bioleaching heap and the operations proposed in pilot 1a.

A simplified flowsheet of the operations proposed in pilot 1b is represented in figure 4.. All reactors are equipped with aeration systems and automatically controlled pumping systems for feeding.

More detailed information on pilot 1b can be found in deliverable D1.3.



Pilot 1b (BRGM)

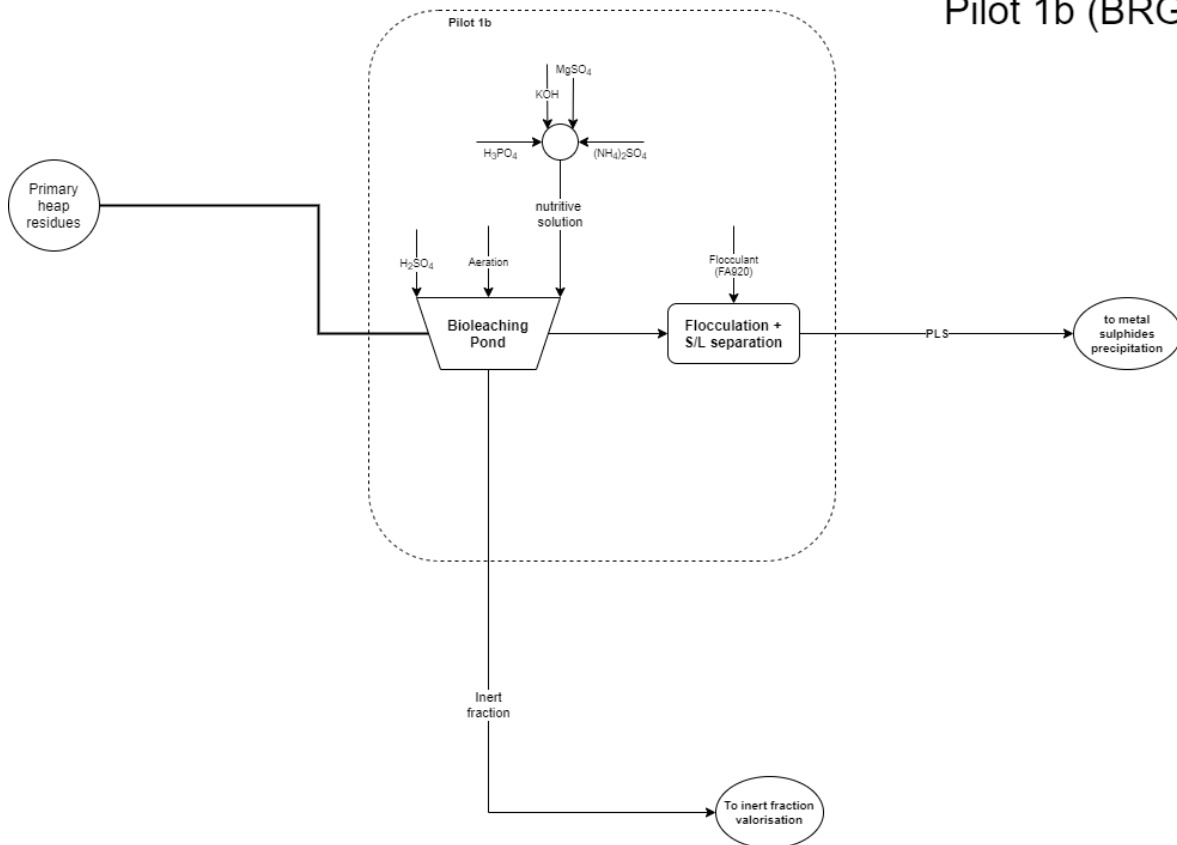


Figure 4: flowsheet pilot 1b

3.2.1 Pilot 1b: LCA inventory

Raw data for pilot 1b have been collected by BRGM during experiments campaigns and communicated to KU Leuven for further elaboration. Based on the raw data received from the experiments, KU Leuven has calculated the consumptions (in terms of materials and energy) of pilot 1b for the treatment of 1 tonne per hour of primary heap residue. The calculation is carried out by mathematically upscaling the raw data (based on a lab and pilot-scale) to the treatment of 1 t/h primary heap residue, and the inventory list of all materials and energy consumptions needed in the operation of pilot 1b is reported in table 2.

Table 2: Inventory table pilot 1b

Fixed Parameters		
Residence time	11	days
Total content in pulp	30%	w/w
Pulp density	1,16	t/m ³
Pond total volume	759	m ³
surface	126	m ²
lateral surface	270	m ²
Variable parameters		
Primary bioleaching residue	1	t/h
Total flow	3	t/h
Volumetric flow	3	m ³ /h
number of ponds	1	
Input		



<i>Nutrients</i>		
Phosphoric acid (H ₃ PO ₄)	0.8	kg/h
Potassium hydroxide (KOH)	0.6	kg/h
Ammonium sulphate (NH ₄) ₂ SO ₄	4.3	kg/h
Magnesium sulphate (MgSO ₄)	0.6	kg/h
Sulphuric acid (H ₂ SO ₄)	43	kg/h
Water	26	t/h
Flocculant	0,4	kg/h
<i>Agitation</i>		
Electricity demand	758	kW
<i>Aeration</i>		
Electricity demand	0,99	kW

As it can be seen from the inventory list, the electricity demand for pilot 1b can be divided into two different requirements: electricity demand for agitation and electricity demand for the aeration. Because no value was available from the raw data, both electricity demands have been calculated based on several parameters, provided by BRGM.

Table 3: Pilot 1b; electricity demand calculation parameters

<i>Agitation</i>		
Agitator influence surface	144	m ²
Agitator influence height	6	m
Agitator capacity	864	m ³
N° agitators (per pond)	1	
agitation power	1	kW/m ³
Total electricity demand	758	kWh
<i>Aeration</i>		
O ₂ consumption	0,054	kgO ₂ /kg ore
O ₂ consumed	0,054	t/h
O ₂	21%	% (vol)
O ₂ transfer efficiency	35%	%
Air flow	514	Nm ³ /h
Theoretical electricity demand	0,86	kW
Efficiency	0,87	
Real electricity demand	0,99	kW

The electricity demand for agitation is calculated through the following equations:

$$[1] \quad \text{Agitator capacity} = (\text{surface influence}) \cdot (\text{height influence}) = 144 [m^2] \cdot 6[m] = 864 [m^3]$$

$$[2] \quad n^{\circ} \text{ agitators} = \frac{\text{Pond total volume}}{\text{agitator capacity}} = \frac{759[m^3]}{864[m^3]} = 0.87 \approx 1 \text{ agitator}$$

$$[3] \quad \text{Electricity demand} = \text{Pond total volume} \cdot \text{agitator power} = 759 [m^3] \cdot 1 \left[\frac{kWh}{m^3} \right] = 759 kWh$$



3.2.2 Pilot 1b: Environmental results

The results of the environmental analysis for pilot 1b are shown in figure 5. The contribution of each element in the figure (chemicals, electricity) is normalized as a % of the total impact for each category.

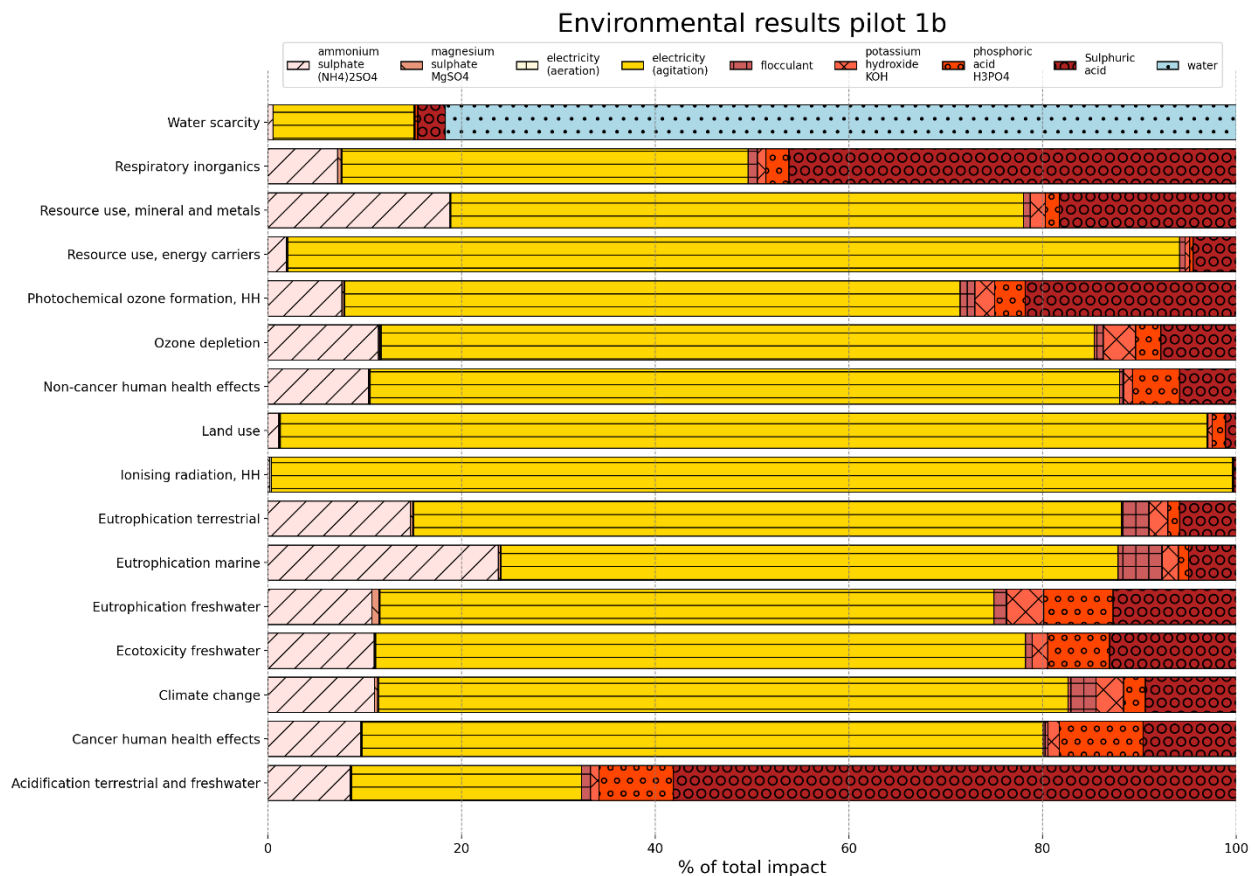


Figure 5: LCA results pilot 1b

Figure 5 highlights the main contribution to the environmental impacts for most categories as the electricity consumption for agitation. It is important to highlight that, because of the low solid inflow assumed for the study (only 1 t/h) the system is over-sized compared to the real needs for agitation. The agitation capacity for one single agitator is about 846 m³, whereas the volume of the pond needed to treat a inflow of 1 t/h is only 759 m³. This may lead to an overestimation of the energy needed for the agitation, and the final need of the electricity for agitation in a bigger scale can be significantly reduced.

For the categories “resource use, energy”, “land use”, and “ionising radiation” the contribution of electricity for agitation is >90%. Only for the categories “water scarcity” and “acidification” the contribution of electricity is <25%. Other relevant contributions to the final impacts of many categories are given by the production of sulphuric acid and ammonium sulphate. A less relevant contribution is given by the production of potassium hydroxide and phosphoric acid. Also, these calculations do not consider potential recirculation of nutrients as well as acid from other process steps, which may also lead to overestimation of their consumption. Finally, for the category water scarcity, water consumption represents, obviously, the highest contribution.



3.2.3 Pilot 1b: conclusions

From the results in figure 5, it can be concluded that some optimisation steps can be undertaken to increase the environmental performances of pilot 1b. First of all, further optimisation in the agitation process can lead to significant improvement in the final environmental balance for the whole process. Because the efficiency of the agitation depends on the surface and the total volume of the pond, it is reasonable to assume that the development at an industrial scale will increase the efficacy of agitation and reduce the relative consumption per tonne of treated residue. Concerning the use of chemicals, future optimisation steps should focus on the consumption of sulphuric acid and ammonium sulphate.

3.3 Pilot 2: Bioleaching + sulphide precipitation

Pilot 2 is located at the Boliden's pilot facilities in Boliden, Sweden, and it treats samples from the Kylahti mine in Finland. The treated samples are residual sulphides produced after the extraction of Au, Cu, Co-Ni concentrates from the original ore. The residual sulphides (named afterword sulphur concentrate) is currently stockpiled, but it contains varying amount of Co, Ni, Cu, Zn that can be recovered.

Operations in pilot 2 are divided into several process steps, as shown in figure 6.

Sulphidic residues are first milled to achieve grain size $> 20\mu\text{m}$ and then sent to the bioleaching reactor, whose goal is to extract the valuable metals from the sulphidic residues by using mesophilic bacteria. Water and oxygen are constantly added to the process through pumps, and the addition of limestone (CaCO_3) keeps the pH around 1.3.

