Supplementary Information file (S1) for

Improving process granularity of life cycle inventories for battery grade nickel

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For each processing pathway, the following data is provided:

1. Parameters used for the scaling of the mining and beneficiation inventory as well as allocation
2. Inventory used in OpenLCA, with background information from the ecoinvent v.3.9.1 database
3. Detailed (absolute and percentage) contribution analyses of climate impacts

Then, supporting and underlying data of each figure in the research article is presented for reproduction.

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Supplementary Note 1: Inventory for POX leaching processing of sulfide ores

Scaling of reference mining and beneficiation inventory data was performed using the parameters described in Supplementary Table 1.

To provide a better estimate for comminution energy requirements during beneficiation, the electricity demand was estimated with the Bond equation (S1)[1]. The estimation is based on the difference between the particle size of the feed (F80) and product streams (P80).

$$E_{Bond} = WI\left(\frac{10}{\sqrt{P80}} - \frac{10}{\sqrt{F80}}\right) \qquad \textit{Equation S1}$$

The electrical requirement (kWh/tonne) is also a function of a proprietary parameter of the ore, the bond grinding work index (WI), which is ~15 kWh/tonne for sulphide ores. When unspecified, F80 is set to default values of 5000 µm, and P80 to 75 µm for sulphide ores comminution [1].

Parameters passed to the Bond equation to compute comminution electricity requirements are also listed in Supplementary Table 1.

Supplementary Table 1: Parameters utilized for the scaling of the mining and beneficiation inventory for POX leaching

Parameters	Reference inventory	Scaled inventory	Precisions
$Strip\ ratio\ (S)$	2.67[2]		Obtained from the process model for nickel mine operation and beneficiation to nickel concentrate, 16% Ni
$x_{Ni,ore}$	2.80%[3]	2.83%[4]	
$m_{Ni,concentrate}$	16%[2]	19%[5]	
$m_{rock}/m_{concentrate}$	26.5[2]	22.1	For the scaled inventory: calculated from Equation 3 (main manuscript)
$m_{concentrate}/m_{Ni,final}$	-	5.38[5]	
P80 (µm)	-	20[6]	
F80 (µm)	-	5000[1]	

The inventory for POX leaching is obtained on a kg Ni_{eq} basis via a mass allocation factor of 89% to nickel, due to co-production of copper (7%) and cobalt (4%)[5].

Supplementary Table 2: Inventory for POX leaching of 19% Ni concentrate and refining to nickel metal

Flow	Amount	Unit	Provider/Description
Inputs			
Concentrate processing to nickel metal			
nickel concentrate, 19% Ni	**4.79**	**kg**	**nickel mine operation and beneficiation to nickel concentrate, 16% Ni, scaled for POX leaching processing**
boric acid, anhydrous, powder	4.60E-03	kg	market for boric acid, anhydrous, powder | GLO
cationic resin	2.20E-04	kg	market for cationic resin | RoW
chemical, organic (proxy for Cyanex 272)	5.00E-05	kg	market for chemical, organic | GLO
chemical, organic (proxy for sodium laurel sulphate)	9.00E-05	kg	market for chemical, organic | GLO
chemical, organic (proxy for DEPHA)	2.00E-04	kg	market for chemical, organic | GLO
chemical, organic (proxy for LIX 84)	6.00E-04	kg	market for chemical, organic | GLO
chemical, organic (proxy for sodium lignosulphonate)	0.12	kg	market for chemical, organic | GLO
electricity, high voltage	11.43	kWh	electricity, high voltage, production mix | CA-NF

heat, district or industrial, other than natural gas (light fuel oil)	0.02	MJ	heat production, light fuel oil, at industrial furnace 1MW | heat, district or industrial, other than natural gas | CA-QC
heat, district or industrial, other than natural gas (diesel)	0.32	MJ	heat production, light fuel oil, at industrial furnace 1MW | heat, district or industrial, other than natural gas | CA-QC
hydrochloric acid, without water, in 30% solution state	0.15	kg	market for hydrochloric acid, without water, in 30% solution state | RoW
kerosene	3.82E-03	kg	market for kerosene | RoW
limestone, crushed, washed	2.15	kg	market for limestone, crushed, washed | Row
oxygen, liquid	2.74	kg	air separation, cryogenic | oxygen, liquid | CA-NF
Polyacrylamide (proxy for flocculants)	0.01	kg	market for polyacrylamide | GLO
soda ash, dense	0.20	kg	market for soda ash, dense | soda ash, dense | GLO
sodium chloride, powder	0.02	kg	market for sodium chloride, powder | GLO
sodium hydrogen sulfite (proxy for sodium metabusulphite)	0.02	kg	market for sodium hydrogen sulfite | GLO
sodium hydrosulfide	0.02	kg	market for sodium hydrosulfide | GLO
sodium hydroxide, without water, in 50% solution state	0.01	kg	market for sodium hydroxide, without water, in 50% solution state | GLO
sulfuric acid	0.62	kg	market for sulfuric acid | RoW
Water, unspecified natural origin, CA	0.08	m^3	
Outputs			
Nickel equivalent	**1**	**kg**	
Carbon dioxide	1.50E-03	kg	Elementary flows/Emission to air/unspecified
Chlorine	7.00E-07	kg	Elementary flows/Emission to air/unspecified
Cobalt II	1.00E-05	kg	Elementary flows/Emission to air/unspecified
Copper ion	3.00E-05	kg	Elementary flows/Emission to air/unspecified
Hydrogen chloride	2.70E-04	kg	Elementary flows/Emission to air/unspecified
Iron ion	8.00E-05	kg	Elementary flows/Emission to air/unspecified
Kerosene	5.00E-09	kg	Elementary flows/Emission to air/unspecified
Lead II	1.25E-06	kg	Elementary flows/Emission to air/unspecified
Manganese II	3.56E-06	kg	Elementary flows/Emission to air/unspecified
Nickel refinery dust	1.80E-04	kg	Elementary flows/Emission to air/unspecified
Nitrogen oxides	1.67E-03	kg	Elementary flows/Emission to air/unspecified
Particulates	1.71E-03	kg	Elementary flows/Emission to air/unspecified
sodium carbonate	1.80E-04	kg	Elementary flows/Emission to air/unspecified
Sulfur dioxide	3.77E-03	kg	Elementary flows/Emission to air/unspecified
Sulfuric acid	1.30E-04	kg	Elementary flows/Emission to air/unspecified

The inventory for nickel metal is used as a provider for the ecoinvent v.3.9.1 nickel sulfate production process model, using electricity, high voltage, production mix | CA-NF. We neglect the contribution of the market for a chemical factory (0.15 $kgCO_{2eq}/kg\ Ni_{eq}$ or 3% of the overall impacts) in the nickel sulfate process model, for a fair comparison with the other process-based inventories in this study which do not retain this level of detail.

Supplementary Table 3: Contribution analysis of climate impacts for POX leaching processing route

supply chain step	contributor	$kgCO_{2eq}$/ kg Ni_{eq}	%
Mining	Mobile equipment energy	0.77	16.0%
Mining	Explosives	0.10	2.1%
Mining	Cement	0.67	14.0%
Mining	Other (EG, lubricating oil, sand)	0.15	3.2%
Beneficiation	Flotation chemicals	0.20	4.1%
Beneficiation	Electricity for grinding	7.21E-02	1.5%
Concentrate processing	Hydromet chemicals	1.20	24.8%
Concentrate processing	Electricity for hydromet plant	0.91	18.9%
Concentrate processing	Thermal energy for hydromet plant	0.03	0.7%
Concentrate processing	Hydromet process emissions	0.0015	0.0%
Nickel sulfate conversion	Sulfuric acid	0.30	6.1%
Nickel sulfate conversion	Thermal energy	0.33	6.9%
Nickel sulfate conversion	Electricity	0.08	1.7%
Sum		4.83	100.0%

Supplementary Note 2: Inventory for HPAL processing of laterite ores

Scaling of the disaggregated contribution data was performed using the parameters described in Supplementary Table 4.

