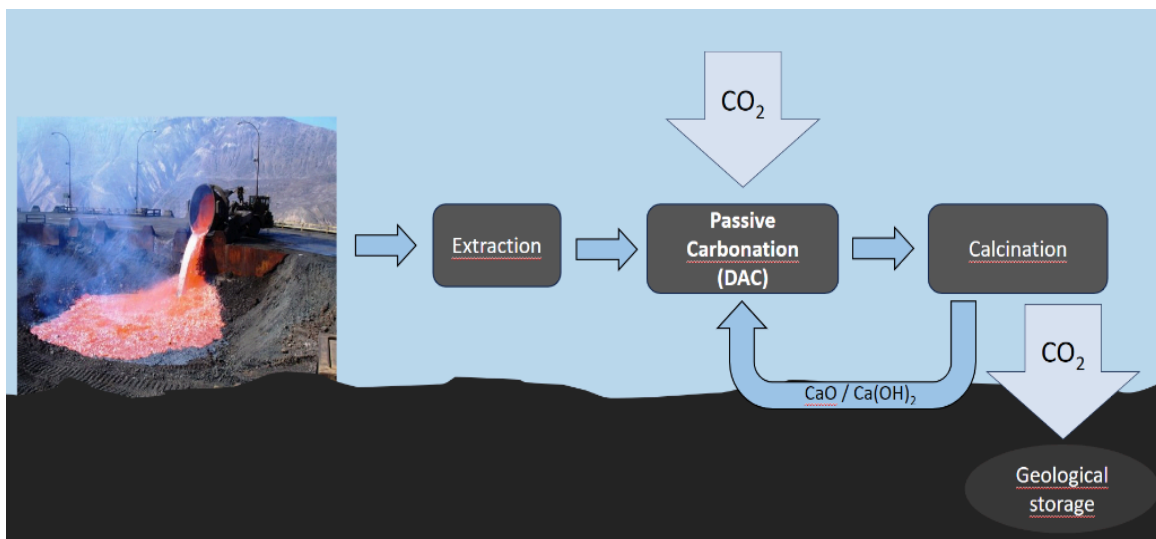




UNIVERSITY OF
GOTHENBURG

DEPARTMENT OF BIOLOGICAL AND ENVIRONMENTAL
SCIENCES

Life Cycle Analysis on the Extraction of $\text{Ca}(\text{OH})_2$ from Industrial Waste Products for Use in a Passive-DAC System for CO_2 Capture



Samia Ishaque

Degree project for Master of Science (45 Hec)

ES2571, Degree Project Environmental Science (Master)

Second cycle

Semester/year: Autumn 2025

Zareen Abbas (Department of Chemistry), Carl Johan Linderholm and Muhammad

Supervisors: Nauman Saeed (Chalmers University of Technology)

Examiner: Dan Strömberg (Biology and Environmental Science)

CONTENTS

I. Abstract	5
II. Acknowledgement	7
1. Introduction	10
1.1 Climate change and the role of CO ₂ emissions	10
1.2 Need for both CO ₂ reduction and removal	11
1.3 Overview of climate agreements and policy frameworks (e.g., Paris Agreement, IPCC Reports)	11
1.4 Overview of Carbon Capture Technologies	12
1.5 Direct Air Capture (DAC) Through passive carbonation	14
1.6 Use of Industrial By-Products in Carbon Capture	15
1.7 Extraction of Ca(OH) ₂	15
1.7.1 Stage 1: Calcium Extraction	15
1.7.2 Stage 2: Impurity Removal for filtrate produced using HCl	15
1.7.3 Stage 3: Precipitation of Ca(OH) ₂	16
1.7.4 Difference between HCl and NH ₄ Cl	16
1.8 Life Cycle Assessment (LCA) in CO₂ Capture	17
1.8.1 Definition and importance of LCA	17
1.8.2 Types of LCA approaches	17
• Time (Temporal Scope)	17
• Technology Maturity	17
• Causality (Purpose)	17
1.9 Components of a Life Cycle Assessment	18
2. Methodology	19
2.1 Goal and Scope	19
2.2 Functional Unit (FU)	19
2.3 Linz-Donawitz slag (LD-Slag)	20
2.4 Flow diagram:	20
2.5 Life Cycle Inventory (LCI):	23
2.5.1 Data collection:	23
2.5.2 Calculation of how much Ca(OH) ₂ is needed to capture 1 tonne of CO ₂	24
2.5.3 Scale factor calculation for HCl	24
2.5.3 Allocation	26
3. Modelling and Sensitivity Analysis	28
3.1 Sensitivity Analysis:	28
3.2 Additional Sensitivity Analysis: Transport Distance Variations	30
4. Life Cycle Assessment Impact (LCIA)	32
4.1 Characterization:	33
4.2 Normalization	34