Following the bioleaching reactor, a series of other processes (Fe-removal, solution concentrating, sulphide precipitation) are performed to concentrate the valuable elements and to precipitate them from the PLS in the form of sulphide concentrates. All post-bioleaching processes are based on precipitation, which is a

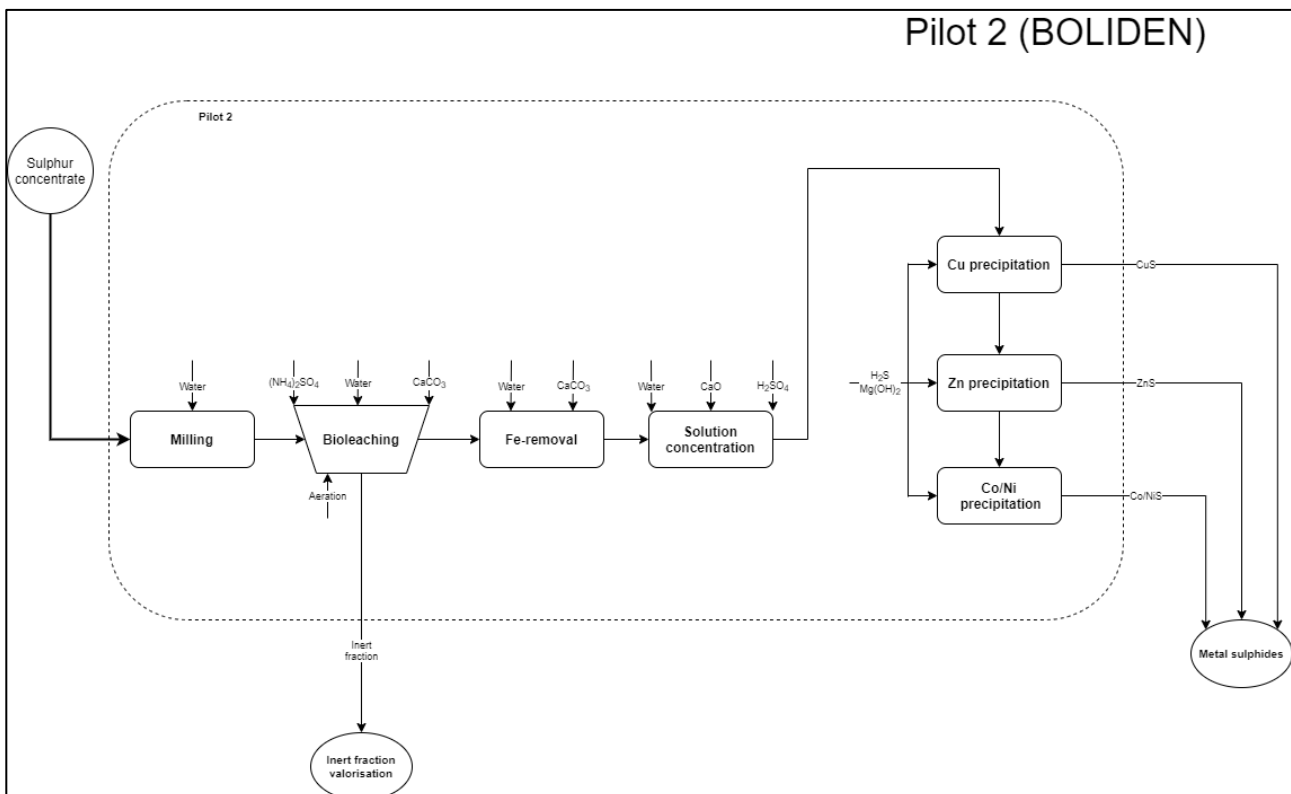


Figure 6: flowsheet pilot 2



physical-chemical process in which soluble metals and inorganics are converted to relatively insoluble metals and inorganic salts by the addition of precipitating agents, such as alkaline reagents that raise the pH and lower the solubility of the dissolved elements [6]. More specifically, Fe-removal precipitates the remaining Fe-ions in the form of iron hydroxides, while the goal of the solution concentrating reactors is to hydrate and concentrate the valuable metals in the form of hydroxides. In the last step of the process, a series of sulphide precipitation reactors precipitates the metal sulphides via the reaction of the dissolved metals with hydrogen sulphide (H₂S) in solution.

A more detailed description of pilot 2 can be found in deliverable D 2.4.

3.3.1 Pilot 2: LCA inventory

The inventory list for pilot 2b has been compiled at the end of a data-sharing process between Boliden and KU Leuven, based on several face-to-face meetings, online calls, emails exchange. The collected data are based on a pilot test campaign performed at Boliden facilities, for the treatment of ≈70 kg of sulphur concentrate. The data analysis included also the calculation of all internal flows that are recycled, and the calculation of water needs and chemicals concentrations. For concision, all these calculations are not reported in this deliverable, and table 4 only reports the final list of inputs and outputs of pilot 2 operations. All quantities have been mathematically upscaled to the treatment of 1-tonne sulphur concentrate.

The inventory list for pilot 2 is shown in table 4.

Table 4: inventory table pilot 2

	Test (70 kg input)	Upscale (1 tonne input)
Milling		
<i>Input</i>		
Sulphur concentrate	70 kg	1000 kg
Water	70 kg	1000 kg
Electricity	11.9 kWh	170 kWh
Bioleaching		
<i>Input</i>		
Electricity	38.4 kWh	549.1 kWh
Water	326.7 kg	4666.7 kg
Calcium carbonate (CaCO ₃)	2.8 kg	40 kg
Ammonium sulphate ((NH ₄) ₂ SO ₄)	1.19 kg	17 kg
<i>Waste</i>		
Leach residue (to landfill)	35.7 kg	510 kg
CO ₂ (air emission)	1.4 kg	20 kg
Fe-removal		
<i>Input</i>		
Calcium carbonate (CaCO ₃)	46.5 kg	664.7 kg
Water	717 kg	10 237.09 kg
Electricity	3.85 kWh	55 kWh
<i>Waste</i>		
CO ₂ (air emission)	20.3 kg	290 kg
Fe-Hydroxide residue (to landfill)	120.8 kg	1 727 kg



Solution concentrating		
<i>Input</i>		
CaO	1.4 kg	20 kg
Water	114.1 kg	1 630 kg
Sulphuric acid (H ₂ SO ₄)	2.1 kg	30 kg
Electricity	2.03 kWh	29 kWh
<i>Output</i>		
Gypsum residues (to landfill)	1.4 kg	20 kg
Sulphide precipitation		
<i>Input</i>		
Hydrogen sulphide (H ₂ S)	2.1 kg	30 kg
Magnesium hydroxide (Mg(OH) ₂)	1.1 kg	17 kg
CaO	2.1 kg	30 kg
Electricity	1.4 kWh	20 kWh
<i>Product</i>		
CuS	0.21 kg	3 kg
ZnS	0.7 kg	10 kg
CoS/NiS (100%)	1.05 kg	15 kg
CoS (63%)	0.66 kg	9.45 kg
<i>of which Co(65%)</i>	0.42 kg	6.14 kg
NiS (37%)	0.38 kg	5.55 kg
<i>of which Ni(64%)</i>	0.24 kg	3.55 kg
<i>Waste</i>		
Gypsum residues (to landfill)	8.4 kg	120 kg



3.3.2 Pilot 2: Environmental results

The results for the environmental analysis of pilot 2 are reported in figure 7.

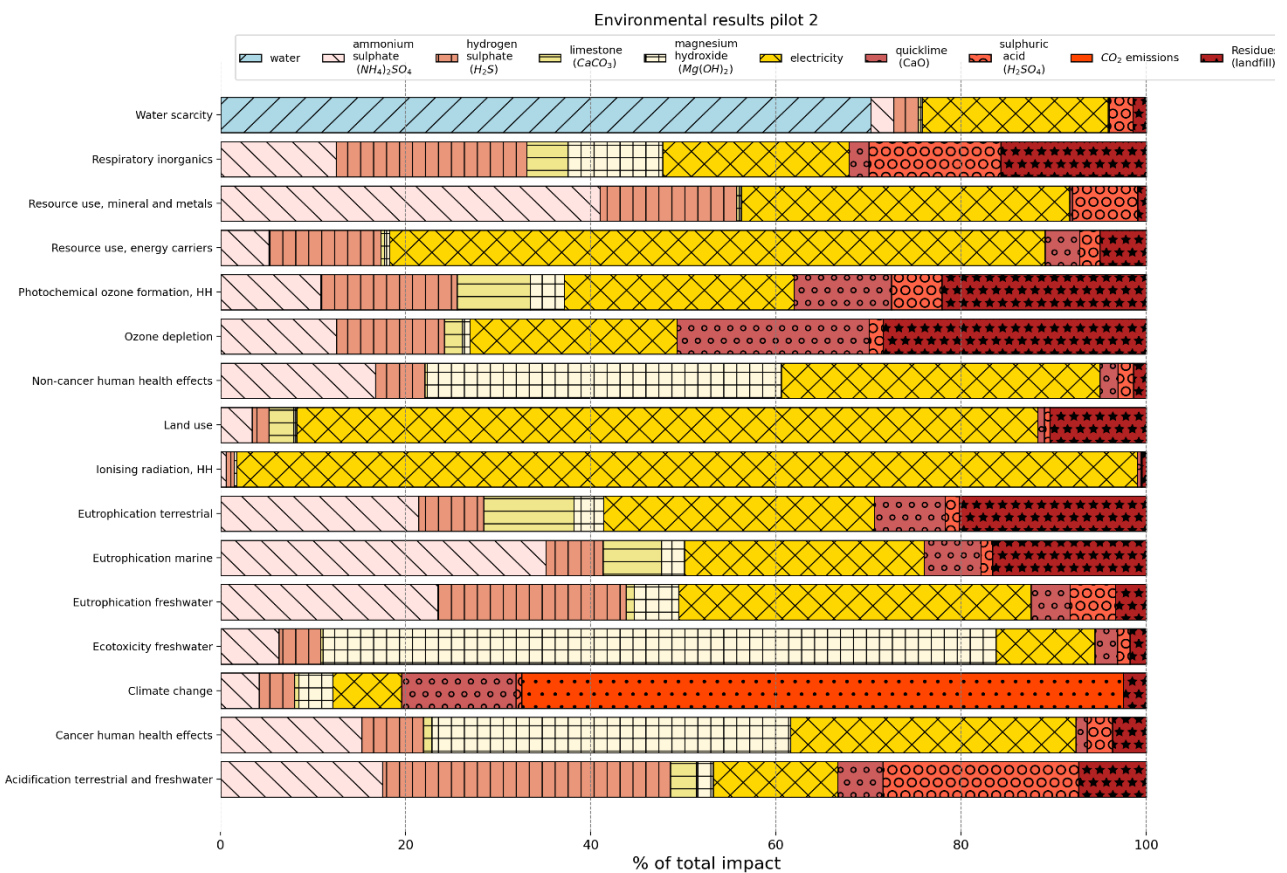


Figure 7: LCA results pilot 2

For some of the analysed categories, the environmental results for pilot 2 are similar to the ones already obtained for pilot 1b. The production of electricity has the highest contribution to many categories, especially resource use – energy, land use and ionizing radiation. For the category climate change, the main contribution (>60%) is given by the CO₂ emissions directly occurring at the plant site. For the category ecotoxicity freshwater, the main impact is represented by the production of magnesium hydroxide (>70%), while for the category water scarcity, the use of freshwater (from rivers) contributed to 70%. For all other categories, the results are more scattered, because the contribution to the final impact is shared between chemicals production, electricity and waste treatment.

3.3.3 Pilot 2: conclusions

From the environmental analysis of pilot 2, it is not easy to assess a straightforward strategy for optimization of the environmental profile, because the contributions of the different elements (chemicals, electricity, waste treatment) can significantly vary depending on the environmental category. This means that the best action to reduce the environmental impact of pilot 2 strongly depends on the environmental category. On the other hand, such a scattered result provides useful insights to the process developers, and it allows to adapt the optimisation actions depending on the environmental aspect to be improved.



3.4 Pilot 3a: Improved sulphide precipitation

Pilot 3a demonstrates the sulphide precipitation of Ni, Co, and Zn from multi-metals solutions from bioleaching processes. Pilot 3a is designed to treat the current bioheap leaching solution from Sotkamo, enhancing the current precipitation process at the Sotkamo mine. Also, in the future integration plan of NEMO, pilot 3a is designed to treat leaching solutions from pilot 1a and pilot 1b. The process steps for pilot 3a are shown in figure 8.

The pilot 3a operations are divided into seven-unit steps. During the conditioning, the PLS is heated, and pH can be adjusted (if necessary). The precipitation step, which can be performed in one or two reactors, mixes the PLS with NaOH and H₂S, forming ions H⁺ which results in decreased pH and consequent metals precipitation. Both reactors are equipped with pH and temperature controls, and H₂S gas inlets. The scope of the buffer tank is to enable unreacted H₂S from the precipitation step to react with the solution. The thickener and filter separate the underflow, rich in solid, from the overflow. The underflow is sent back to the precipitation reactor, to provide seeds for the precipitation process. The overflow is collected and stored. Finally, the scrubber process neutralizes the unreacted H₂S gas from the other process units. A more detailed explanation of pilot 3a operations can be found in deliverable 3.2.