Supplementary Table 4: Parameters utilized for the scaling of the mining and beneficiation inventory for HPAL processing

Parameters	Reference inventory	Scaled inventory	Precisions
$Strip\ ratio\ (S)$	1[7]		
$x_{Ni,ore}$	1.30%[7]	1.22%[8]	
$\eta_{beneficiation}$	1[7]		
$\eta_{concentrate\ processing}$	95.0%[7]		
$\eta_{refining}$	99.5%[2]		
$m_{rock}/m_{Ni,final}$	162.8	173.5	Calculated from Equation 2 (main manuscript)
$m_{concentrate}/m_{Ni,final}$	81.4	86.7	Calculated from Equation 5 (main manuscript)

Supplementary Table 5: HPAL processing route life cycle inventory – sulfur burning flowsheet

Inputs			
Flow	**Amount**	**Unit**	**Provider/Description**
Mining			
blasting	0.02	kg	market for blasting | GLO
diesel, burned in building machine	12.86	MJ	diesel, burned in building machine | GLO
diesel, burned in diesel-electric generating set, 10MW	3.39	MJ	diesel, burned in diesel-electric generating set, 10MW | GLO
Laterite ore	**86.74**	**kg**	
Occupation, industrial area, ID	0.06	m^2*a	
Transformation, to industrial area, ID	0.06	m^2	

Aluminium	2.58	kg	Resource / in ground
Calcium	0.04	kg	Resource / in ground
Chromium	1.99	kg	Resource / in ground
Cobalt	0.18	kg	Resource / in ground
Iron	39.05	kg	Resource / in ground
Magnesium	0.80	kg	Resource / in ground
Manganese	1.02	kg	Resource / in ground
Nickel	1.06	kg	Resource / in ground
Beneficiation			
electricity, high voltage	1.65	kWh	electricity production, hard coal | RoW
Concentrate processing to MHP			
lime, packed	4.00	kg	market for lime, packed | RoW
limestone, crushed, washed	15.00	kg	market for limestone, crushed, washed | RoW
magnesium oxide	2.50	kg	market for magnesium oxide | GLO
sulfur	11.00	kg	sulfur production, petroleum refinery operation | RoW
Water, unspecified natural origin, ID	0.16	m^3	
Nickel sulfate refining			
electricity, high voltage	2.82	kWh	electricity production, hard coal | RoW
heat, district or industrial, natural gas	2.00	MJ	market group for heat, district or industrial, natural gas | GLO
sodium hydroxide, without water, in 50% solution state	0.36	kg	market for sodium hydroxide, without water, in 50% solution state | GLO
sulfuric acid	2.91	kg	market for sulfuric acid | RoW
Water, unspecified natural origin, ID	0.01	m^3	
Outputs			
Carbon dioxide	6.6	kg	Direct CO_2 emissions from limestone for Fe/Al removal
Carbon dioxide	0.06	kg	Process CO_2 emissions for nickel sulfate conversion
Tailings	96.28	kg	Tailings impoundment model for nickel-bearing laterite, from HPAL, Indonesia
Nickel equivalent	1	kg	

Supplementary Table 6: Tailings impoundment model for HPAL residues

Flow	**Category**	**Amount**	**Unit**
Disposal of HPAL tailings		**1**	**kg**
Inputs			
Occupation, dump site	Elementary flows/Resource/land	0.0011	m^2*a
Transformation, from unspecified	Elementary flows/Resource/land	8.4416E-06	m^2
Transformation, to dump site	Elementary flows/Resource/land	8.4416E-06	m^2
Outputs			
Aluminium III	Elementary flows/Emission to water/ground water, long-term	0.01348	kg
Aluminium III	Elementary flows/Emission to water/ground water	0.000040744	kg
Antimony ion	Elementary flows/Emission to water/ground water	1.2102E-10	kg
Antimony ion	Elementary flows/Emission to water/ground water, long-term	2.0319E-08	kg
Arsenic ion	Elementary flows/Emission to water/ground water	3.1909E-09	kg
Arsenic ion	Elementary flows/Emission to water/ground water, long-term	5.7275E-07	kg

Barium II	Elementary flows/Emission to water/ground water, long-term	0.000020344	kg
Barium II	Elementary flows/Emission to water/ground water	5.4844E-10	kg
Beryllium II	Elementary flows/Emission to water/ground water, long-term	1.927E-07	kg
Beryllium II	Elementary flows/Emission to water/ground water	2.2975E-09	kg
Boron	Elementary flows/Emission to water/ground water, long-term	8.9636E-07	kg
Boron	Elementary flows/Emission to water/ground water	5.2078E-09	kg
Cadmium II	Elementary flows/Emission to water/ground water	1.6422E-09	kg
Cadmium II	Elementary flows/Emission to water/ground water, long-term	1.0236E-07	kg
Calcium II	Elementary flows/Emission to water/ground water, long-term	0.04624	kg
Calcium II	Elementary flows/Emission to water/ground water	0.00394	kg
Chromium VI	Elementary flows/Emission to water/ground water	2.4999E-06	kg
Chromium VI	Elementary flows/Emission to water/ground water, long-term	0.00047	kg
Cobalt II	Elementary flows/Emission to water/ground water, long-term	0.00085	kg
Cobalt II	Elementary flows/Emission to water/ground water	0.000037943	kg
Copper ion	Elementary flows/Emission to water/ground water	1.4634E-07	kg
Copper ion	Elementary flows/Emission to water/ground water, long-term	0.000066804	kg
Iron ion	Elementary flows/Emission to water/ground water, long-term	0.30743	kg
Iron ion	Elementary flows/Emission to water/ground water	0.00067	kg
Lead II	Elementary flows/Emission to water/ground water, long-term	9.0954E-07	kg
Lead II	Elementary flows/Emission to water/ground water	4.5626E-10	kg
Magnesium	Elementary flows/Emission to water/ground water	0.00078	kg
Magnesium	Elementary flows/Emission to water/ground water, long-term	0.00903	kg
Manganese II	Elementary flows/Emission to water/ground water	0.00024	kg
Manganese II	Elementary flows/Emission to water/ground water, long-term	0.00737	kg
Mercury II	Elementary flows/Emission to water/ground water, long-term	4.7249E-08	kg
Mercury II	Elementary flows/Emission to water/ground water	2.0108E-10	kg
Molybdenum VI	Elementary flows/Emission to water/ground water	1.5676E-08	kg
Molybdenum VI	Elementary flows/Emission to water/ground water, long-term	3.0931E-07	kg
Nickel II	Elementary flows/Emission to water/ground water, long-term	0.00451	kg
Nickel II	Elementary flows/Emission to water/ground water	0.000064237	kg
Potassium I	Elementary flows/Emission to water/ground water	4.2118E-08	kg
Potassium I	Elementary flows/Emission to water/ground water, long-term	0.000016448	kg
Scandium	Elementary flows/Emission to water/ground water, long-term	0.000063972	kg
Scandium	Elementary flows/Emission to water/ground water	8.9817E-07	kg
Selenium IV	Elementary flows/Emission to water/ground water	1.8771E-09	kg
Selenium IV	Elementary flows/Emission to water/ground water, long-term	2.682E-07	kg
Silicon	Elementary flows/Emission to water/ground water	0.000051797	kg
Silicon	Elementary flows/Emission to water/ground water, long-term	0.01044	kg
Silver I	Elementary flows/Emission to water/ground water	6.0994E-10	kg
Silver I	Elementary flows/Emission to water/ground water, long-term	1.1434E-06	kg
Sodium I	Elementary flows/Emission to water/ground water	0.000079988	kg
Sodium I	Elementary flows/Emission to water/ground water, long-term	0.00179	kg
Strontium	Elementary flows/Emission to water/ground water	1.4157E-07	kg
Strontium	Elementary flows/Emission to water/ground water, long-term	0.000022153	kg
Thallium I	Elementary flows/Emission to water/ground water, long-term	1.2989E-07	kg
Thallium I	Elementary flows/Emission to water/ground water	1.0951E-10	kg

Tin ion	Elementary flows/Emission to water/ground water, long-term	8.4101E-07	kg
Tin ion	Elementary flows/Emission to water/ground water	3.9866E-09	kg
Titanium ion	Elementary flows/Emission to water/ground water	3.2148E-08	kg
Titanium ion	Elementary flows/Emission to water/ground water, long-term	0.00019	kg
Tungsten	Elementary flows/Emission to water/ground water	3.6785E-09	kg
Tungsten	Elementary flows/Emission to water/ground water	3.2915E-07	kg
Vanadium V	Elementary flows/Emission to water/ground water, long-term	1.6669E-06	kg
Vanadium V	Elementary flows/Emission to water/ground water	8.358E-09	kg
Zinc II	Elementary flows/Emission to water/ground water	1.7277E-06	kg
Zinc II	Elementary flows/Emission to water/ground water	0.000085372	kg

Supplementary Table 7: Contribution analysis of climate impacts for HPAL processing route –sulfur burning flowsheet

supply chain step	contributor	$kgCO_{2eq}$/ kg Ni_{eq}	%
Mining	Mobile equipment energy	1.28	5.9%
Mining	Explosives	0.11	0.5%
Mining	Electricity for open-pit mining	0.32	1.5%
Beneficiation	Electricity for grinding	1.81	8.4%
Concentrate processing	Limestone - embodied	0.09	0.4%
Concentrate processing	Magnesia - embodied	5.19	24.0%
Concentrate processing	Lime - embodied	0.28	1.3%
Concentrate processing	Direct CO_2 emissions from limestone	6.60	30.5%
Concentrate processing	Electricity and acid production	1.73	8.0%
Sulfate conversion	Sulphuric acid	0.51	2.4%
Sulfate conversion	Electricity (Coal)	3.09	14.3%
Sulfate conversion	Sodium Hydroxide	0.47	2.2%
Sulfate conversion	Process emissions	0.06	0.3%
Sulfate conversion	Thermal Energy (Natural gas)	0.11	0.5%
	Total	21.64	100.0%

To convert the HPAL inventory to an off-site coal-powered electricity mix, the heat of reactions of on-site sulfuric acid production were first summed as potential heat to recover [9].