5. Results and Discussion	35
5.1 HCl vs NH ₄ Cl	35
5.1.1 Midpoint	35
5.2 Results for HCl Scenario 1 Baseline.	40
5.2.1 Midpoint results	40
Freshwater Eutrophication:	42
Mineral resources:	43
5.2.2 Endpoint results	44
5.3 Results for NH₄Cl Scenario 1.	46
5.3.1 Midpoint	46
5.3.2 Endpoint	50
5.4 Sensitivity Analysis 1: HCl Scenario 1 vs HCl Scenario 2	52
5.5 Sensitivity Analysis 1: Scenario 1 vs Scenario 2 NH₄Cl	53
5.6 Transport Sensitivity analysis HCl scenarios	56
5.7 Transport Sensitivity analysis NH₄Cl scenarios	60
5.8 Sensitivity analysis on energy type within the model.	64
5.9 HCl Scenario sensitivity analysis varying electricity source	64
5.10 NH₄Cl Scenario sensitivity analysis varying the electricity source	65
6. Conclusions	66
7. Future Work	67
APPENDIX	69
REFERENCES	75

1. Abstract

Climate change mitigation is a problem that requires a two-pronged approach, which is a reduction in Greenhouse gas emissions and the large-scale removal of potent greenhouse gases such as Carbon dioxide (CO_2). Passive Direct Air Capture (Passive DAC) using alkaline minerals presents as a less energy and cost-intensive approach for carbon dioxide removal, particularly when using porous materials produced with alkaline minerals derived from industrial by-products like LD-slag from the steel making industry. This study evaluates the environmental feasibility of extracting alkaline minerals, specifically $\text{Ca}(\text{OH})_2$, from steel-making by-products (LD-slag) for application in passive DAC systems, using a cradle to gate Life Cycle Assessment (LCA) with a functional unit of 1 tonne of captured CO_2 . Two extraction routes for $\text{Ca}(\text{OH})_2$: route 1 using hydrochloric acid (HCl) and route 2 using ammonium chloride (NH_4Cl) were modelled across different environmental impact categories, including climate change, acidification, toxicity, and resource depletion. Results indicate that the NH_4Cl pathway consistently exhibits about 6-7 times higher impacts than the HCl route across all categories. For both pathways, upstream chemical production, particularly NaOH, HCl, and ammonia, dominates the overall footprint, outweighing impacts from $\text{Ca}(\text{OH})_2$ extraction itself. Transport sensitivity analysis highlights the influence of supply-chain distance, while renewable electricity substitution yields only marginal improvements. In all modelled scenarios, total life-cycle emissions exceed the CO_2 captured, underscoring the trade-offs inherent in $\text{Ca}(\text{OH})_2$ production for DAC applications. This ultimately implies that the extraction of $\text{Ca}(\text{OH})_2$ from Industrial waste products for the capture of CO_2 in a passive DAC system is not a viable solution to address industrial waste and reduce atmospheric CO_2 levels.