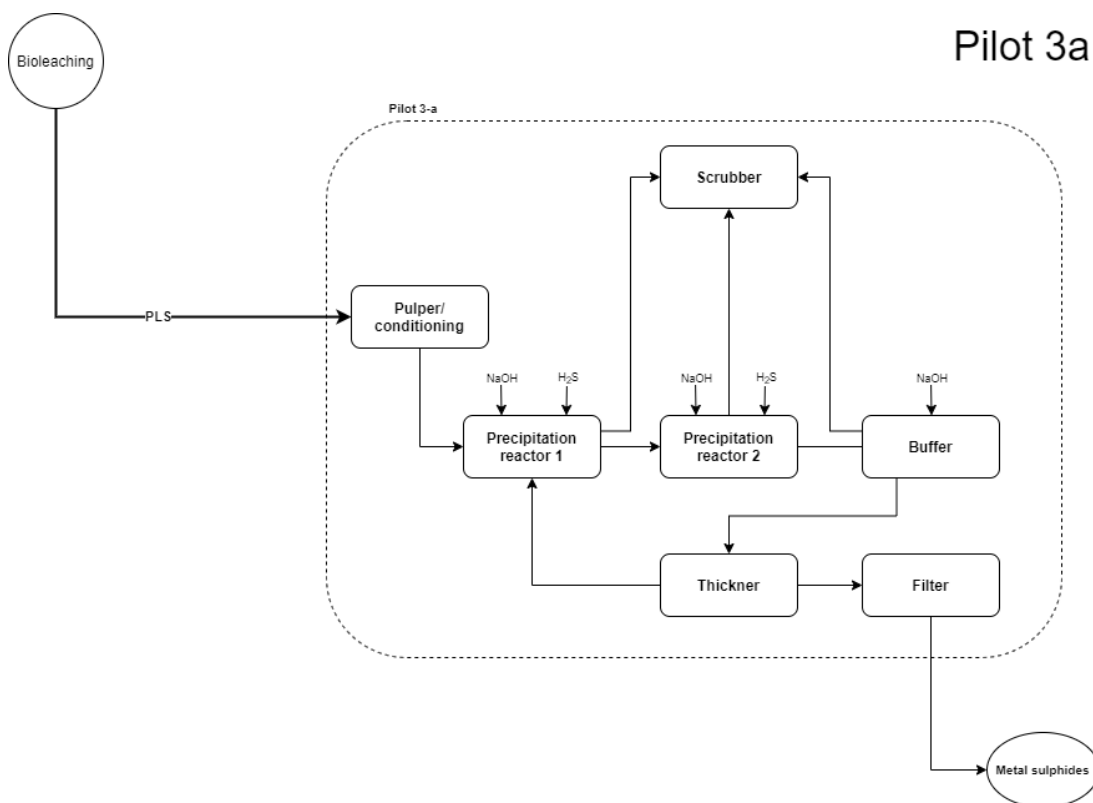


Figure 8: flowsheet pilot 3a

3.4.1 Pilot 3a: inventory analysis

Inventory analysis for pilot 3a is based on a data collection campaign performed by VTT. Raw data describing inputs/outputs parameters were collected for 16 tests, all run with different settings and then communicated to KU Leuven. Using the raw data, KU Leuven was able to calculate the inventory table based on the calculation of the mean value for each parameter (more specifically, the geometric mean was used, since all parameters presented a lognormal distribution along with the 16 runs). After that, all values were



mathematically upscaled to the treatment of 1000 L PLS solution from bioleaching. The calculated means and the upscaling are reported in table 5.

Table 5: inventory list pilot 3a

Pilot 3a					
Duration	3.32 h (average)				
Input	raw data (geom mean)			upscaling (1000 L)	
	amount	unit	amount	unit	
PLS	10	l/h	301.4	l/h	
Total	33.1	l	1000	l	
<i>composition</i>					
	Zinc	4994.67	mg/l	4.99	kg
	Copper	4.89	mg/l	0.005	kg
	Cadmium	8.79	mg/l	0.01	kg
	Nickel	2355.46	mg/l	2.36	kg
	Cobalt	33.93	mg/l	0.03	kg
<i>Other input</i>					
Electricity	1.87	KWh	56.42	kWh	
Sodium hydroxide (NaOH)	0.11	l/h	10.68	l	
Hydrogen sulphide (H ₂ S)	25.34	l/h	2534.31	l	
<i>Output</i>					
Metal-S products					
	Zinc	137.92	mg/l	0.14	kg
	Copper	4.86	mg/l	0.005	kg
	Cadmium	0.10	mg/l	0.0001	kg
	Nickel	2350.26	mg/l	2.35	kg
	Cobalt	34.20	mg/l	0.03	kg

3.4.2 Pilot 3a: Environmental results

The LCA results for pilot 3a are presented in figure 9. From the figure, it is possible to appreciate the major contribution (>45%) given by the production of sodium hydroxide to the total environmental impact for all categories, except the category “ionising radiation”. As already seen in the analysis of pilots 1 and 2, the main contribution for the category ionising radiation is represented by the electricity consumption, because of the nuclear-derived energy in the Swedish mix. However, electricity represents the second-highest contribution for most of the other categories. For five categories (respiratory inorganics, resource use- minerals and metals, photochemical ozone formation, ecotoxicity and acidification) the impacts coming from the production of hydrogen sulphate overcome the impacts from electricity production.



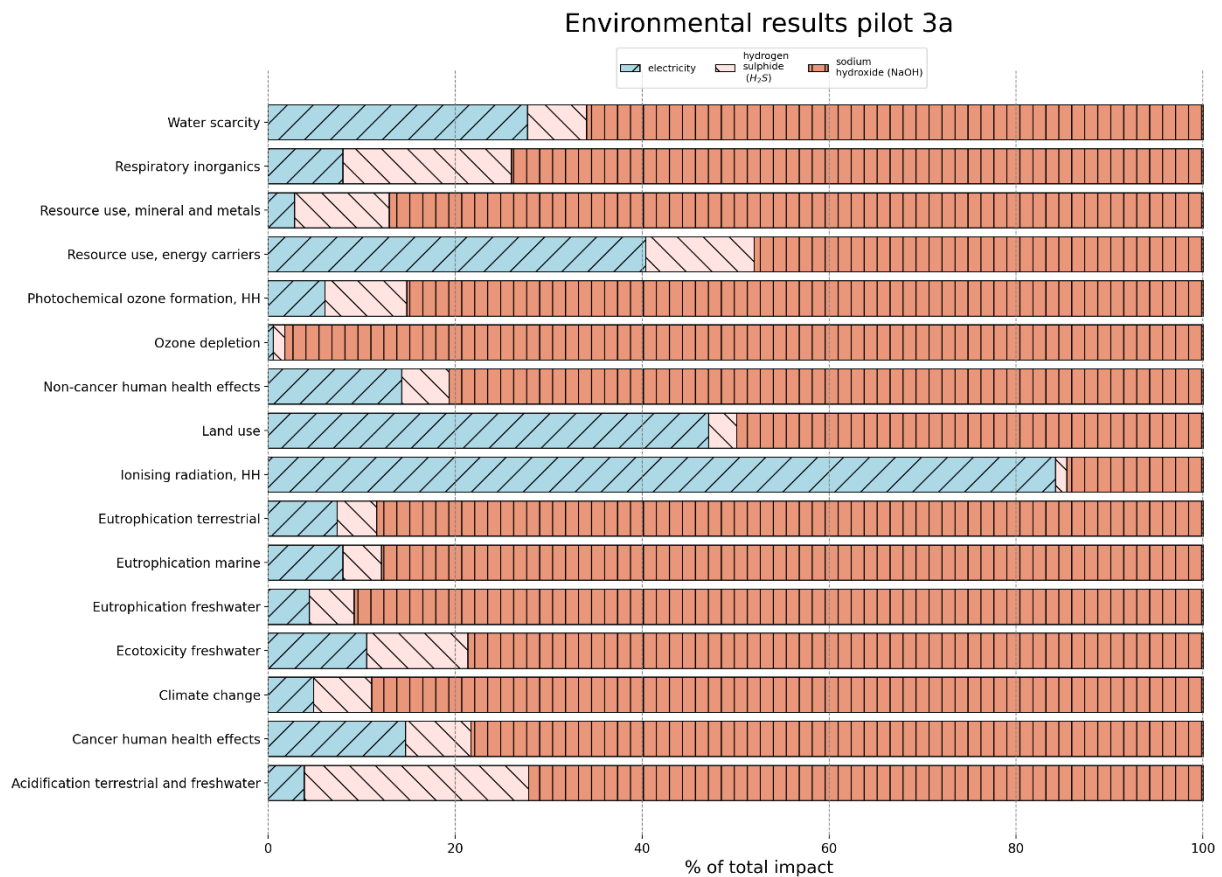


Figure 9: LCA results pilot 3a

3.4.3 Pilot 3a: conclusions

The environmental results shown in figure 9 for pilot 3a, indicate the optimisation of sodium hydroxide as the most effective strategy to reduce the overall environmental impact of the process operation. The optimisation of the electricity consumption (which can be easily achieved with the upscaling of the whole process) and the use of hydrogen sulphate can also reduce, to a lower extent, the environmental impact of some categories.

3.5 Pilot 3b: Separation of REE

The overall objective of pilot 3b is to demonstrate a procedure for REE (rare earth element) recovery from the scrubbing solution produced by the uranium solvent extraction process in the Sotkamo mine. The whole pilot 3b is divided into three steps. Step 1, managed by VTT, has the goal of extracting the REE from scrubbing solution, through solvent extraction followed by precipitation. Steps 2 and 3 of pilot 3b, managed by KU Leuven, aims at developing non-aqueous solvent extraction methods for selective separation of the recovered REE. A simplified flowsheet of pilot 3b is represented in figure 10.

Pilot 3b-step 1 is divided into three unit operations. In the solvent extraction, the organic (Cyanex923) and liquid phase (scrubbing solution) are mixed, for a mixing time of 3h. In the first precipitation reactor, iron and aluminium are precipitated using $\text{Ca}(\text{OH})_2$. The value of pH strongly affects the precipitation process, and the



value of pH in the reactor can be controlled thanks to $\text{Ca}(\text{OH})_2$. The target of the second precipitation reactor is to precipitate rare earth metals as hydroxides. The pH is controlled by NaOH. The REE precipitated are the inputs of pilot 3b-step 2.

Pilot 3b steps 2 and 3 develop solvo-metallurgical methods to separate and recover REE and Sc, using non-aqueous chloride solution solvent extraction in combination with neutral extractant (Cyanex 923). The process developed in pilot 3b-steps 2-3 is an alternative to the traditional REE processes, based on extraction from aqueous solutions using acidic extractant. Traditional processes use large quantities of chemicals for pH control and stripping, requiring thousands of mixing-settling stages for complete separation between neighbouring REE. Pilot 3b-steps 2-3 consists of two main steps: (step 2) *dissolution* of the REE hydroxide concentrate, produced by pilot 3b-step 1, in EG+HCl solution, and (step 3) *solvent extraction* using either basic Aliquat 336 or solvating Cyanex 923 as extractant, to separate heavy REE (HREE) into two groups: Dy-group (containing Dy, Y, Ho and Er) and Tm-group (Tm, Yb and Lu). After stripping, the REE are recovered by precipitation by oxalic acid, followed by calcination.

Figure 10 reports only the main inputs and outputs of pilot 3b. A certainly more exhaustive description of pilots 3b can be found in deliverables 3.1, 3.2 and 3.4, where also more detailed flowsheets are reported (including internal recirculation flows). Finally, as it can be seen in figure 10, the boundaries of the analysis do not include the further valorisation of the products (REE oxalates) of pilot 3b. As already discussed in the introduction, the goal of the LCA analysis presented in this report is to highlight the environmental hotspot driving the environmental footprint of each pilot. Further work on the integration of the pilots in a full valorisation route chain (from the mining of the residues to final production of secondary metals concentrate) will also allow considering the environmental benefits deriving from the recovery of secondary metals concentrates, and the avoided production of primary metals concentrates (see chapter 4 of this report to have an example of integration of various NEMO pilots in a full valorisation route).