$S + O_2 \rightarrow SO_2$	$\Delta H^0 = -296.9 \frac{kJ}{mol}$
$SO_2 + \frac{1}{2} O_2 \rightarrow SO_3$	$\Delta H^0 = -99.0 \frac{kJ}{mol}$
$SO_3 + H_2O \rightarrow H_2SO_4$	$\Delta H^0 = -132.5 \frac{kJ}{mol}$
$S + \frac{3}{2} O_2 + H_2O \rightarrow H_2SO_4$	$\Sigma\Delta H^0 = -528.4 \frac{kJ}{mol}$

Converting on a mass basis, (32g/mol of sulfur), we find that 16.51 MJ are produced per kg of sulfur converted into sulfuric acid. To convert on a basis of sulfuric acid, we can use a stoichiometric ratio of 0.33 kg of sulfur/kg sulfuric acid (32 g/mol S / 98 g/mol H_2SO_4), for 5,392 MJ/tonne of sulfuric acid. To obtain the final heat recovered, energy requirements to operate the sulfuric acid plant (834.5 MJ/tonne sulfuric acid) were subtracted [10] and a 40% heat recovery factor was assumed[9].Therefore, we assume that 1,322 MJ are recovered per tonne of sulfuric acid produced.

In Supplementary Table 5, it is reported that 11 kg of sulfur are required per tonne of nickel equivalent. The equivalent stoichiometric amount of sulfuric acid produced is 33.69 kg (11/0.33). Therefore, we will assume that the 44.54 MJ (34 kg*1.3MJ/kg H_2SO_4) recovered from the acid plant are supplied by off-site coal-powered electricity. The carbon emission factor for electricity production from hard coal in ecoinvent v.3.9.1 is nearly identical to the carbon emission factor for the production mix in Indonesia.

Supplementary Table 8 summarizes the changes to the HPAL inventory in the concentrate processing step, the only step that changes in the whole value chain.

Supplementary Table 8 : Changes to the concentrate processing inventory for the HPAL-coal variant

Concentrate processing			
+electricity, high voltage	**44.54**	**MJ**	**electricity production, hard coal | RoW (proxy for lignite, equivalent to Indonesian production mix)**
lime, packed	4.00	kg	market for lime, packed | RoW
limestone, crushed, washed	15.00	kg	market for limestone, crushed, washed | RoW
magnesium oxide	2.50	kg	market for magnesium oxide | GLO
~~sulfur~~	**~~11.00~~**	**~~kg~~**	**~~sulfur production, petroleum refinery operation | Row~~**
+sulfuric acid	**33.69**	**kg**	**market for sulfuric acid | RoW**
Water, unspecified natural origin, ID	0.16	m^3	
Nickel equivalent	1	kg	

Supplementary Table 9: Contribution analysis of climate impacts for HPAL processing route – coal-powered flowsheet

supply chain step	contributor	$kgCO_{2eq}$/ $kg\ Ni_{eq}$	%
Mining	Mobile equipment energy	1.28	3.2%
Mining	Explosives	0.11	0.3%
Mining	Electricity for open-pit mining	0.32	0.8%
Beneficiation	Electricity for grinding	1.81	4.6%
Concentrate processing	Limestone - embodied	0.09	0.2%
Concentrate processing	Magnesia - embodied	5.19	13.1%
Concentrate processing	Lime - embodied	0.28	0.7%
Concentrate processing	Direct CO_2 emissions from limestone	6.60	16.7%
Concentrate processing	Electricity and acid production	19.56	49.6%
Sulfate conversion	Sulphuric acid	0.51	1.3%
Sulfate conversion	Electricity (Coal)	3.09	7.8%
Sulfate conversion	Sodium Hydroxide	0.47	1.2%
Sulfate conversion	Process emissions	0.06	0.1%
Sulfate conversion	Thermal Energy (Natural gas)	0.11	0.3%
	Total	39.48	100.0%

Lastly, a scenario analysis was performed on two parameters of the HPAL inventory 1) electricity mix and 2) ore grade. First, to assess the impact of fossil fuel electricity, the electricity mix was assumed to be sourced from solar[11] for all electricity inputs of the HPAL sulfur- and coal-powered variants. The resulting contribution analysis is presented in Supplementary Table 10.

Supplementary Table 10: Contribution analysis of climate impacts for both HPAL flowsheets, sourcing solar electricity

		Sulfur-powered		Off-site electricity (previously coal-based)	
supply chain step	contributor	$kgCO_{2eq}$/ kg Ni_{eq}	%	$kgCO_{2eq}$/ kg Ni_{eq}	%
Mining	Mobile equipment energy	1.28	7.7%	1.28	6.0%
Mining	Explosives	0.11	0.6%	0.11	0.5%
Mining	**Electricity for open-pit mining**	**0.04**	**0.3%**	**0.04**	**0.2%**
Beneficiation	**Electricity for grinding**	**0.07**	**0.4%**	**0.07**	**0.3%**
Concentrate processing	Limestone - embodied	0.09	0.5%	0.09	0.4%
Concentrate processing	Magnesia - embodied	5.19	31.1%	5.19	24.2%
Concentrate processing	Lime - embodied	0.28	1.7%	0.28	1.3%
Concentrate processing	Direct CO_2 emissions from limestone	6.60	39.6%	6.60	30.8%
Concentrate processing	**Electricity and acid production**	1.73	10.4%	**6.49**	**30.3%**
Sulfate conversion	Sulphuric acid	0.51	3.1%	0.51	2.4%
Sulfate conversion	**Electricity**	**0.13**	**0.8%**	**0.13**	**0.6%**
Sulfate conversion	Sodium Hydroxide	0.47	2.8%	0.47	2.2%
Sulfate conversion	Process emissions	0.06	0.4%	0.06	0.3%
Sulfate conversion	Thermal Energy (Natural gas)	0.11	0.7%	0.11	0.5%
	Total	**16.66**	100.0%	**21.43**	100.0%

Next, the ore grade was declined to 0.5%[12] using our scaling method, to assess the effect of declining ore grade on climate impacts of the mining and beneficiation inventory for HPAL. The resulting contribution analysis is presented in Supplementary Table 11.

Supplementary Table 11: Contribution analysis of climate impacts for both HPAL flowsheets, ore grade declined to 0.5%

		Sulfur-powered		Coal-powered	
supply chain step	contributor	$kgCO_{2eq}$/ kg Ni_{eq}	%	$kgCO_{2eq}$/ kg Ni_{eq}	%
Mining	**Mobile equipment energy**	**3.12**	**11.7%**	**3.12**	**7.0%**
Mining	**Explosives**	**0.26**	**1.0%**	**0.26**	**0.6%**
Mining	**Electricity for open-pit mining**	**0.78**	**2.9%**	**0.78**	**1.8%**
Beneficiation	**Electricity for grinding**	**4.42**	**16.5%**	**4.42**	**9.9%**
Concentrate processing	Limestone - embodied	0.09	0.3%	0.09	0.2%
Concentrate processing	Magnesia - embodied	5.19	19.4%	5.19	11.6%
Concentrate processing	Lime - embodied	0.28	1.0%	0.28	0.6%
Concentrate processing	Direct CO_2 emissions from limestone	6.60	24.7%	6.60	14.8%
Concentrate processing	Electricity and acid production	1.73	6.5%	19.56	43.9%
Sulfate conversion	Sulphuric acid	0.51	1.9%	0.51	1.2%
Sulfate conversion	Electricity	3.09	11.6%	3.09	6.9%
Sulfate conversion	Sodium Hydroxide	0.47	1.8%	0.47	1.1%
Sulfate conversion	Process emissions	0.06	0.2%	0.06	0.1%
Sulfate conversion	Thermal Energy (Natural gas)	0.11	0.4%	0.11	0.3%
	Total	**26.71**	100.0%	**44.55**	100.0%

Supplementary Note 3: Inventory for bioheap leaching processing of sulfide ores

Data sourced for the construction of the mining and beneficiation inventory for bioheap leaching is listed in Supplementary Table 12. The reference year selected for the inventory was 2020 due to its higher data completeness. For inventory modelling, data was primarily sourced from two environmental permits, one for mining and concentrate processing operations until nickel sulfide intermediate [13] and another for refining until battery-grade nickel sulfate [14]. For comminution requirements during beneficiation, the Bond equation (refer to Equation S1) was used as an approximation, with necessary parameters also listed in Supplementary Table 12.