Abstract

Klimatförändringsbegränsning är ett problem som kräver en tvådelad strategi: en minskning av utsläpp av växthusgaser och storskalig borttagning av potenta växthusgaser såsom koldioxid (CO_2). Passiv direkt luftavskiljning (passiv DAC) med användning av alkaliska mineraler framstår som en mindre energi- och kostnadskrävande metod för koldioxidavskiljning, särskilt när porösa material produceras med alkaliska mineraler hämtade från industriella biprodukter som LD-slag från stålindustrin. Denna studie utvärderar den miljömässiga genomförbarheten av att utvinna alkaliska mineraler, specifikt $\text{Ca}(\text{OH})_2$ från stålframställningsbiprodukter (LD-slag), för användning i passiva DAC-system genom en cradle-to-gate livscykelanalys (LCA) med en funktionsenhet på 1 ton infångad CO_2 . Två utvinningsvägar för $\text{Ca}(\text{OH})_2$ modellerades: väg 1 med saltsyra (HCl) och väg 2 med ammoniumklorid (NH_4Cl), och de analyserades över olika miljöpåverkanskategorier, inklusive klimatpåverkan, försurning, toxicitet och resursuttömning. Resultaten visar att NH_4Cl -vägen konsekvent uppvisar cirka 6–7 gånger högre påverkan än HCl -vägen i samtliga kategorier. För båda vägarna dominerar upstream-produktionen av kemikalier, särskilt NaOH , HCl och ammoniak, den totala miljöpåverkan och överstiger effekterna från själva utvinningen av $\text{Ca}(\text{OH})_2$. Känslighetsanalys av transporter belyser leveranskedjans avstånds inverkan, medan ersättning med förnybar el endast ger marginella förbättringar. I alla modellerade scenarier överstiger de totala livscykelutsläppen den mängd CO_2 som fångas, vilket understryker de avvägningar som är förknippade med produktion av $\text{Ca}(\text{OH})_2$ för DAC-tillämpningar. Detta innebär slutligen att utvinning av $\text{Ca}(\text{OH})_2$ från industriella avfallsprodukter för infångning av CO_2 i ett passivt DAC-system inte är en livskraftig lösning för att hantera industriavfall och minska atmosfärens CO_2 -nivåer.



Acknowledgement

First of all, I would like to thank Almighty God for giving me the opportunity and guidance to achieve my goal and to be successful in completing this work.

I would like to express my sincere gratitude and appreciation to all my supervisors, Dr Zareen Abbas, Dr Carl Johan Linderholm and Muhammad Nauman Saeed, for selecting me to work under their supervision, as well as their exceptional guidance, patience, and for taking the time to regularly meet and discuss the project throughout the study period. I would also like to show my appreciation to Mathias Janssen from the Chalmers University of Technology, who also provided exceptional guidance and advice on navigating the LCA process and the OpenLCA tool. Without any of them, the project would not have been completed.

Finally, I would like to thank my family and partner for the support they gave me and their tireless efforts in ensuring that I successfully navigated every path I had to take to achieve my dreams and goals.

1. Introduction

1.1 Climate change and the role of CO₂ emissions

Climate change, as we know it, has severely altered the environment around us; these alterations have caused long-term shifts in both temperature and weather patterns (Lu, 2024). According to NASA, there has been a constant rise in global temperature. Studies reveal that the average temperature of the Earth's surface has increased by about 1.18 °C since the late 19th century. This increase can largely be attributed to the increase in carbon dioxide (CO₂) and other man-made emissions (“Evidence - NASA Science,” 2022). At the core of this warming trend lies carbon dioxide (CO₂), one of the most influential greenhouse gases (GHG) driving climate change. CO₂ is an influential greenhouse gas due to a combination of its molecular properties, its concentration in the atmosphere, and its long residence time. CO₂ can exist in the atmosphere for thousands of years if not sequestered or absorbed, as compared to other potent greenhouse gases like methane (CH₄), Nitrous Oxide (N₂O) chlorofluorocarbons (CFCs), hydrofluorocarbons(HFCs), and hydrochlorofluorocarbons (HCFCs), which have shorter lifetimes in the atmosphere (US EPA, 2016). Between 1990 and 2023, the amount of heat trapped by GHGs increased by 51.5% and 81% of this was caused by CO₂ (“Greenhouse gases,” 2023). Studies prove that the amount of CO₂ in the atmosphere has been on a steady rise since the onset of industrialisation (*Carbon Dioxide - Earth Indicator - NASA Science*, no date).

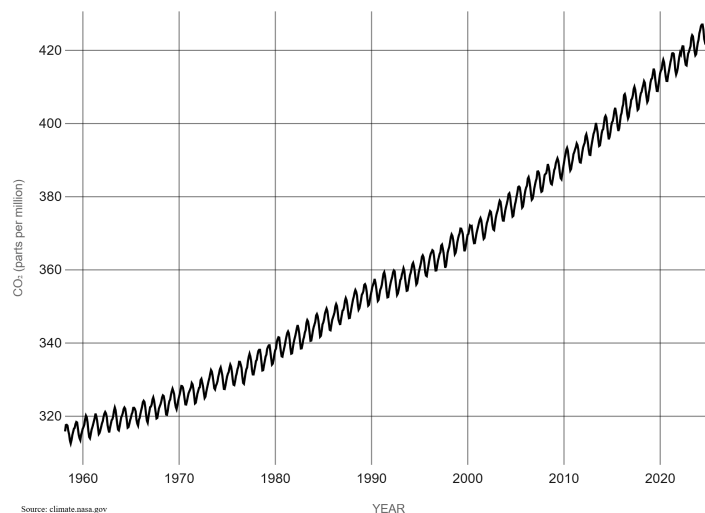


Fig. 1: A figure depicting the upward trajectory of CO₂ levels over decades.