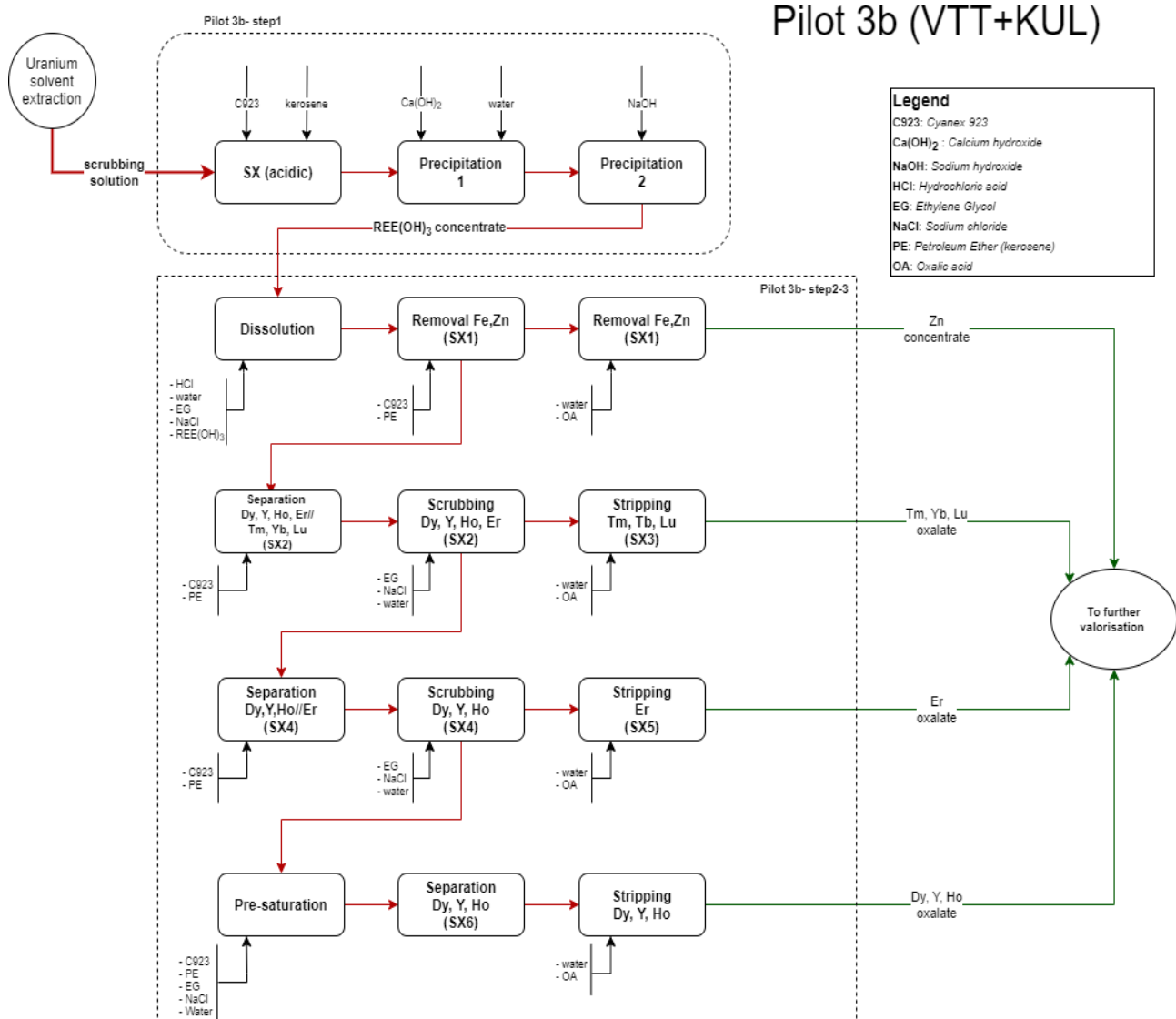


Figure 10: flowsheet pilot 3b

3.5.1 Pilot 3b: Inventory analysis

The inventory table for pilot 3b has been developed in close cooperation with the pilots' manager from VTT and KU Leuven. Because step 1 and steps 2-3 were performed in different locations (Finland and Belgium), test works were run using different quantities and scales, depending on the types of equipment available on site. Test-work for step 1 has been performed on the treatment of 26.6 kg of scrubbing solution, while steps 2-3 has been tested on the extraction of REE from 7.09 kg/h of REEOH (supposedly produced from step 1). Therefore, to align the output from step 1 to the input to steps 2-3, all quantities have been mathematically upscaled to the production of 1000 kg of REEOH (for step 1), and the treatment of 1000 kg REEOH (for steps 2-3). The connection of the two pilots, 3a-step 1 with 3a-steps 2-3, only based on mathematically upscaling of both processes, can raise many questions and issues, which will be discussed later in this report, in chapter 4. Finally, pilot 3b-steps 2-3 runs in different cycles, with a duration of 1h per cycle. For each cycle, a significant amount (up to ≈99%) of several chemical compounds, such as Cyanex 923, petroleum ether and ethylene glycol, can be recycled and reused for the next cycle. Consequently, for each cycle, only 1% of the initial amount of some chemicals needs to be refilled. According to data coming from the lab tests run at KU Leuven, it is estimated that these chemicals can be recycled up to 100 cycles. Therefore, to take this recycling



rate into account for the LCA and considering only 1% addition of new chemicals for each cycle, it is assumed that the pilot 3b-step 2-3 can treat 10 kg REEOH per cycle, for 100 cycles.

The final inventory table for pilot 3b steps 1-2-3 is reported in table 6.

Table 6: inventory analysis pilot 3b

Step 1						
		test work (kg)		upscaling 1 t of REEOH produced		
Scrubbing solution		26.6	kg	2223.3	t	
1.1 SX						
Input						
residence time sx (acidic)		4	h			
Cyanex 923		3.59	kg	299.2	t	
kerosene		5.39	kg	449.2	t	
Electricity*			kWh			
1.2 Precipitation (Fe,Al)						
input						
SX1 (buffer)		1.2	kg/h	103.3		
residence time Fe removal		7.8	h			
reactor volume		15	L			
Calcium hydroxide (Ca(OH) ₂)		2.4	kg/h	200	t	
water		7.1	kg/h	591.7	t	
1.3 Precipitation (REE)						
NaOH		0.07	l/h	5833.3	l	
water		0.06	kg	5	t	
Output						
REE OH		0.012	kg/h	1 000	kg	
Step 2-3						
				Upscaling 1 t		
				1 cycle=10 kg		
				(100		
				cycles=100 h)		
		Lab test				
2.1 Dissolution						
Input from 3b-step 1		RE(OH) ₃	7.09	kg/h	1 000	kg
Electricity for mixing (whole step 2-3)				30	kWh	
Input						
hydrochloric acid (HCl)		13.3	l/h	1 881.9	L	
water (l/h)		23.8	l/h	3 370.3	L	
ethylene Glycol		331.7	l/h	467.9	L	
fresh Ethylene Glycol		3.3	l/h	472.6	L	
NaCl		17.2	kg/h	24.3	kg	
fresh NaCl		0.1	kg/h	24.5	kg	
2.2 Removal Fe,Zn						
Input						
Cyanex 923		91.96	kg/h	129.7	kg	



	fresh Cyanex 923	0.93	kg/h	131.02	kg
	petroleum ether	141.26	l/h	199.2	L
	fresh petroleum ether	1.43	l/h	201.2	L
2.3 Stripping Fe, Zn					
Input					
	water	248.24	l/h	35 013.3	L
	oxalic acid	0.26	kg/h	36.8	kg
Output					
	Zn oxalate	0.15	kg/h	21.24	kg
2.4 Separation Dy-Tm					
Input					
	Cyanex 923	91.96	kg/h	129.7	kg
	fresh Cyanex 923	0.93	kg/h	131.02	kg
	petroleum ether	141.26	l/h	199.2	L
	fresh petroleum ether	1.43	l/h	201.2	L
2.5 Scrubbing Dy,Y,Ho,Er					
Input					
	Ethylene Glycol	331.78	l/h	467.9	L
	fresh Ethylene Glycol	3.35	l/h	472.6	L
	NaCl	17.23	kg/h	24.3	kg
	fresh NaCl	0.17	kg/h	24.5	kg
	water	37.24	l/h	5 252	L
2.6 Stripping Tm,Yb,Lu					
Input					
	oxalic acid	1.23	kg/h	174.07	kg
	water	248.24	l/h	3 5013.3	L
Output					
	Tm,Yb,Lu oxalate	1.28	kg/h	181.3	kg
2.7 Separation Dy-Er					
Input					
	Cyanex 923	206.92	kg/h	291.8	kg
	fresh Cyanex 923	2.09	kg/h	294.7	kg
	petroleum ether	317.83	L/h	448.2	L
	fresh petroleum ether	3.21	L/h	452.8	L
2.8 Scrubbing Dy,Y,Ho					
Input					
	Ethylene Glycol	502.70	L/h	709.02	L
	NaCl	13.06	kg/h	18.4	kg
	water	55.86	L/h	7 878	L
2.9 Stripping Er					
Input					
	oxalic acid	0.57	kg/h	81.6	kg
	water	558.5	L/h	78 780	L
Output					
	(Er) oxalate (kg/h)	0.35	kg/h	49.3	kg
2.10 pre-saturation					
input					



	Cyanex 923	285.01	kg/h	401.9	kg
	fresh Cyanex 923	2.88	kg/h	406.05	kg
	Petroleum ether	50.12	L/h	70.6	L
	fresh petroleum ether	0.51	L/h	71.4	L
	Ethylene Glycol	274.20	L/h	386.7	L
	fresh Ethylene Glycol	368.98	L/h	520.4	L
	NaCl	15.83	kg/h	2232.2	kg
	water	33.85	L/h	4774.5	L
2.12 Stripping Dy, Y, Ho					
Input					
	oxalic acid	1.27	kg/h	179.8	kg
	water	372.3	L/h	52520	L
Output					
	(Dy,Y,Ho) oxalate	1	kg/h	142.3	kg

* The value for electricity demand was calculated based on the average consumption for mixer, set as 0.03 kWh per kg of the treated material

Cyanex 923 is an organic solvent, based on liquid phosphine oxide, well-known for its applications in the solvent extraction recovery of inorganic solutes from aqueous solutions. Cyanex 923 is a registered product from Solvay, and its production process is not publicly disclosed. Consequently, it was not possible to derive the environmental impacts from the production of the Cyanex 923. Another solvent with similar chemical composition has been identified in the Ecoinvent database, namely the Tri-Butyl-Phosphate (TBP). In the environmental results, the impacts from the production of TBP are used as a proxy for the production of Cyanex 923.

3.5.2 Pilot 3b: environmental results

The environmental results of the analysis for pilot 3b-step 1 and pilot 3b-step 2-3 are reported in figure 11.



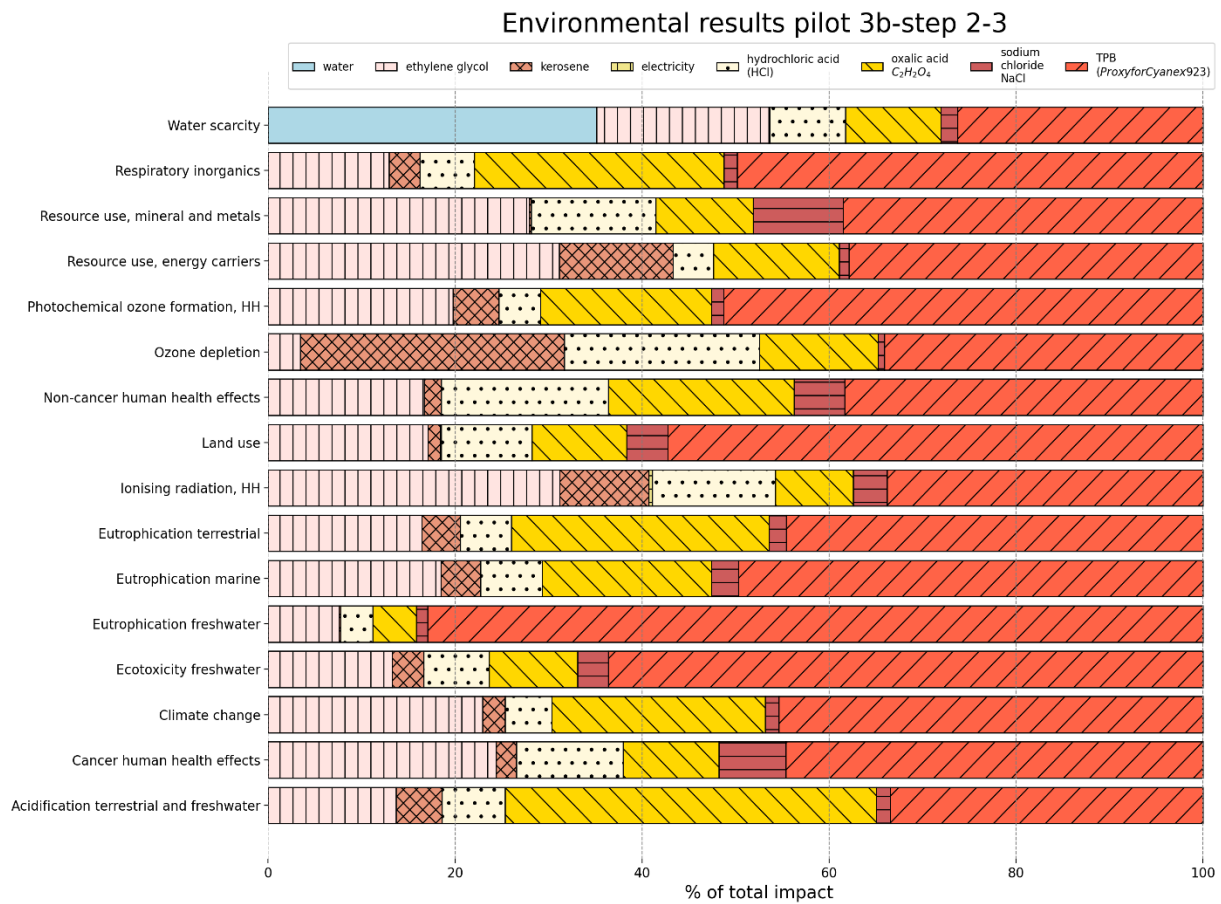
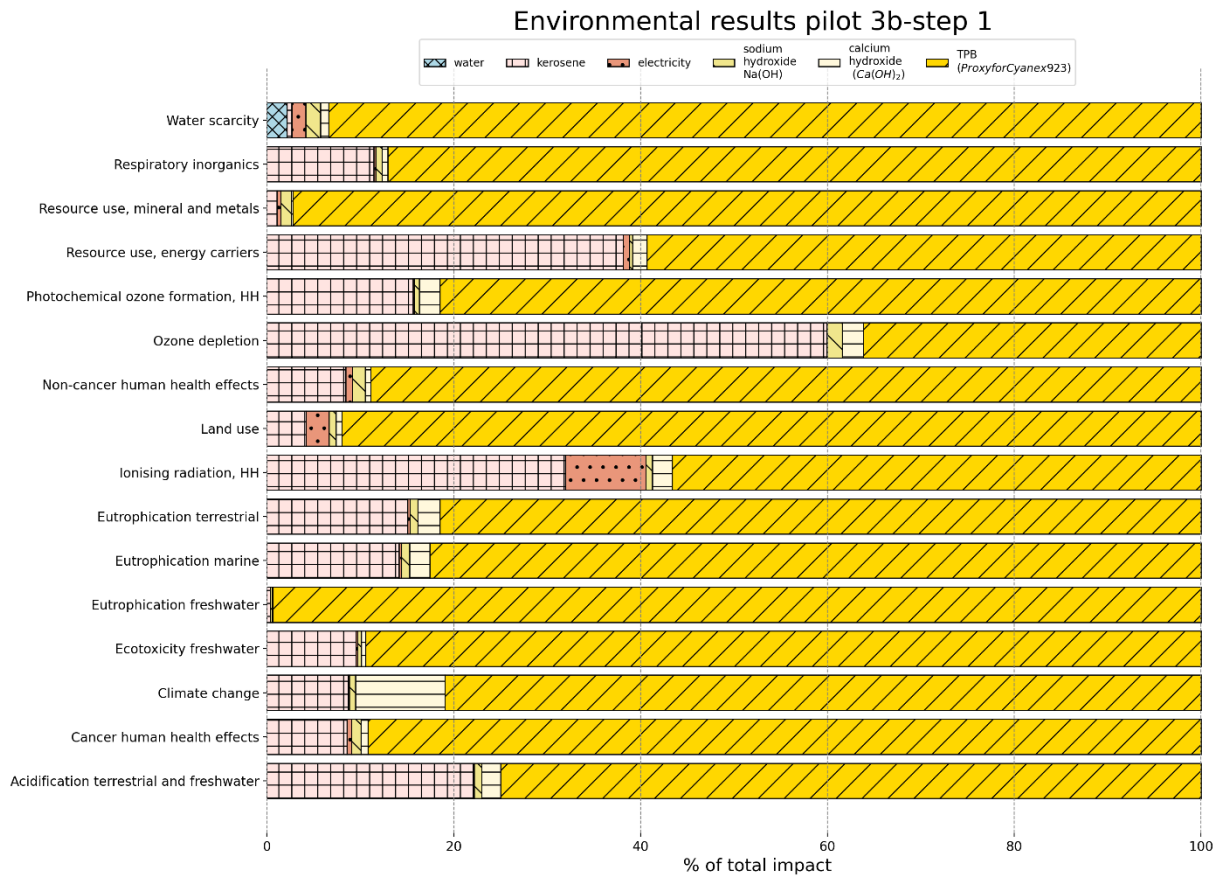