Supplementary Table 12: Parameters utilized for the modelling of the mining and beneficiation inventory for bioheap leaching

Parameters	Reference inventory	Precisions
$Strip\ ratio\ (S)$	0.98[13]	
$x_{Ni,ore}$	0.27%[13]	
P80 (μm)	8000[15]	
F80 (μm)	8000 000	Unknown, but assumed that a 1000 X reduction is performed as conservative estimate. Since P80 is high the energy consumption for grinding remains low according to the Bond equation.
$\eta_{bioleaching}$	99.0%[15]	
$\eta_{processing\ to\ NiS}$	90.0%[13]	
$\eta_{refining}$	99.8%[14]	
$m_{ore}/m_{Ni,final}$ non allocated	588.0[16]	
Mass allocation factor for nickel for mining to concentrate processing inventories	30%	Calculated based on the mass of final products from processing operations to nickel-cobalt sulfide[13]
$m_{ore}/m_{Ni,final}$ allocated to Ni	176.2	$m_{ore}/m_{Ni,final} * allocation\ factor$
$\eta_{beneficiation}$	70.8%	Calculated by rearranging Equation 4 (main manuscript)

Supplementary Table 13: Inventory for bioheap leaching processing route

Inputs			
Flow	**Amount**	**Unit**	**Provider/Description**
Mining and beneficiation			
blasting	0.11	kg	market for blasting | blasting | GLO
diesel, burned in building machine	11.28	MJ	diesel, burned in building machine | GLO
electricity, high voltage	0.29	kWh	electricity, high voltage, production mix | FI
Sulfide ore	**176.17**	**kg**	
Occupation, industrial area, FI	0.009	m^2*a	
Transformation, to industrial area, FI	0.009	m^2	
Cobalt	0.04	kg	Resource/in ground
Copper	0.25	kg	Resource/in ground
Iron	18.15	kg	Resource/in ground
Nickel	0.48	kg	Resource/in ground
Zinc	0.99	kg	Resource/in ground
Concentrate processing to nickel sulfide			
sulfuric acid	1.14	kg	market for sulfuric acid | RER
sulfur dioxide	0.005	kg	market for sulfur dioxide, liquid | RER

sodium hydroxide	0.45	kg	market for sodium hydroxide, without water, in 50% solution state | GLO
limestone, crushed, washed	0.96	kg	market for limestone, crushed, washed | RoW
lime, packed	0.90	kg	market for lime, packed | RoW
foaming agent	0.0039	kg	market for foaming agent | GLO
hydrogen peroxide	0.026	kg	market for hydrogen peroxide, without water, in 50% solution state | RER
hydrogen sulfide	0.63	kg	market for hydrogen sulfide | RER
hydrochloric acid	0.00016	kg	market for hydrochloric acid, without water, in 30% solution state | RoW
electricity, high voltage	2.90	kWh	electricity, high voltage, production mix | FI
heat, district or industrial, other than natural gas (steam from light fuel oil)	0.32	kWh	heat production, light fuel oil, at industrial furnace 1MW | RoW
Nickel sulfate refining			
electricity, high voltage	1.86	kWh	electricity, high voltage, production mix | FI
heat, district or industrial, other than natural gas (heat from biomass)	2.34	kWh	heat production, wood chips from industry, at furnace 1000kW | RoW
ammonia	0.73	kg	market for ammonia, anhydrous, liquid | RER
oxygen	1.56	kg	air separation, cryogenic | oxygen, liquid | FI
sulfur dioxide	0.0004	kg	market for sulfur dioxide, liquid | RER
sodium hydroxide, without water, in 50% solution state	0.13	kg	market for sodium hydroxide, without water, in 50% solution state | GLO
soda ash, dense	0.05	kg	market for soda ash, dense | GLO
chemical, organic (proxy for precipitation agent)	0.04	kg	market for chemical, organic | GLO
chemical, organic (proxy for organic extraction solvent)	0.0018	kg	market for chemical, organic | GLO
chemical, organic (proxy for Cyanex 272)	0.00013	kg	market for chemical, organic | GLO
chemical, organic (proxy for D-2EHPA)	0.00013	kg	market for chemical, organic | GLO
chemical, organic (proxy for V10)	0.00013	kg	market for chemical, organic | GLO
sulfuric acid	2.60	kg	market for sulfuric acid | RER
water, deionized	5.20	kg	market for water, deionised | Europe without Switzerland
Outputs			
carbon dioxide	0.42	kg	Direct CO_2 emissions from limestone usage Elementary flows/Emission to air/unspecified
Nickel equivalent	1	kg	
Ammonium sulfate	6.50E-05	kg	Elementary flows/Emission to air/unspecified
Copper ion	9.47E-08	kg	Elementary flows/Emission to water/surface water
Manganese II	6.62E-05	kg	Elementary flows/Emission to water/surface water
Nickel II	1.88E-06	kg	Elementary flows/Emission to water/surface water
Nickel refinery dust	0.00016	kg	Elementary flows/Emission to air/unspecified
NMVOC, non-methane volatile organic compounds	0.00359	kg	Elementary flows/Emission to air/unspecified

Sodium I	9.04E-06	kg	Elementary flows/Emission to water/surface water
Sulfate	0.00011	kg	Elementary flows/Emission to water/surface water
Zinc II	4.04E-06	kg	Elementary flows/Emission to water/surface water

Supplementary Table 14: Contribution analysis for bioheap leaching of sulfide ores

supply chain step	contributor	$kgCO_{2eq}$ / kg Ni_{eq}	%
Mining	Mobile equipment energy	1.12	14.6%
Mining	Explosives	0.49	6.4%
Beneficiation	Electricity for grinding	6.29E-02	0.8%
Concentrate processing	Chemicals for mixed sulphide refining	1.19	15.5%
Concentrate processing	Electricity for mixed sulphide refining	0.64	8.3%
Concentrate processing	Steam for mixed sulphide refining	0.09	1.1%
Concentrate processing	Hydromet process emissions	0.42	5.5%
Nickel sulfate conversion	Electricity for sulfate refining	0.41	5.4%
Nickel sulfate conversion	Chemicals for sulfate refining	3.20	41.7%
Nickel sulfate conversion	Steam for sulphate refining	0.05	0.7%
	Total	7.66	100.0%

Supplementary Note 4: Inventory for the bioleaching of sulfidic tailings

To adjust the inventory on a 1 kg Ni_{eq} basis, mass allocation was performed on two different datasets, one for concentrate processing[17] and one for nickel sulfate refining[14]. For the latter, refer to Supplementary Note 4. It is to be noted that using the inventory from bioheap leaching for nickel sulfide refining is the main limitation of the tailings bioleaching inventory. Indeed, the consumption of chemicals will vary based on the proportion of impurities found in the nickel sulfide compound. As a comparative standpoint, the nickel sulfide intermediate from bioheap leaching contains between 43-60% Ni[13], while NiS from tailings bioleaching contains 65% Ni[17]. Therefore, using the inventory from a less pure intermediate as proxy may be a conservative estimate, assuming similar impurities in both intermediates.

For concentrate processing, mass allocation was performed to attribute impacts to each tonne of metal (in this case nickel), based on the following valuable products breakdown[17].

Supplementary Table 15: Mass allocation for bioleaching of tailings

Valuable products	**Mass (tonnes)**
Copper equivalent in CuS	335
Zinc equivalent in ZnS	1,126
Nickel equivalent in NiS	603
Cobalt equivalent in CoS	1,028
Sum	3,091

Supplementary Table 16: Inventory for tailings bioleaching processing route

Inputs			
Flow	**Amount**	**Unit**	**Provider/Description**
Concentrate processing			
Tailings (dry mass)	**54.31**	**kg**	
sulfuric acid	1.63	kg	market for sulfuric acid | RER
lime, packed	2.72	kg	market for lime, packed | RER
magnesium oxide	0.92	kg	market for magnesium oxide | RER
calcium carbonate, precipitated	38.27	kg	market for calcium carbonate production, precipitated | RER
ammonium sulfate	0.92	kg	market for ammonium sulfate | RER
hydrogen sulfide	1.63	kg	market for hydrogen sulfide | RER
cement, Portland	1.46	kg	market for cement, Portland | Europe without Switzerland
electricity, high voltage	0.045	MJ	electricity, high voltage, production mix | SE
water, unspecified natural origin, SE	0.95	m^3	
process-specific burdens, inert material landfill	101.40	kg	process-specific burdens, inert material landfill | CH
Nickel sulfate refining			
electricity, high voltage	1.86	kWh	electricity, high voltage, production mix | SE
heat, district or industrial, other than natural gas (heat from biomass)	2.34	kWh	heat production, wood chips from industry, at furnace 1000kW | heat, district or industrial, other than natural gas | RoW
ammonia	0.73	kg	market for ammonia, anhydrous, liquid | ammonia, anhydrous, liquid | RER
oxygen	1.56	kg	air separation, cryogenic | oxygen, liquid | SE
sulfur dioxide	0.0004	kg	market for sulfur dioxide, liquid | RER
sodium hydroxide, without water, in 50% solution state	0.13	kg	market for sodium hydroxide, without water, in 50% solution state | GLO
soda ash, dense	0.05	kg	market for soda ash, dense | GLO
chemical, organic (proxy for precipitation agent)	0.04	kg	market for chemical, organic | GLO
chemical, organic (proxy for organic extraction solvent)	0.0018	kg	market for chemical, organic | GLO
chemical, organic (proxy for Cyanex 272)	0.00013	kg	market for chemical, organic | GLO
chemical, organic (proxy for D-2EHPA)	0.00013	kg	market for chemical, organic | GLO
chemical, organic (proxy for V10)	0.00013	kg	market for chemical, organic | GLO
sulfuric acid	2.60	kg	market for sulfuric acid | RER
water, deionized	5.20	kg	market for water, deionised | Europe, without Switzerland
Outputs			
carbon dioxide	16.84	kg	Direct CO_2 emissions from limestone usage

Nickel equivalent	1	kg	
sand	16.91	kg	
gravel, round	16.91	kg	
Ammonium sulfate	6.50E-05	kg	Elementary flows/Emission to air/unspecified
Nickel refinery dust	0.00016	kg	Elementary flows/Emission to air/unspecified
NMVOC, non-methane volatile organic compounds	0.00359	kg	Elementary flows/Emission to air/unspecified

It is to be noted that since very low, electricity requirements to grind tailings to 20 µm before the bioleaching reactor is accounted for in the concentrate processing electricity contributor[17], and not in the beneficiation stage.