Figure 11: LCA results pilot 3b



This project has received funding from the European Union's EU Framework Programme for Research and Innovation Horizon 2020 under Grant Agreement No 776846 - <https://h2020-nemo.eu/>

Results for step 1 show the predominant contribution of the TBP to the final environmental impact for all categories. Only for the category ozone depletion and resource use-energy, the contribution of kerosene is higher than 35%. Production of kerosene represents the second-highest contribution in all categories, except for the category climate change, where the impact of kerosene production equals the one for sodium hydroxide production (although the TBP represents always the highest contribution).

The environmental results of steps 2-3 are more scattered compared to the one of step 1. Also for steps 2-3, there is a predominant contribution of TBP production, especially for categories such as eutrophication and ecotoxicity (>60%). However, in most of the categories, many other elements play a significant role in the final impact.

3.5.3 Pilot 3b: conclusions

Looking at the results for pilot 3b-step 1, 2-3 from a global perspective, it becomes clear that optimizing the use of the solvent (the TBP in this study, the Cyanex 923 in real demonstrators) can significantly decrease the environmental impact of pilot 3b unit operations. However, such an optimisation strategy may have different effects on steps 2-3, compared to step 1. While for step 1 the reduction in the use of the solvent will lead to an overall decrease of the environmental impacts for all categories, for steps 2-3 many other elements can contribute to the final environmental footprint of the process. As shown in the figure, the reduction of different elements may lead to the reduction of the impacts for specific environmental categories. Consequently, a more diversified strategy, based on the general optimisation in the use of chemicals, is strongly advised to significantly decrease the overall environmental impact of the process. Finally, it is worth noticing the minor role played by the electricity in pilot 3b, compared to what we saw e.g. pilot 1b or pilot 2.

3.6 Pilot 4: Flash calcination (4a) and granulation (4b) of inert fraction

The goal of pilot 4 is to process the inert fraction resulting after the bioleaching process, to produce secondary composite cement or aggregates. In particular, this study analyses two alternative unit operations: (i) flash calcination for the production of alternative composite cement (pilot 4a, managed by Thyssenkrupp), and (ii) granulation to produce aggregates for construction materials (pilot 4b, managed by VITO).

In **Pilot 4a**, the inert fraction is activated by calcination and converted into artificial pozzolan. This calcinated fraction can be then used as supplementary cementitious materials, to replace traditional Portland cement. The test operation for pilot 4a have been performed using tailings from the BOLIDEN Tara mine, in Ireland, and the thermal process has been tested in a pilot-scale flash calciner. The thermal process aims to decompose the pyrite, in a temperature range between 600 and 700 °C. The unit operations of pilot 4a are summarized in figure 12, while a detailed description can be found in deliverable 4.5. The calcinated material resulting after the calcination has been then tested as an additive to CEM I, replacing a part of portland cement used in conventional concrete. Considering that the production of Portland cement is responsible for 10% of global anthropogenic CO₂ emissions, the replacement by calcinated material can have significant benefits in reducing global CO₂ emissions. As it was already discussed for pilots 3a and 3b, the beneficial effects of pilot 4a for producing secondary cement will be discussed in chapter 4, when discussing the integration of several NEMO pilots into a complete valorisation process.

Pilot 4b produces artificial aggregates for construction purposes, through the granulation of the inert fraction from the bioleaching process. The test was performed using tailings from the BOLIDEN mine located in Tara, Ireland. A simplified flowsheet of pilot 4b is presented in figure 12, while a detailed description of the pilot is presented in deliverables D4.4 and 4.6.



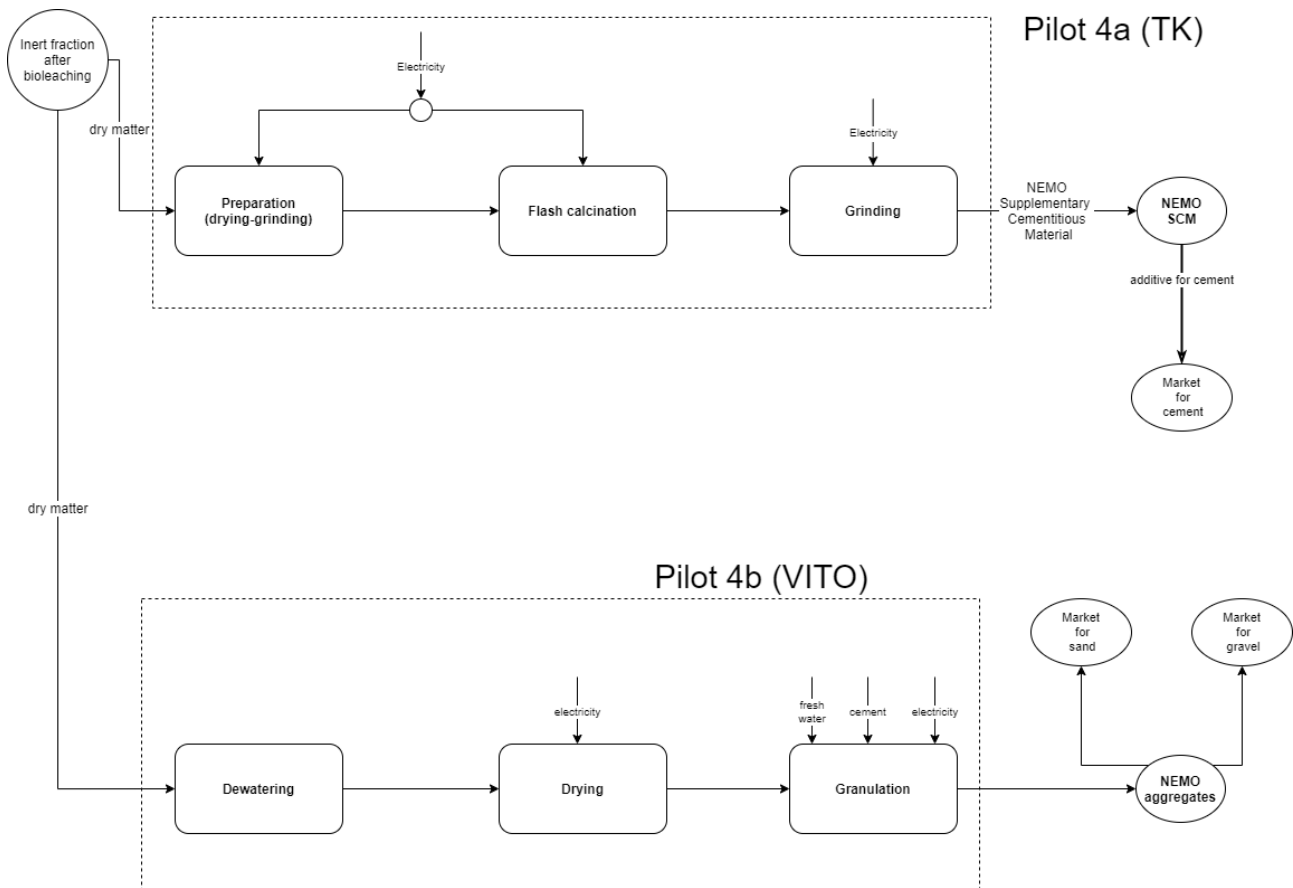


Figure 12: flowsheet pilots 4a and 4b

3.6.1 Pilot 4: inventory analysis

The inventory analysis for pilot 4 has been developed through several meetings and emails exchanges between Thyssenkrupp, VITO and KU Leuven. Both data for pilots 4a and 4b refer to tests processing a large amount of tailings (550 tonnes for pilot 4a, and 475 tonnes for pilot 4b). All data have been downscaled to the treatment of 1 tonne. The inventory list for pilots 4a and 4b are reported in table 7.

Table 7: inventory table pilot 4a and 4b

Pilot 4a			
	Pilot Test (TK)		Data for 1-tonne input
<i>Input (inert fraction from bioleaching)</i>	550	t	1 t
Preparation + Calcination			
Electricity	15	MWh	27.3 kWh
<i>per unit of product</i>	30	KWh/t _{product}	
CO ₂ emissions	125	tCO ₂	0.2 t
<i>per unit of product</i>	0.25	tCO ₂ /t _{product}	
Grinding			
Electricity	17.5	MWh	31.8 kWh
<i>per unit of product</i>	35	KWh/t _{product}	
Product			
calcinated product	500	t	0.91 t
Pilot 4b			

Pilot Test (VITO)

Data per 1 tonne input



This project has received funding from the European Union's EU Framework Programme for Research and Innovation Horizon 2020 under Grant Agreement No 776846 - <https://h2020-nemo.eu/>

<i>Input (inert fraction from bioleaching)</i>	475 t	1 t
Drying		
Electricity (drying)	188 MJ	1.42 kWh
Granulation		
Electricity (granulation)	27 MJ	0.20 kWh
Cement (CEM III/B)	25 t	0.053 t
Water (only without dewatering)	23.7 t	0.05 t
Product		
NEMO aggregates	580 t	1.22 t
50% replacing sand	290 t	0.61 t
50% replacing sand	290 t	0.61 t

3.6.2 Pilot 4: environmental results

The results of the environmental analysis for pilots 4a and 4b are reported in figure 13. For pilot 4a, the analysis shows how the environmental impact for all categories (except climate change) is caused by the electricity for grinding and calcination, with a slightly higher contribution of the first one (53%). For the category climate change, the direct CO₂ emission produced during the calcination process is responsible for almost the total CO₂ emissions.

For pilot 4b, the predominant contribution to the final impact of all categories is given by the production of the Portland cement. A slightly higher contribution (>25%) is given by the electricity (for both grinding and drying) for the category ionizing radiation, and by the water consumption for the category water scarcity (30%).