Supplementary Table 17: Contribution analysis for bioleaching of sulfidic tailings

supply chain step	contributor	$kgCO_{2eq}$ / kg Ni_{eq}	%
Concentrate processing	Chemicals	19.17	47.39%
Concentrate processing	Electricity	2.84E-04	0.00%
Concentrate processing	Process emissions	16.84	41.61%
Concentrate processing	Inert waste treatment (tailings back-filling)	1.57	3.89%
Nickel sulfate conversion	Electricity for sulfate refining	0.04	0.11%
Nickel sulfate conversion	Chemicals for sulfate refining	2.78	6.87%
Nickel sulfate conversion	Heat for sulfate refining	0.05	0.13%
	Total	40.46	100.00%

Supplementary Note 5: Inventory for the pyrometallurgical treatment of sulfide ores

Only energetic requirements are provided in the corresponding mining and beneficiation inventory for flash smelting of sulfide ores [18]. For completeness, we scaled the material portion of the inventory for mining and beneficiation of sulfide concentrate (16%) in the ecoinvent database [2]. Conversion to nickel sulfate is also based on the corresponding dataset in ecoinvent [2].

Supplementary Table 18: Parameters utilized for the scaling of the material mining and beneficiation inventory for flash smelting

Parameters	Reference inventory	Scaled inventory	Precisions
$Strip\ ratio\ (S)$	2.67[2]		Obtained from the process model for nickel mine operation and beneficiation to nickel concentrate, 16% Ni
$x_{Ni,ore}$	2.80%[3]	2.05%[18]	
$m_{Ni,concentrate}$	16.0%[2]	11.5%[18]	
$m_{rock}/m_{concentrate}$	26.5[2]	26.0	For the scaled inventory: calculated from Equation 3 (main manuscript)

Supplementary Table 19: Inventory for flash smelting of sulfide ores and ammoniacal hydrogen precipitation to nickel metal

Inputs			
Flow	**Amount**	**Unit**	**Provider/Description**
Mining and beneficiation			
Nickel concentrate	**7.79**	**kg**	**scaled material inventory for nickel mine operation and beneficiation to nickel concentrate, 16% Ni**
diesel, burned in building machine	3.64	MJ	market for diesel, burned in building machine | GLO
electricity, medium voltage (mine operation)	2.28	kWh	market for electricity, medium voltage | CA-ON
electricity, medium voltage (mine operation)	3.06	kWh	market for electricity, medium voltage | CA-ON
Concentrate processing			
transport, freight, lorry >32 metric ton, EURO4	3.54	t*km	transport, freight, lorry >32 metric ton, EURO4 | RoW
Flash smelting			
heat, district or industrial, natural gas	8.20	MJ	heat production, natural gas, at industrial furnace >100kW | CA-QC
heat, district or industrial, other than natural gas	6.24	MJ	heat production, light fuel oil, at industrial furnace 1MW | CA-QC
heat, district or industrial, other than natural gas	11.22	MJ	heat production, at hard coal industrial furnace 1-10MW | CA-QC
oxygen, liquid	0.49	kg	air separation, cryogenic | ON
silica sand	2.24	kg	market for silica sand | GLO
Settling furnace			
heat, district or industrial, other than natural gas	9.01	MJ	heat production, at coal coke industrial furnace 1-10MW | CA-QC
electricity, high voltage	0.70	kWh	electricity, high voltage, production mix | CA-ON
Converter			
silica sand	0.29	kg	market for silica sand | GLO
Hydrogen reduction to nickel metal			
transport, freight, lorry >32 metric ton, EURO4	0.91	t*km	transport, freight, lorry >32 metric ton, EURO4 | RoW
ammonia, anhydrous, liquid	0.64	kg	market for ammonia, anhydrous, liquid | RoW
hydrogen, liquid	0.07	kg	market for hydrogen, liquid | RoW
electricity, high voltage	2.90	kWh	electricity, high voltage, production mix | CA-ON
heat, district or industrial, natural gas	18.50	MJ	heat production, natural gas, at industrial furnace >100kW | CA-QC
Outputs			
Nickel metal	1	kg	

The following contribution analysis for the flash smelting route was obtained for refining up to nickel sulfate.

Supplementary Table 20: Contribution analysis for the flash smelting of sulfide ores up to nickel sulfate

supply chain step	contributor	$kgCO_{2eq}$/ kg Ni_{eq}	%
mining	Mobile equipment energy	0.36	3.0%
mining	Explosives	0.19	1.6%
mining	Cement	1.29	10.9%
mining	Electric energy	0.16	1.4%
mining	Other (EG, lubricating oil, sand)	0.29	2.5%
beneficiation	Flotation chemicals	0.38	3.2%
beneficiation	Electricity for grinding	0.22	1.8%
concentrate processing	Concentrate drying	0.46	3.9%
concentrate processing	Chemical reagents	2.69	22.7%
concentrate processing	Silica sand	0.11	0.9%
concentrate processing	Electricity	0.26	2.2%
concentrate processing	Reductants	2.86	24.1%
concentrate processing	Thermal energy	1.50	12.7%
concentrate processing	Transportation	0.37	3.1%
nickel sulfate conversion	Sulfate - Sulfuric acid	0.30	2.5%
nickel sulfate conversion	Sulfate - Energy	0.41	3.4%
	Sum	11.86	100.0%

The following contribution analysis was generated by considering the full product system available in the ecoinvent v.3.9.1 dataset for smelting and refining of 16% nickel concentrate, adding the step for nickel sulfate conversion which process model is also provided in the database[2]. The contribution analysis is scaled from a kg nickel sulfate basis to a kg Ni_{eq} using a nickel content of 39% in anhydrous nickel sulfate.

Supplementary Table 21: Contribution analysis of smelting and refining of sulfide concentrate to nickel sulfate (ecoinvent)

supply chain step	contributor	$kgCO_{2eq}$/ kg Ni_{eq}	%
mining	Mobile equipment energy	1.10	9.1%
Mining	Electricity	0.07	0.6%
mining	Explosives	0.14	1.2%
mining	Cement	0.96	8.0%
mining	Other (EG, lubricating oil, sand)	0.33	2.8%
beneficiation	Flotation chemicals	0.28	2.4%
concentrate processing	Ammonia	0.24	2.0%
concentrate processing	Hydrogen	0.01	0.1%
concentrate processing	Lime	0.14	1.1%
concentrate processing	Silica sand	0.08	0.7%
concentrate processing	Electricity	2.55	21.3%
concentrate processing	Heat from natural gas	0.72	6.0%
concentrate processing	Heat, other than natural gas	2.74	22.9%
concentrate processing	Transportation	0.25	2.1%
concentrate processing	Process emissions	0.87	7.3%
nickel sulfate conversion	Sulfate - Sulfuric acid	0.30	2.5%
nickel sulfate conversion	Sulfate - Thermal energy	0.33	2.8%
nickel sulfate conversion	Sulfate - Electricity	0.74	6.2%
nickel sulfate conversion	Other (chemical factory, nitrogen)	0.13	1.1%
	Total	11.99	100.0%

Supplementary Note 6: Inventory for RKEF-NPI processing of laterite ores

Scaling of the disaggregated contribution data was performed using the parameters described in Supplementary Table 22.

Supplementary Table 22: Parameters utilized for the scaling of the mining and beneficiation inventory

Parameters	**Reference inventory**	**Scaled inventory**	**Precisions**
$Strip\ ratio\ (S)$	1[7]		
$x_{Ni,ore}$	1.30%[7]	1.22%[8]	
$\eta_{beneficiation}$	n/a (no beneficiation) [7]		
$\eta_{concentrate\ processing}$	93.0%[19]	88.0%[8]	
$\eta_{refining}$	99.5%[2]		
$m_{rock}/m_{Ni,final}$	166.3	187.3	Calculated from Equation 2 (main manuscript)
$m_{concentrate}/m_{Ni,final}$	83.2	93.6	Calculated from Equation 5 (main manuscript)

Supplementary Table 23: RKEF-NPI processing route life cycle inventory

Inputs			
Flow	**Amount**	**Unit**	**Provider/Description**
Mining			
blasting	0.03	kg	market for blasting | GLO
diesel, burned in building machine	13.59	MJ	diesel, burned in building machine | GLO
diesel, burned in diesel-electric generating set, 10MW	3.56	MJ	diesel, burned in diesel-electric generating set, 10MW | GLO
Laterite ore	**93.64**	**kg**	
Occupation, industrial area, ID	0.07	m^2*a	
Transformation, to industrial area, ID	0.07	m^2	
Aluminium	2.78	kg	
Calcium	0.04	kg	Resource / in ground
Chromium	2.15	kg	Resource / in ground
Cobalt	0.19	kg	Resource / in ground
Iron	42.15	kg	Resource / in ground
Magnesium	0.86	kg	Resource / in ground
Manganese	1.10	kg	Resource / in ground
Nickel	1.15	kg	Resource / in ground
Potassium	0.01	kg	Resource / in ground
Sodium	0.12	kg	Resource / in ground
Concentrate processing			
electricity, high voltage	37.00	kWh	electricity, high voltage, production mix | ID
heat, district or industrial, natural gas	34.00	kWh	market for heat, district or industrial, natural gas | RoW
heat, district or industrial, other than natural gas	317.90	MJ	heat production, at hard coal industrial furnace 1-10MW | RoW
Nickel sulfate refining			
electricity, high voltage	40.10	kWh	electricity, high voltage, production mix | ID
heat, district or industrial, natural gas	5.56	MJ	market group for heat, district or industrial, natural gas | RoW
limestone, crushed, washed	6.10	kg	market for limestone, crushed, washed | RoW
soda ash, dense	0.10	kg	market for soda ash, dense | GLO
sodium hydroxide, without water, in 50% solution state	0.10	kg	market for sodium hydroxide, without water, in 50% solution state | GLO
sulfuric acid	7.50	kg	market for sulfuric acid | RoW
Water, unspecified natural origin, ID	0.14	m^3	
Outputs			
Carbon dioxide	2.68	kg	Direct CO_2 emissions from limestone usage
Nickel equivalent	1	kg	

Supplementary Table 24: Contribution analysis of climate impacts for RKEF-NPI processing route

supply chain step	contributor	$kgCO_{2eq}$/ kg Ni_{eq}	%
Mining	Mobile equipment energy	1.35	1.0%
Mining	Explosives	0.11	0.1%
Mining	Electricity for open-pit mining	0.34	0.2%
Concentrate processing	Char and hard coal - Calcination	43.84	31.4%
Concentrate processing	Fuel - Drier	4.67	3.3%
Concentrate processing	Electric arc furnace consumption	40.76	29.2%
Nickel sulfate conversion	Limestone	0.04	0.0%
Nickel sulfate conversion	Limestone - direct emissions	2.68	1.9%
Nickel sulfate conversion	Sodium carbonate	0.13	0.1%
Nickel sulfate conversion	Thermal energy	0.21	0.2%
Nickel sulfate conversion	Electricity - conversion to sulphate	44.17	31.6%
Nickel sulfate conversion	Sulfuric acid	1.15	0.8%
Nickel sulfate conversion	Sodium hydroxide	0.13	0.1%
	Total	139.58	100.0%

Lastly, a scenario analysis was performed on two parameters of the RKEF-NPI inventory 1) electricity mix and 2) ore grade. First, to assess the impact of fossil fuel electricity, the electricity mix was assumed to be sourced from solar[11] for all electricity inputs. The resulting contribution analysis is presented in Supplementary Table 25.

Supplementary Table 25: Contribution analysis of climate impacts for RKEF-NPI processing route, sourcing solar electricity

supply chain step	contributor	$kgCO_{2eq}$/ kg Ni_{eq}	%
Mining	Mobile equipment energy	1.35	2.3%
Mining	Explosives	0.11	0.2%
Mining	**Electricity for open-pit mining**	**0.04**	**0.1%**
Concentrate processing	Char and hard coal - Calcination	43.84	75.8%
Concentrate processing	Fuel - Drier	4.67	8.1%
Concentrate processing	**Electric arc furnace consumption**	**1.67**	**2.9%**
Nickel sulfate conversion	Limestone	0.04	0.1%
Nickel sulfate conversion	Limestone - direct emissions	2.68	4.6%
Nickel sulfate conversion	Sodium carbonate	0.13	0.2%
Nickel sulfate conversion	Thermal energy	0.21	0.4%
Nickel sulfate conversion	**Electricity - conversion to sulphate**	**1.80**	**3.1%**
Nickel sulfate conversion	Sulfuric acid	1.15	2.0%
Nickel sulfate conversion	Sodium hydroxide	0.13	0.2%
	Total	**57.82**	100.0%

Next, the ore grade feeding the RKEF process was declined to 0.5%[12] using our scaling method, assuming an effect of declining ore grade on climate impacts of the mining inventory only. The resulting contribution analysis is presented in Supplementary Table 26.

Supplementary Table 26: Contribution analysis of climate impacts for RKEF-NPI processing route, ore grade declined to 0.5%

supply chain step	contributor	$kgCO_{2eq}$/ kg Ni_{eq}	%
Mining	**Mobile equipment energy**	**3.30**	**2.3%**
Mining	**Explosives**	**0.27**	**0.2%**
Mining	**Electricity for open-pit mining**	**0.82**	**0.6%**
Concentrate processing	Char and hard coal - Calcination	43.84	30.8%
Concentrate processing	Fuel - Drier	4.67	3.3%
Concentrate processing	Electric arc furnace consumption	40.76	28.7%
Nickel sulfate conversion	Limestone	0.04	0.0%
Nickel sulfate conversion	Limestone - direct emissions	2.68	1.9%
Nickel sulfate conversion	Sodium carbonate	0.13	0.1%
Nickel sulfate conversion	Thermal energy	0.21	0.1%
Nickel sulfate conversion	Electricity - conversion to sulphate	44.17	31.1%
Nickel sulfate conversion	Sulfuric acid	1.15	0.8%
Nickel sulfate conversion	Sodium hydroxide	0.13	0.1%
	Total	**142.18**	100.0%

Supplementary Note 7: Underlying data of figures

Supplementary Table 27: Underlying data of Figure 1

supply chain step	contributor	Tailings bioleaching	Bioheap leaching	POX leaching	Flash smelting	HPAL	RKEF-NPI
Mining	Mining operations	0.00	11.28	7.76	11.86	16.25	17.17
Beneficiation	Electricity for grinding	0.00	1.03	3.25	11.03	5.94	0.00
Concentrate processing	Process electricity including electric heating	4.48E-02	10.46	41.15	12.94	44.56	133.20
Concentrate processing	Process heat from combustion	0.00	1.16	0.34	53.17	0.00	440.30
Nickel sulfate conversion	Electricity for refining	6.71	6.71	3.77	3.77	10.15	144.36
Nickel sulfate conversion	Heat for refining	8.43	8.43	5.92	5.92	2.05	5.56

Supplementary Table 28: Underlying data of Figure 2

contributor	POX leaching	Bioheap leaching	Tailings bioleaching	Flash smelting	Smelting ecoinvent	GLO ecoinvent
Mobile equipment energy	0.77	1.12	0.00	0.36	1.10	0.00
Explosives	0.10	0.49	0.00	0.19	0.14	0.21
Cement	0.67	0.00	0.00	1.29	0.96	0.00
Other (EG, lubricating oil, sand)	0.15	0.00	0.00	0.29	0.33	1.02
Mine operation	0.00	0.00	0.00	0.16	0.00	3.55
Electricity for concentrate	0.07	0.06	0.00	0.22	0.07	1.87
Chemicals for beneficiation	0.20	0.00	0.00	0.38	0.28	0.31
Reductants	0.00	0.00	0.00	2.86	2.74	0.60
Chemicals	1.20	1.19	19.17	2.80	0.47	0.00
Electricity	0.91	0.64	2.84E-04	0.26	2.55	2.53
Thermal energy	0.03	0.09	0.00	1.96	0.72	1.60
Process emissions	0.0015	0.42	16.84	0.00	0.87	5.84
Transportation	0.00	0.00	0.00	0.37	0.25	0.00
Inert waste treatment	0.00	0.00	1.57	0.00	0.00	0.00
Electricity for sulfate refining	0.09	0.41	0.04	0.07	0.74	0.74
Chemicals for sulfate refining	0.30	3.20	2.78	0.30	0.30	0.26
Heat for sulfate refining	0.33	0.05	0.05	0.33	0.33	0.23
Sulfate refining direct emissions	0.00	0.00	0.00	0.00	0.00	0.00
Other (factory, nitrogen)	0.00	0.00	0.00	0.00	0.13	0.26

The same data now processed in percentage form is presented in Supplementary Table 29.

Supplementary Table 29: Underlying data of Figure 2 in percentage form

contributor	POX leaching	Bioheap leaching	Tailings bioleaching	Flash smelting	Smelting ecoinvent	GLO ecoinvent
Mobile equipment energy	16.0%	14.6%	0.0%	3.0%	9.1%	0.0%
Explosives	2.1%	6.4%	0.0%	1.6%	1.2%	1.1%
Cement	13.9%	0.0%	0.0%	10.9%	8.0%	0.0%
Other (EG, lubricating oil, sand)	3.2%	0.0%	0.0%	2.5%	2.8%	5.4%
Mine operation	0.0%	0.0%	0.0%	1.4%	0.0%	18.7%
Electricity for concentrate	1.5%	0.8%	0.0%	1.8%	0.6%	9.8%
Chemicals for beneficiation	4.1%	0.0%	0.0%	3.2%	2.4%	1.6%
Reductants	0.0%	0.0%	0.0%	24.1%	22.9%	3.2%
Chemicals	24.8%	15.5%	47.4%	23.6%	3.9%	0.0%
Electricity	18.9%	8.3%	0.0%	2.2%	21.3%	13.3%
Thermal energy	0.7%	1.1%	0.0%	16.6%	6.0%	8.4%
Process emissions	0.0%	5.5%	41.6%	0.0%	7.3%	30.7%
Transportation	0.0%	0.0%	0.0%	3.1%	2.1%	0.0%
Inert waste treatment	0.0%	0.0%	3.9%	0.0%	0.0%	0.0%
Electricity for sulfate refining	1.8%	5.4%	0.1%	0.6%	6.2%	3.9%