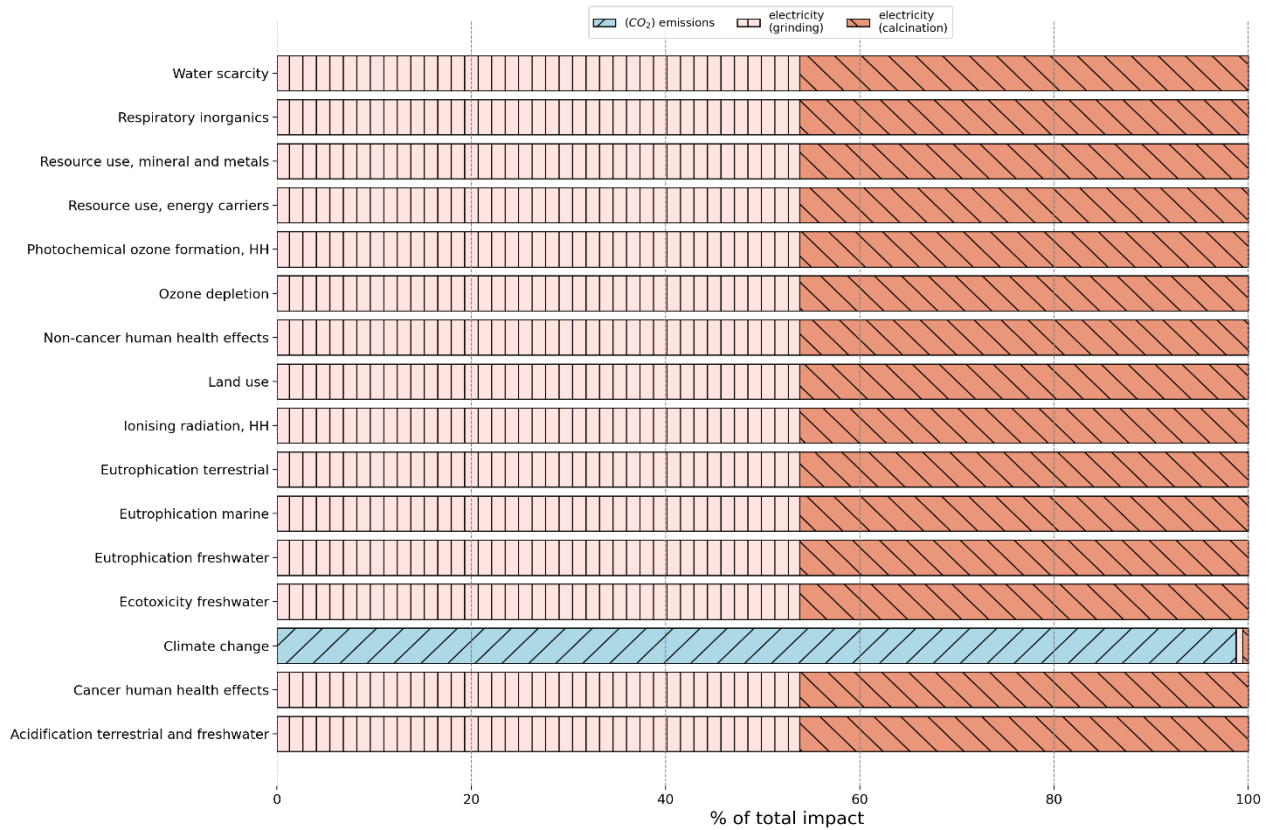
3.6.3 Pilot 4: Conclusions

From the environmental results of pilots 4, it is evident the importance of the electricity consumption and the cement used in the process. Therefore, the best strategy to control and minimize environmental impacts is the optimization in the use of these two resources. Looking at an alternative source of energy and cement replacement can significantly reduce the environmental profile of both pilot 4a and pilot 4b. It is important to highlight that both pilots produce secondary products that can replace similar products from primary resources. Therefore, to put these results into a wider perspective, the environmental benefits due to the avoided production of primary products must be also assigned as a credit to the whole valorisation scheme for sulphidic mine tailings.

The environmental benefits arising from the replacement of primary products will be discussed in the next chapter when the integration of the different NEMO pilots will be discussed.



Environmental results pilot 4a



Environmental results pilot 4b

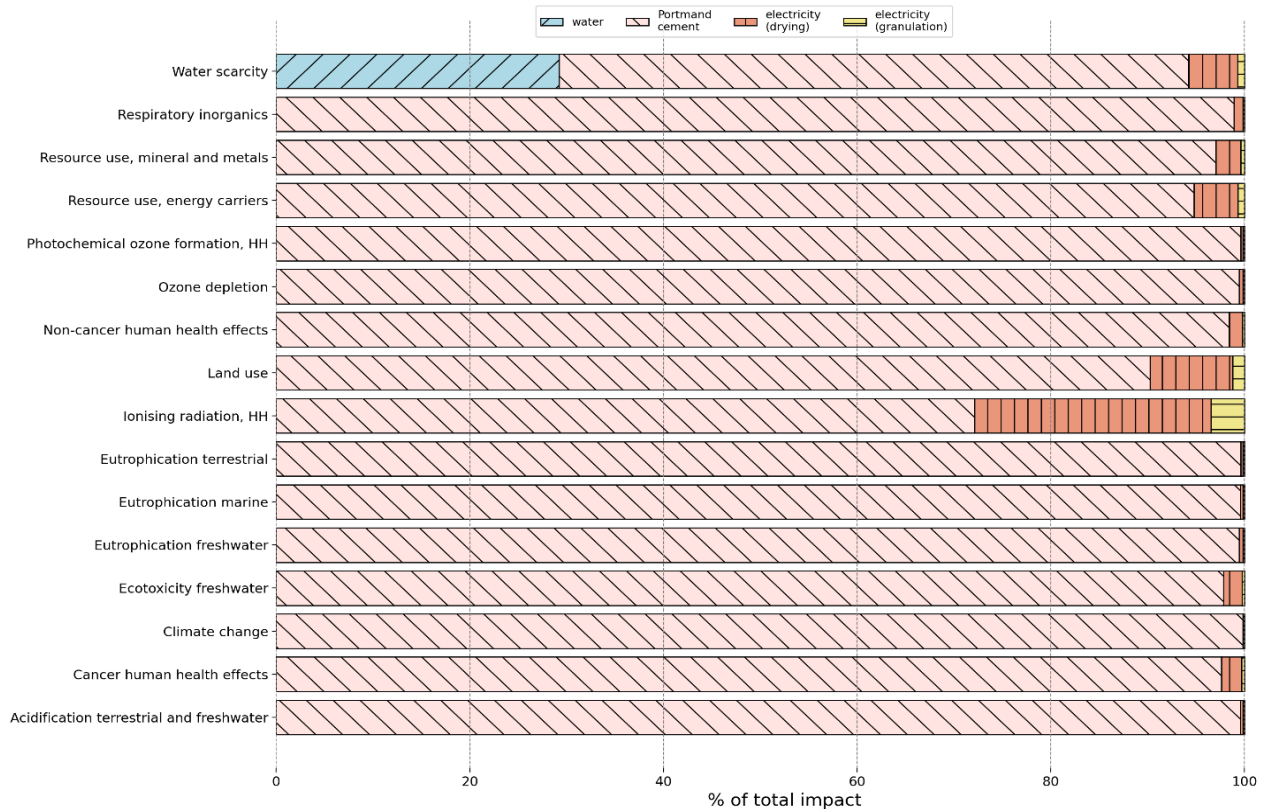


Figure 13: LCA results pilot 4a and 4b



4 Integration of NEMO pilots

The previous chapter presented the environmental results identifying the drivers for each of the NEMO pilots. However, to have a clear picture of the environmental impacts and benefits of the near-zero waste strategy proposed by NEMO, it is important to consider the whole valorisation chain for recovery of sulphidic mine tailings, from mining to metals precipitation and inert fraction valorisation. By considering the valorisation process as a whole, the production of secondary metals and construction materials achieved in NEMO can be benchmarked with the production of equivalent products from primary resources (namely mining and production of primary metal concentrates, Portland cement and natural aggregates).

Building on this need, the integration of NEMO pilots is a fundamental aspect in the last phase of NEMO, to ensure that material produced in one pilot meets the requirements to be processed in the subsequent pilot. To ensure successful integration of NEMO pilots into the zero-waste recycling concept, IDENER and KUL are cooperating in task 5.3, on the “*Technology integration into zero-waste recycling concept for sulphidic mine tailings*”. Task 5.3 is expected to produce the deliverables D5.3 (*Report on integrated pilot engineering (internal)*) and D5.4 (*Peer-reviewed publication on integrated NEMO concept (public)*) at months 54 (October 2022).

With the information available at the moment, it is possible to draw a potential integration scheme for NEMO pilots, as shown in figure 14. Four possible valorisation routes have been identified:

- S1→Pilot 1a + Pilot 3a + Pilot 4a (S4a) or Pilot 4b (S4b)
- S2→Pilot 1b + Pilot 3a + Pilot 4a (S4a) or Pilot 4b (S4b)
- S3→Pilot 3b step 1 + Pilot 3b steps 2-3
- S4→Pilot 2 + Pilot 4a (S4a) or Pilot 4b (S4b)

For the time being (month 48 of the NEMO project), the final data for the different integrated treatment processes are still under development, and environmental analysis of the integrated process was not possible. In the coming months, based on the information collected from each pilot, KUL and IDENER will work together in developing digital models of final integrated processes. The data generated from these digital simulations will be used to perform an environmental analysis of the full valorisation scheme, that can be benchmarked with the current production of metals concentrates, aggregates and cement from primary sources. These further LCA analyses will be reported either as an integration of deliverable D 5.3 or of deliverable D 5.4 (depending on the final decision of the NEMO consortium to make the results produced publicly available or confidential).



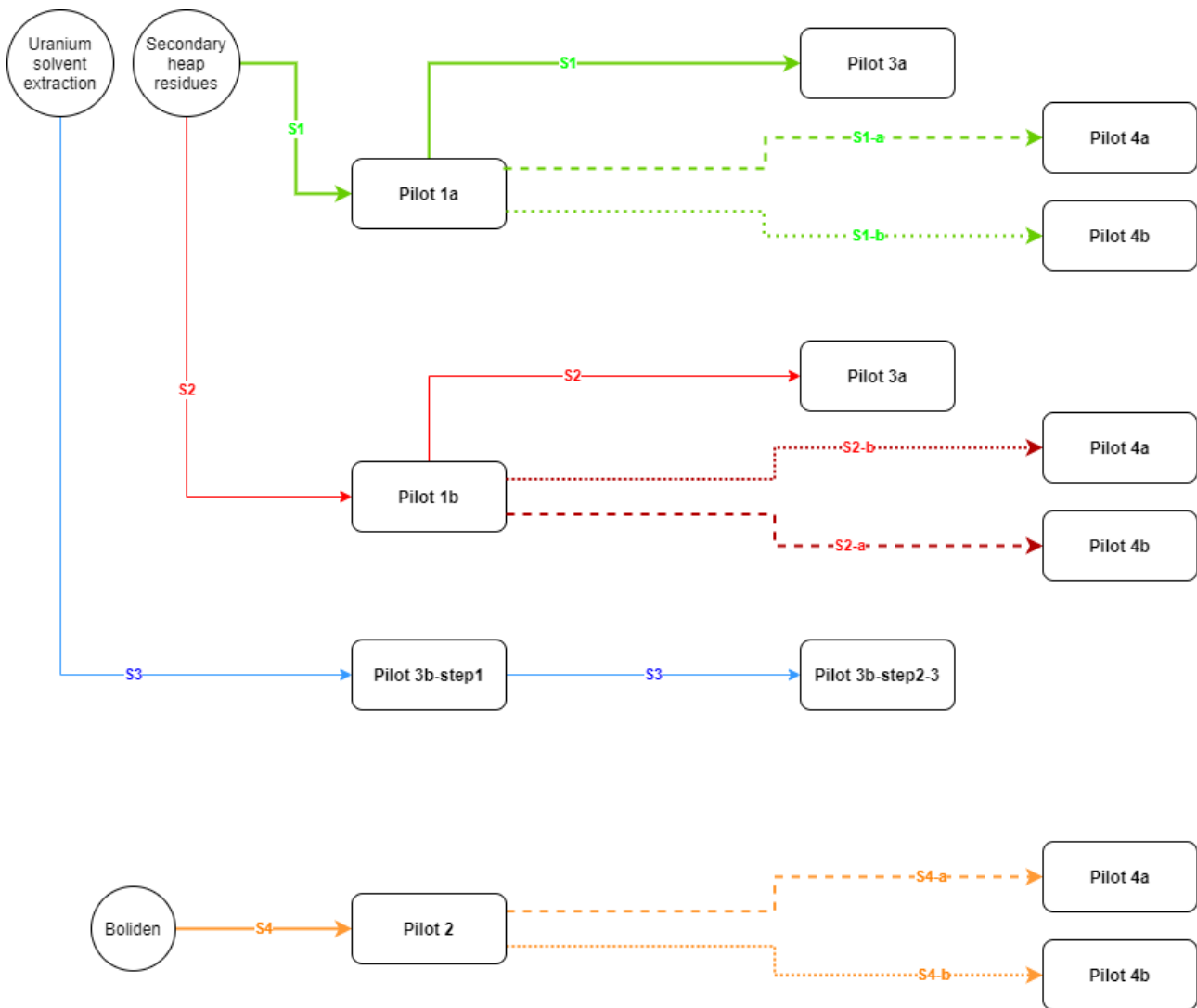


Figure 14: Potential integration of NEMO pilots

4.1 A case study from the integration of Pilot 2 + Pilots 4

To put some of the results presented in this report into a wider perspective, an example of the environmental impacts calculated for an integrated process “pilot 2 + pilot 4” (route S4 in figure 14) is reported in this section. This example is based on a potential upscaling scenario where pilot 2 treats 500 t per day of sulphidic mine tailings, to produce different metals concentrates through bioleaching and sulphide precipitation. The inert fraction resulting from the bioleaching process is further treated by pilot 4a, to produce secondary binder replacing traditional Portland cement (route S4a), or by pilot 4b, to produce secondary aggregates replacing natural aggregates in construction materials (route S4b).