Chemicals for sulfate refining	6.1%	41.7%	6.9%	2.5%	2.5%	1.4%
Heat for sulfate refining	6.9%	0.7%	0.1%	2.8%	2.8%	1.2%
Sulfate refining direct emissions	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Other (factory, nitrogen)	0.0%	0.0%	0.0%	0.0%	1.1%	1.3%

Supplementary Table 30: Underlying data of Figure 3

contributor	HPAL-sulfur	HPAL-coal	RKEF-NPI	GLO ecoinvent
Mobile equipment energy	1.28	1.28	1.35	0.00
Explosives	0.11	0.32	0.11	0.21
Electricity for open-pit mining	0.32	0.11	0.34	0.00
Energy for mine operation	0.00	0.00	0.00	3.55
Other (EG, lubricating oil, sand)	0.00	0.00	0.00	1.02
Electricity for concentrate	1.81	1.81	0.00	1.87
Chemicals for beneficiation	0.00	0.00	0.00	0.31
Char and hard coal	0.00	0.00	43.84	0.60
Chemicals	5.55	5.55	0.00	0.00
Electricity and acid for HPAL	1.73	19.56	0.00	0.00
Electricity	0.00	0.00	40.76	2.53
Thermal energy	0.00	0.00	4.67	1.60
Process direct emissions	6.60	6.60	0.00	5.84
Electricity for sulfate refining	3.09	3.09	44.17	0.74
Chemicals for sulfate refining	0.98	0.98	1.45	0.26
Heat for sulfate refining	0.11	0.11	0.19	0.23
Sulfate refining process emissions	0.06	0.06	2.68	0.00
Other (factory, nitrogen)	0.00	0.00	0.00	0.26

The same data now processed in percentage form is presented in Supplementary Table 31.

Supplementary Table 31: Underlying data of Figure 3 in percentage form

contributor	HPAL-sulfur	HPAL-coal	RKEF-NPI	GLO ecoinvent
Mobile equipment energy	5.9%	3.2%	1.0%	0.0%
Explosives	0.5%	0.8%	0.1%	1.1%
Electricity for open-pit mining	1.5%	0.3%	0.2%	0.0%
Energy for mine operation	0.0%	0.0%	0.0%	18.7%
Other (EG, lubricating oil, sand)	0.0%	0.0%	0.0%	5.4%
Electricity for concentrate	8.4%	4.6%	0.0%	9.8%
Chemicals for beneficiation	0.0%	0.0%	0.0%	1.6%
Char and hard coal	0.0%	0.0%	31.4%	3.2%
Chemicals	25.6%	14.1%	0.0%	0.0%
Electricity and acid for HPAL	8.0%	49.6%	0.0%	0.0%
Electricity	0.0%	0.0%	29.2%	13.3%

Thermal energy	0.0%	0.0%	3.3%	8.4%
Process direct emissions	30.5%	16.7%	0.0%	30.7%
Electricity for sulfate refining	14.3%	7.8%	31.7%	3.9%
Chemicals for sulfate refining	4.5%	2.5%	1.0%	1.4%
Heat for sulfate refining	0.5%	0.3%	0.1%	1.2%
Sulfate refining process emissions	0.3%	0.1%	1.9%	0.0%
Other (factory, nitrogen)	0.0%	0.0%	0.0%	1.3%

Underlying data supporting the discussion in Results section 2.4 is presented below.

Supplementary Table 32: Equivalent distances supporting the discussion in Results section 2.4

Processing pathway	Embodied energy in nickel content of EV battery cells (kWh)	Equivalent distance for energy (km)	Embodied carbon in nickel content of EV battery cells ($kgCO_2$)	Equivalent distance for CO_2 (km)
POX leaching	570	5,505	159	647
Bioheap leaching	358	3,458	253	1,026
Tailings bioleaching	139	1,344	1,335	5,420
Flash smelting	904	8,735	391	1,589
HPAL	723	6,987	712	2,891
RKEF-NPI	6,786	65,549	4,605	18,699

Underlying data for the generation of Figure 4 is presented in Supplementary Table 33.

Supplementary Table 33: Underlying data of Figure 4's subplots

Impact category	**POX leaching**	**Bioheap leaching**	**Tailings bioleaching**	**Smelting ecoinvent**	**HPAL**	**RKEF-NPI**
GWP-l	-74%	-59%	118%	-36%	17%	664%
GWP-s	-74%	-60%	109%	-37%	12%	632%
FNEU	-82%	-52%	20%	-56%	-51%	393%
FAP	-99%	-98%	-97%	-73%	-94%	-87%
FETP	-46%	-96%	-83%	-26%	415%	-42%
FEP	-98%	-97%	-90%	-96%	-86%	-95%
HTP-c	-44%	-92%	-63%	-9%	7735%	114%
HTP-nc	-79%	-96%	-80%	-71%	-59%	23%
IR	-97%	-19%	-19%	-85%	-95%	-88%
LU-o	5%	-89%	-60%	-62%	-53%	6%
LU-t	-49%	13%	-64%	-68%	123%	171%
MEP	-82%	-73%	-43%	-81%	-79%	15%
MRU	-9%	-63%	322%	16%	-43%	-20%
ODP	-65%	52%	112%	-70%	-2%	66%
PMF	-81%	-66%	-50%	210%	-14%	1424%
POF	-81%	-44%	-34%	8%	-37%	206%

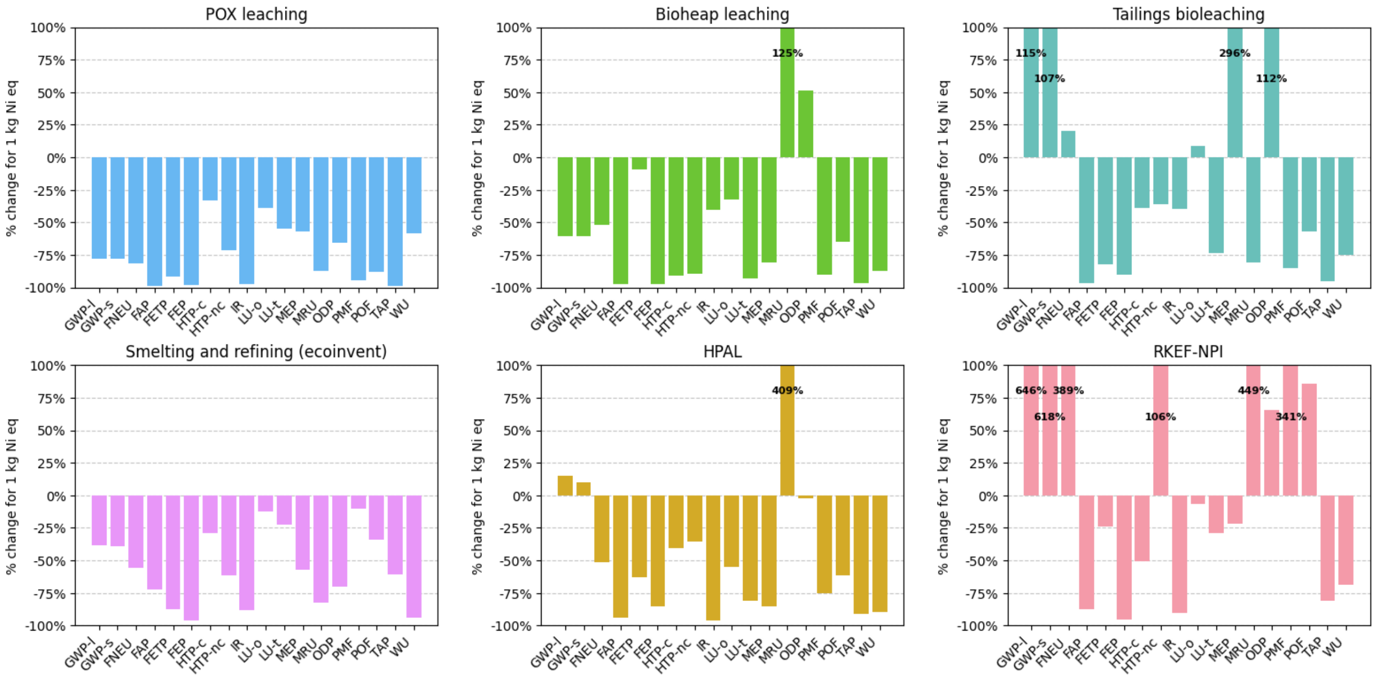
TAP	-99%	-97%	-95%	-61%	-91%	-81%
WU	-75%	-68%	-100%	-88%	-87%	-73%

Raw LCIA data before normalization with ecoinvent's global (GLO) nickel sulfate dataset's results is presented in Supplementary Table 34.

Supplementary Table 34: IMPACT WORLD+ v.1.29 midpoint results

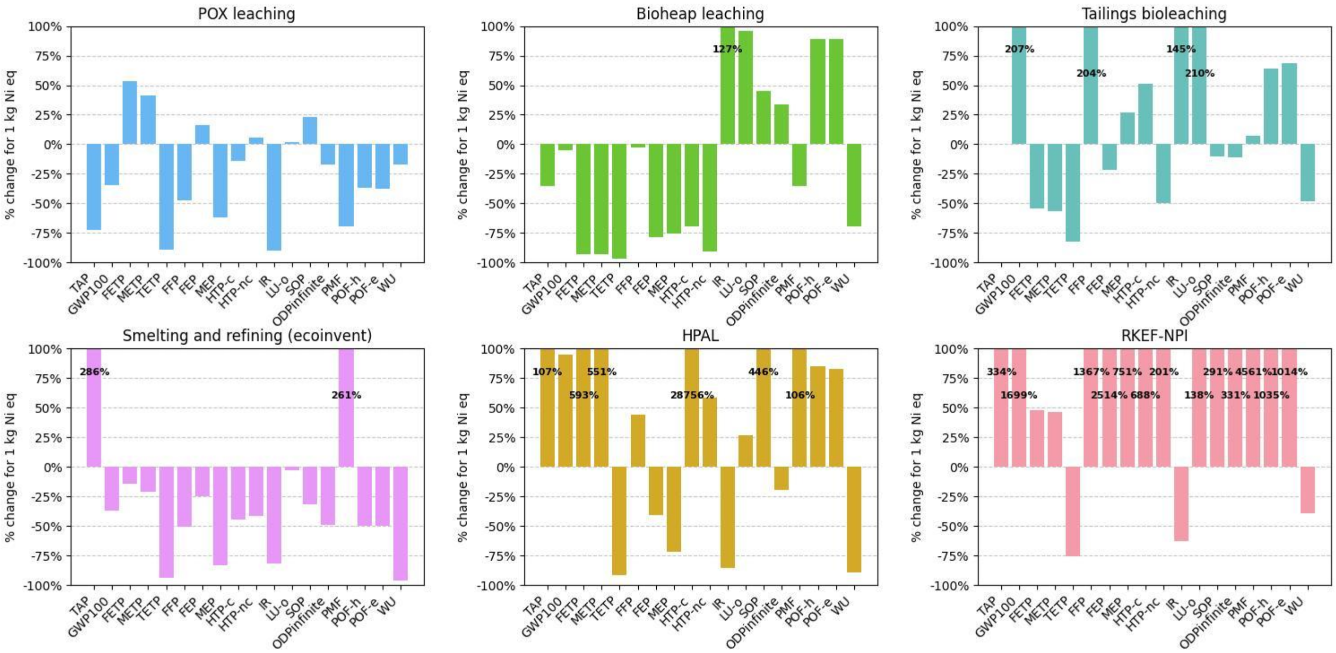
Impact category	**POX leaching**	**Bioheap leaching**	**Tailings bioleaching**	**Smelting ecoinvent**	**HPAL**	**RKEF-NPI**	**GLO ecoinvent**
Climate change, long term ($kgCO_{2eq}$)	4.75E+00	7.33E+00	3.92E+01	1.14E+01	2.10E+01	1.37E+02	1.80E+01
Climate change, short term ($kgCO_{2eq}$)	5.11E+00	7.84E+00	4.08E+01	1.22E+01	2.18E+01	1.43E+02	1.95E+01
Fossil and nuclear energy use (MJ deprived)	5.54E+01	1.45E+02	3.64E+02	1.33E+02	1.47E+02	1.49E+03	3.02E+02
Freshwater acidification ($kgSO_{2eq}$)	3.70E-13	9.26E-13	1.39E-12	1.10E-11	2.41E-12	5.15E-12	4.02E-11
Freshwater ecotoxicity (CTUe)	1.68E+06	1.13E+05	5.45E+05	2.30E+06	1.60E+07	1.80E+06	3.11E+06
Freshwater eutrophication ($kgPO_4$ P-lim_{eq})	1.03E-05	1.36E-05	4.77E-05	1.89E-05	6.79E-05	2.18E-05	4.74E-04
Human toxicity cancer (CTUh)	3.63E-06	4.93E-07	2.38E-06	5.82E-06	5.04E-04	1.38E-05	6.43E-06
Human toxicity non cancer (CTUh)	5.16E-06	9.70E-07	4.97E-06	7.24E-06	1.02E-05	3.03E-05	2.47E-05
Ionizing radiations (Bq C-14_{eq})	1.30E+01	3.28E+02	3.27E+02	5.91E+01	1.87E+01	4.85E+01	4.03E+02
Land occupation, biodiversity (m^2 arable $land_{eq}$ .yr)	4.07E-01	4.14E-02	1.55E-01	1.46E-01	1.81E-01	4.11E-01	3.87E-01
Land transformation, biodiversity (m^2 arable $land_{eq}$)	3.57E-03	7.85E-03	2.53E-03	2.24E-03	1.55E-02	1.89E-02	6.97E-03
Marine eutrophication (kg N N-lim_{eq})	9.21E-04	1.43E-03	2.99E-03	1.00E-03	1.10E-03	6.00E-03	5.24E-03
Mineral resources use (kg deprived)	1.91E-01	7.85E-02	8.85E-01	2.44E-01	1.20E-01	1.69E-01	2.10E-01
Ozone Layer Depletion (kg CFC-11_{eq})	1.35E-07	5.92E-07	8.26E-07	1.16E-07	3.81E-07	6.47E-07	3.91E-07
Particulate matter formation (kg $PM2.5_{eq}$)	4.70E-03	8.37E-03	1.23E-02	7.64E-02	2.13E-02	3.76E-01	2.47E-02
Photochemical oxidant formation (kg $NMVOC_{eq}$)	2.83E-02	8.34E-02	9.84E-02	1.61E-01	9.42E-02	4.57E-01	1.49E-01
Terrestrial acidification (kg SO_{2eq})	2.24E-07	5.54E-07	8.64E-07	6.64E-06	1.47E-06	3.19E-06	1.71E-05
Water scarcity (m^3 $world_{eq}$)	3.00E+01	3.86E+01	2.40E+02	1.46E+01	1.51E+01	3.25E+01	1.20E+02

Alternatives to Figure 4 using IMPACT WORLD+ version 2.01 and ecoinvent - ReCiPe 2016 v1.03, midpoint (H) impact assessment methods are presented below (Supplementary Figure 1 and Supplementary Figure 2 respectively).



Supplementary Figure 1: Alternative to Figure 4, using version 2.01 of IMPACT WORLD+.

Values are normalized as percentage change from the value obtained with the global nickel sulfate dataset in ecoinvent, for 1 kg Ni_{eq}. Abbreviations: GWP-l: Climate change, long term ($kgCO_{2eq}$), GWP-s: Climate change, short term ($kgCO_{2eq}$), FNEU: Fossil and nuclear energy use (MJ deprived), FAP: Freshwater acidification ($kgSO_{2eq}$), FETP: Freshwater ecotoxicity (CTUe), FEP: Freshwater eutrophication ($kgPO_4$ $P\text{-}lim_{eq}$), HTP-c: Human toxicity cancer (CTUh), HTP-nc: Human toxicity non cancer (CTUh), IR: Ionizing radiations (Bq $C\text{-}14_{eq}$), LU-o: Land occupation, biodiversity (m^2 arable land eq .yr), LU-t: Land transformation, biodiversity (m^2 arable $land_{eq}$), MEP: Marine eutrophication (kg N $N\text{-}lim_{eq}$), MRU: Mineral resources use (kg deprived), ODP: Ozone Layer Depletion (kg $CFC\text{-}11_{eq}$), PMF: Particulate matter formation (kg $PM2.5_{eq}$), POF: Photochemical oxidant formation (kg $NMVOC_{eq}$), TAP: Terrestrial acidification (kg SO_{2eq}), WU: Water scarcity (m^3 $world_{eq}$).



Supplementary Figure 2: Alternative to Figure 4, using ReCiPe 2016(H) impact assessment method.

*Values are normalized as percentage change from the value obtained with the global nickel sulfate dataset in ecoinvent, for 1 kg Ni_{eq}. Abbreviations: TAP: terrestrial acidification potential (kgSO_{2eq}), GWP100: global warming potential (kgCO_{2eq}), FETP: freshwater ecotoxicity potential (kg 1,4-DCB_{eq}), METP: marine ecotoxicity potential (kg 1,4-DCB_{eq}), TETP: terrestrial ecotoxicity potential (kg 1,4-DCB_{eq}), FFP: fossil fuel potential (kg oil_{eq}), FEP: freshwater eutrophication potential (kg P_{eq}), MEP: marine eutrophication potential (kg N_{eq}), HTP-c: carcinogenic - human toxicity potential (kg 1,4-DCB_{eq}), HTP-nc: non-carcinogenic - human toxicity potential (kg 1,4-DCB_{eq}), IR: ionising radiation potential (kBq Co-60_{eq}), LU-o: agricultural land occupation (m^2*a $crop_{eq}$), SOP: surplus ore potential (kg Cu_{eq}), ODPinfinite: ozone depletion potential (kg CFC-11_{eq}), PMF: particulate matter formation potential (kg PM2.5_{eq}), POF-h: photochemical oxidant formation potential, humans (kg NO_{xeq}), POF-e: photochemical oxidant formation potential, ecosystems (kg NO_{xeq}), WU: water consumption potential (m^3)*

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