A simplified flowsheet for the integration of pilot 2 and pilots 4 is presented in figure 15.



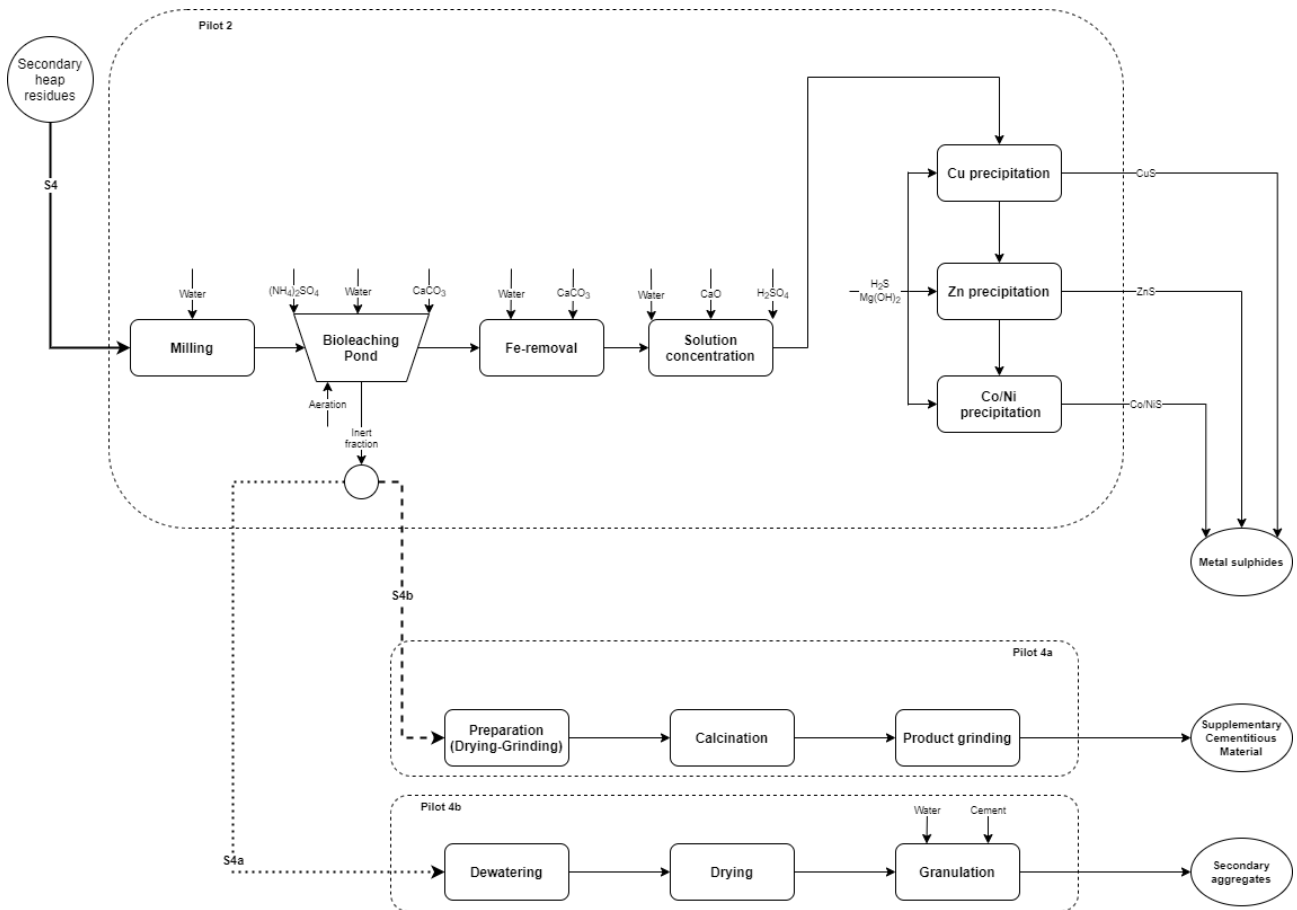


Figure 15: flowsheet pilot 2 + pilots 4

4.1.1 Integration Pilot 2 + Pilots 4: inventory analysis

The inventory analysis for the integration of pilot 2 and pilots 4 is based on a hypothetical upscaled scenario for the treatment of 500 tonnes per day of sulphidic mine tailing. The data for the upscaled scenario has been agreed with BOLIDEN, the manager of pilot 2.

Table 8: inventory list pilot 2 + pilots 4

Pilot 2	
Milling	Upscaled scenario
<i>Input</i>	
Sulphidic mine tailings	500 t
Electricity	85 MWh
Water (lake)	500 m3
Bioleaching	
<i>Input</i>	
Ammonium sulphate ((NH ₄) ₂ SO ₄)	8.5 t
Electricity	274.6 MWh
Calcium carbonate (CaCO ₃)	20 t
Water (lake)	2333 m3
<i>Output</i>	
Leach residue (to landfill)	255 t



CO ₂ emissions	10 t
Inert fraction	255 t
Fe-removal	
<i>Inputs</i>	
Electricity	27.5 MWh
Calcium carbonate (CaCO ₃)	332.4 t
Water (lake)	5118.5 m ³
<i>Outputs</i>	
CO ₂ emissions	145 t
Fe-Hydroxide residue (to landfill)	863.5 t
Solution Concentrating	
<i>Inputs</i>	
Electricity	14.5 MWh
CaO	10 t
Sulphuric acid (H ₂ SO ₄)	15 t
Water (lake)	815 m ³
<i>Outputs</i>	
Gypsum residues (to landfill)	10 t
Sulphide precipitation	
<i>Inputs</i>	
Electricity	10 MWh
Hydrogen sulphide (H ₂ S)	15 t
Magnesium hydroxide (Mg(OH) ₂)	8.5 t
CaO	15 t
<i>Outputs</i>	
Gypsum residues (to landfill)	60 t
Products	
Cobalt concentrate	3.1 t
Copper concentrate	1.5 t
Nickel concentrate	1.8 t
Zinc concentrate	5 t
Pilot 4a	
<i>Input</i>	
Inert fraction from bioleaching	255 t
Preparation + Calcination	
<i>Input</i>	
Electricity	6.95 MWh
<i>Output</i>	
CO ₂ emissions	57.9 t _{CO2}
Grinding	
Electricity	8.11 MWh
Product	
Calcinated material	231.8 t
Pilot 4b	
<i>Input</i>	
Inert fraction from bioleaching	255 t
Drying	



<i>Input</i>	
Electricity	0.36 MWh
<hr/>	
Granulation	
<i>Inputs</i>	
Electricity	0.05 MWh
Cement	13.4 t
Water	12.8 t
<i>Outputs</i>	
Aggregates from NEMO	311.4 t
<hr/>	

4.1.2 Integration Pilot 2 + Pilots 4: Environmental results

The results for the two hypothetical valorisation routes S4a and S4b are reported in figures 16 and 17. The graphs on top of figures 16 and 17 show the comparison of the impacts caused by the valorisation process vs the environmental benefits due to the avoided production of materials from primary resources. The right side of the graphs (the positive part of the abscissa) reports the environmental impacts caused by the process operations of pilot 2 and pilot 4a and 4b. The left side of the graph (the negative part of the abscissa) reports the benefits due to the avoided production of primary materials. Therefore, for the indicators where the left column (in green) is bigger than the right column (in red), the environmental benefits of the avoided processes are higher than the environmental costs of performing the valorisation process. An opposite conclusion can be drawn when the right column is bigger than the left column. The graphs at the bottom of figures 16 and 17 detail the contribution of pilot 2 and pilot 4a and 4b to the final impact for each category.

From figure 16 (top) is possible to see how, for most of the categories, the environmental benefits for S4a overcome the impacts, giving a beneficial environmental footprint to the valorisation route. The largest environmental benefits are given by the avoided production of cobalt and nickel concentrates and by the avoided production of Portland cement. Only for the categories land use and ionising radiation, the environmental impacts are larger than the benefits. In figure 16 (bottom) it is possible to appreciate that the largest impact for S4a is given by the pilot 2 operations. Only for climate change, pilot 4a has a significant contribution (=20%), due to the CO₂ emissions produced during flash calcination.

Figure 17 (top) shows the environmental balance between impacts vs benefits in the case of S4b. It is possible to see the limited benefits given by the avoided production of sand and gravel, compared to the benefits derived from the avoided production of Portland cement in pilot 4a. While the benefits from the production of secondary metals concentrate remained unchanged, the production of secondary aggregates instead of secondary Portland cement may lower the environmental benefits of the whole valorisation process, despite the lower energy requirements of granulation compared to flash calcination. Although the environmental benefits of S4b are lower compared to the ones of S4a, for most of the categories the total benefits overcome the impacts. Finally, figure 17 (bottom) shows how for all categories the majority of the impacts derived from pilot 2 compared to pilot 4b.

4.1.3 Integration Pilot 2 + Pilots 4: Conclusions

The integration of pilot 2 with pilot 4a and 4b allows calculating the final environmental balance of the whole near-zero waste strategy proposed by NEMO. From the environmental results, it appears clear the potential

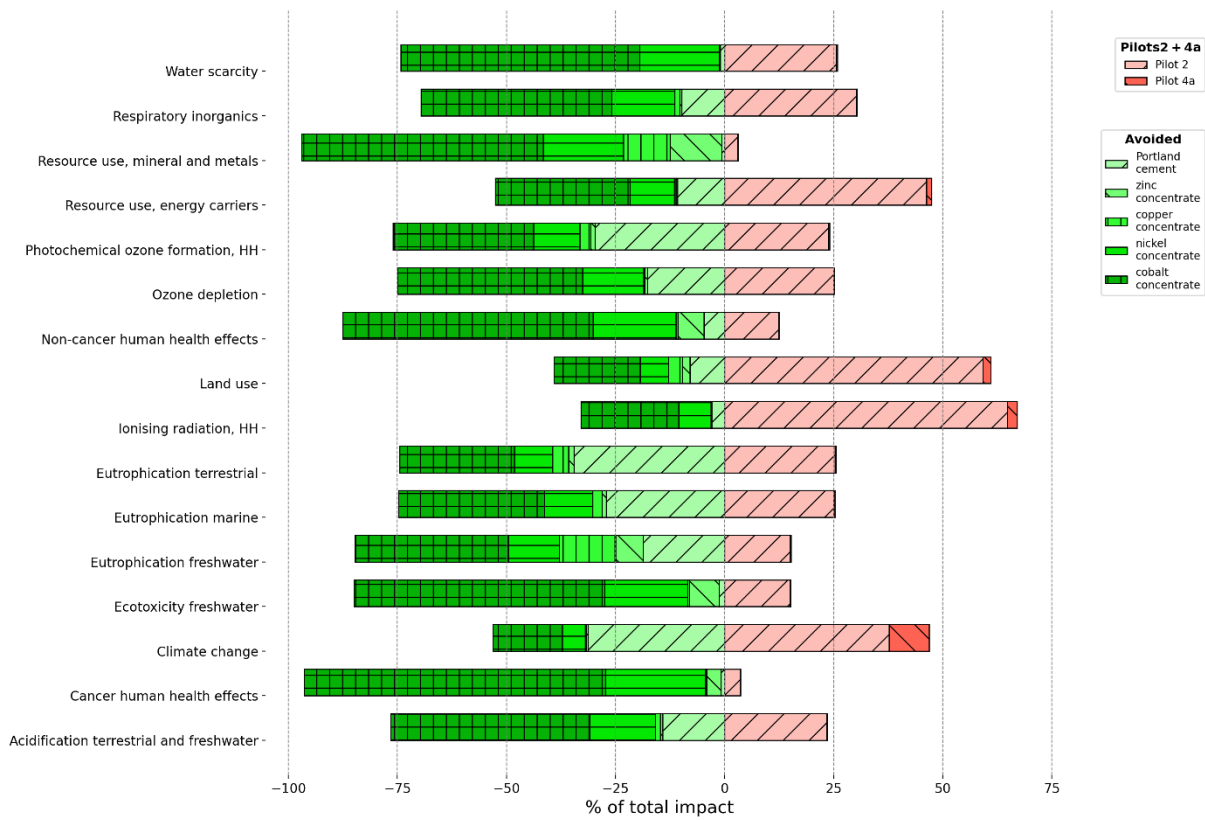


benefits deriving from the valorisation of sulphidic mine residue, thanks to the recovered metals concentrates and the production of secondary binder and secondary aggregates.



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Environmental results Pilot 2 + 4a: benefits vs impacts



Environmental results pilot 2 + pilot 4a

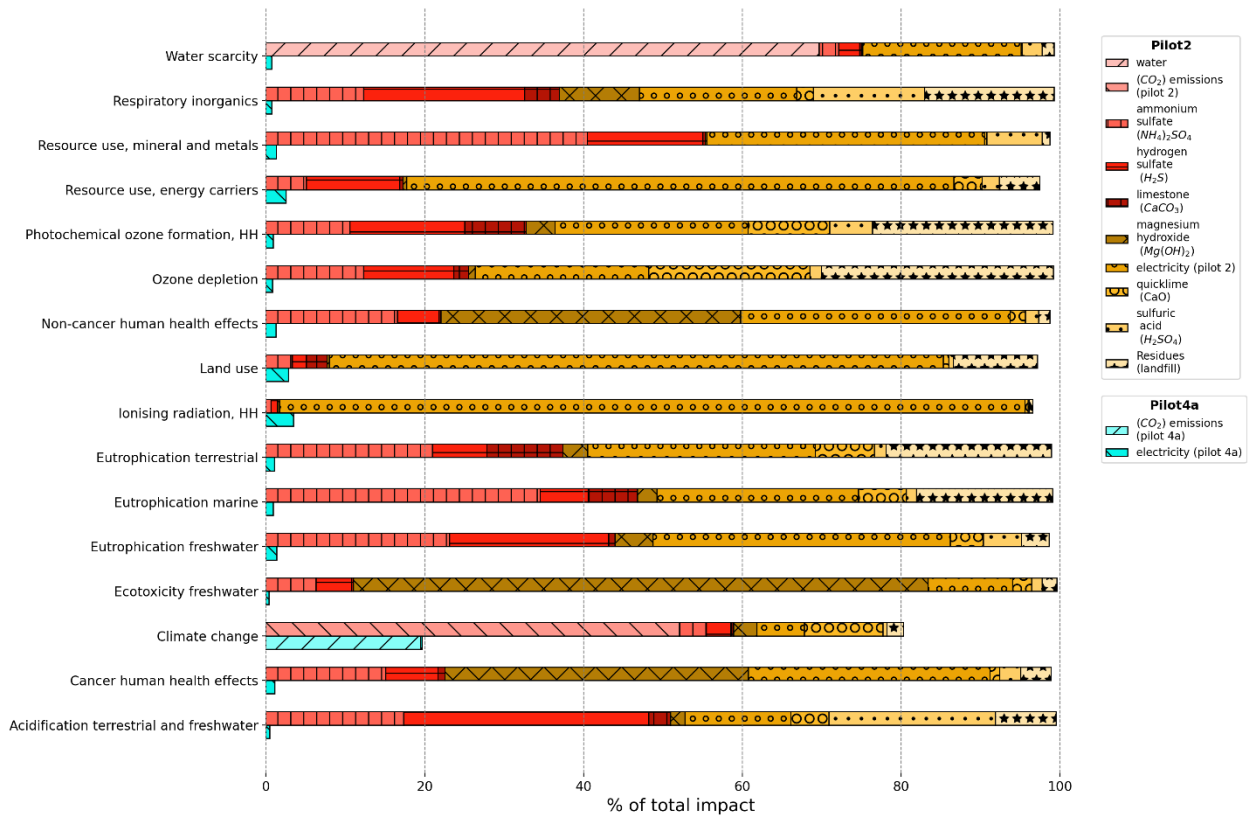
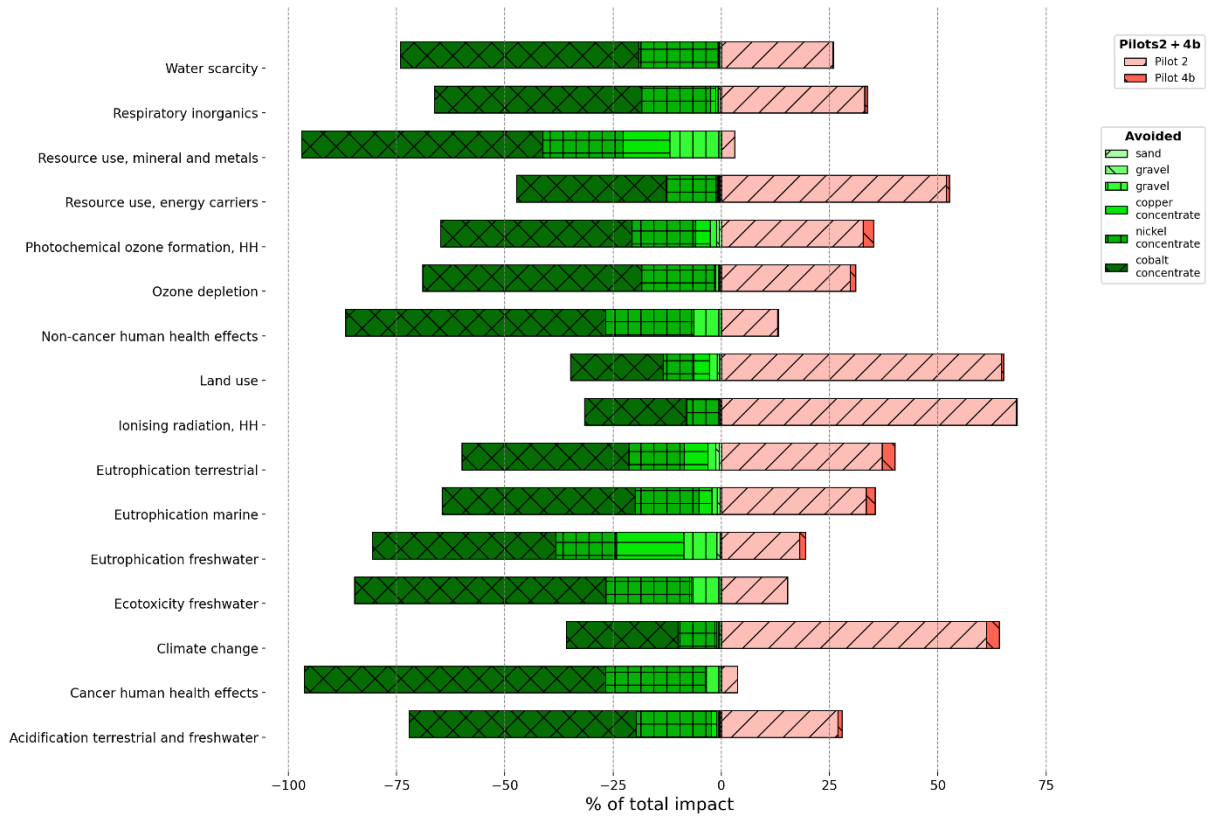


Figure 16: LCA results pilot 2 + pilot 4a



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Environmental results Pilot 2 + 4b: benefits vs impacts



Environmental results pilot 2 + pilot 4b

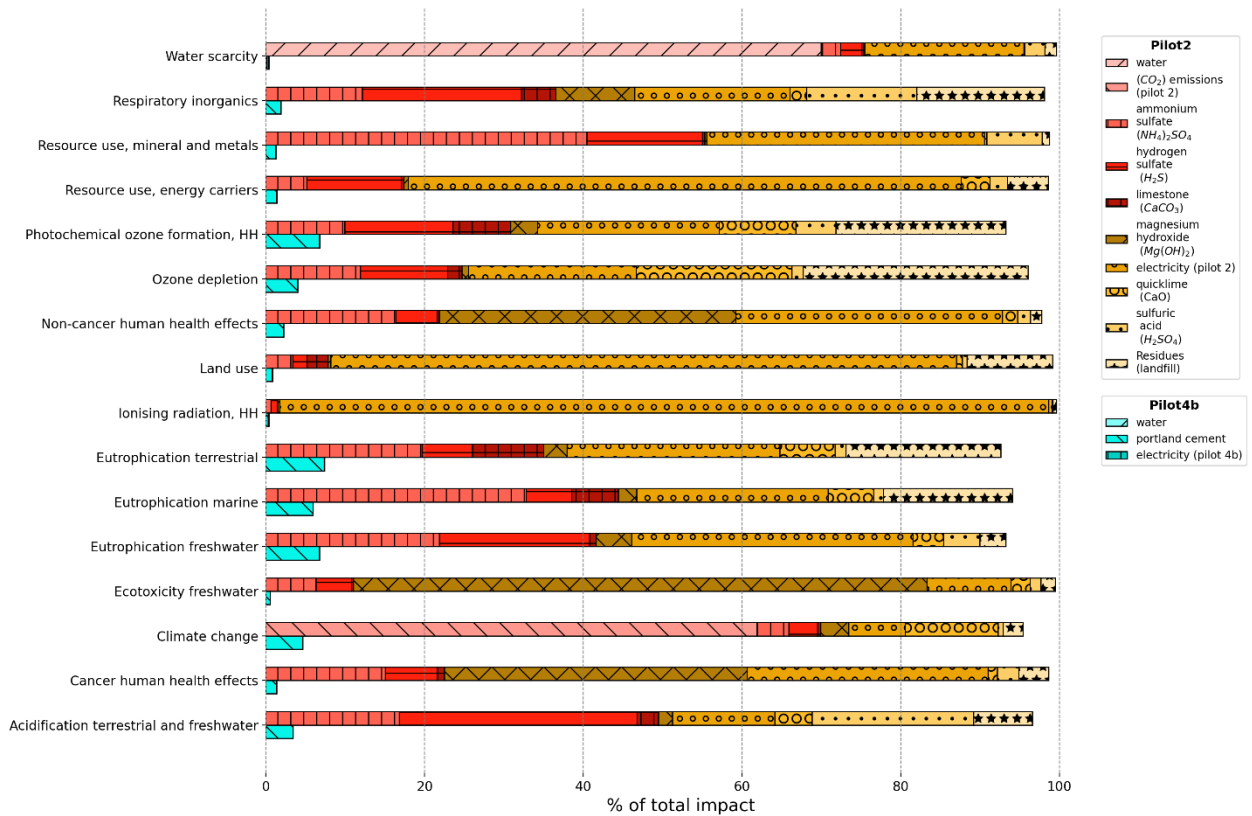


Figure 17: LCA results pilot 2 + pilot 4b



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5 Conclusions

After 48 months from the start of the NEMO project, in which the 8 analysed pilots have been designed, implemented, and tested, the main conclusions derived from the environmental analysis are summarized in the following points:

- The data collection process from the above-mentioned pilots, with the contribution of all pilots manager involved, have been extremely successful, and it has proved smooth and efficient cooperation among all partners. In the end, a detailed inventory table and flowsheet for each analysed pilot has been achieved. It is also worth mentioning the strong and successful effort made by all pilot managers in understanding the needs and rules to perform a proper LCA, considering that they did not have previous expertise in the field.
- **Pilot 1a:** The main environmental drivers are represented by the consumption of sulphuric acid and the electricity demand. The pilot achieved high metals dissolution rate with low concentrations of nutritive elements required by the process, showing good values in terms of environmental performance.
- **Pilot 1b:** Electricity demand, sulphuric acid and ammonium sulphate represent the main environmental hotspots of the process. Further optimisation in the agitation process can lead to reducing electricity consumption and therefore to improvement in the final environmental balance for the whole process.
- **Pilot 2:** Several elements were found to drive the final environmental profile of the pilot (chemicals, electricity, waste treatment). The best action to decrease the environmental impact of pilot 2 strongly depends on the environmental category to be reduced.
- **Pilot 3a:** the optimisation of sodium hydroxide is the most effective strategy to reduce the overall environmental impact of pilot 3a. The reduction in the electricity consumption (which can be easily achieved with the upscaling of the whole process) and in the use of hydrogen sulphate can also reduce, to a lower extent, the environmental impact of some categories.
- **Pilot 3b:** the optimisation in the use of the solvent (the TBP in this study, the Cyanex 923 in real demonstrators) can significantly decrease the environmental impacts. However, such optimisation may have different effects on steps 2-3, compared to step 1. A diversified strategy, based on the general optimisation in the use of chemicals, is strongly advised to significantly decrease the overall environmental impact of the process.
- **Pilot 4:** it is evident the importance of the electricity consumption and the cement used in the process. Therefore, the best strategy to control and minimize environmental impacts is the optimization in the use of these two resources
- **Integration:** The study shows the relevance of integrating the NEMO pilots into a whole near-zero waste valorisation strategy, from mining to recovery metals concentrates and secondary construction materials. Such an integrated scheme can be indeed benchmarked with current mining operations for the production of equivalent products from primary sources, highlighting the environmental benefits brought by the technologies developed in NEMO.
- **Pilot 2+Pilots 4:** The environmental results of the integrated valorisation route Pilot 2+ Pilots 4 showed that environmental benefits overcome the environmental impacts for most of the environmental categories analysed, thanks to the avoided production of primary cobalt and nickel concentrates, and the avoided production of primary Portland cement.



These results highlighted, once more, the complexity of providing a straightforward interpretation of the environmental results, especially when various processes are involved. In light of the above, all the results presented in this report should be considered as a starting point for further discussions and developments of efficient strategies to reduce the overall environmental impacts of the proposed technologies.

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