1.2 Need for both CO₂ reduction and removal

These long-term shifts have affected the ability to produce food reliably, creating food insecurity in certain areas as a result of extended periods of drought (Abnett and Abnett, 2025). Extended periods of drought have also directly contributed to a heightened risk of fires and, in some areas, extended and intensified wildfire seasons (*Effects - NASA Science*, no date). Higher temperatures and extreme weather events have also been linked to an increase in the risk of food and water-borne diseases such as cholera and salmonella (McMichael, Woodruff and Hales, 2006). These negative effects, coupled with a few others like the melting of the Glaciers and the decrease in ice sheet mass in Greenland and Antarctica, are direct outcomes of climate change and global warming (Velicogna *et al.*, 2020). The ocean serves as a huge carbon sink, absorbing about 30% of CO₂ emissions from anthropogenic activities (CSIRO, no date). However, in response to this, CO₂ uptake studies show that the ocean is continuing to acidify. The pH level of the ocean has been steadily decreasing; the first signs of this were observed in the 1950s. The gradual increase in acidification has made it difficult for species like corals, shellfish, and some plankton to form shells and skeletons because higher pH reduces the availability and stability of some essential minerals (Pörtner and Roberts, no date). This results in the gradual extinction of these species that play crucial roles in the food chain, without which there will be massive effects felt throughout the ocean ecosystem.

It is therefore evident that reduction in CO₂ emissions as well as the removal/sequestration of emitted CO₂ will play a critical role in slowing down global warming, preserving biodiversity and maintaining the stability of natural ecosystems. If climate change and its causes remain unchecked and uncontrolled, the environmental changes brought on will be too much for many species to adapt to, leading to the mass extinction of several species (McNutt, 2013).

1.3 Overview of climate agreements and policy frameworks (e.g., Paris Agreement, IPCC Reports)

Given the global scale and urgency of global warming and overall climate change, addressing these problems goes beyond individual efforts and requires international coordinated action. This has led to the establishment of global policy frameworks and agreements aimed at unifying the world's response to climate change. One of such initiatives is the Paris Agreement, which was established in 2016 to prevent the global temperature from continuously rising. The main aim of the treaty is to keep global warming well below 2°C, and preferably to 1.5°C, compared to pre-industrial levels (*The Paris Agreement*, 2016). Another example of such initiatives is the Intergovernmental Panel on Climate Change (IPCC), which is the United Nations body for assessing science related to climate change. The IPCC was created to provide policymakers worldwide with regular scientific assessments on climate change, its implications and potential future risks, as well as to put forward adaptation and mitigation strategies, to inform decisions and help address climate change ("IPCC — Intergovernmental Panel on Climate Change," no date). Another notable initiative is the United Nations Framework Convention on Climate Change (UNFCCC). This convention's main goal was to stabilize greenhouse gas concentrations that would prevent anthropogenic activities from harming the climate (*United Nations Framework Convention on*

Climate Change | UNFCCC, no date). The Kyoto protocol, established in 1997, was established to keep emissions from developed countries and economies in check, as it was established through studies that they were the biggest emitters of GHGs. The aim was to place heavy burdens on these parties under the principle of “common but differentiated responsibility and respective capabilities”, requiring them to keep their GHG emissions below set targets (UNFCCC, no date).

Despite these initiatives and global efforts, even if the world halved CO₂ emissions or stopped emitting altogether, the planet would continue to warm due to the existing high levels of CO₂ already in the atmosphere and its long lifespan. This highlights the need for a dual solution that not only limits CO₂ emissions but also addresses the pressing need to remove the existing CO₂ from the atmosphere.

1.4 Overview of Carbon Capture Technologies

The reduction of the amount of CO₂ in the atmosphere requires the use of systems, practices and mechanisms that are specifically designed to remove and durably store carbon dioxide from the atmosphere, commonly referred to as Carbon Dioxide Removal Methods (CDRMs). These CDR methods are essential for achieving the global target of net zero CO₂ and Greenhouse Gas (GHG) emissions; they differ in terms of removal processes, time scale of carbon storage, mitigation effectiveness, potential costs, benefits, and disadvantages (Babiker Sudan *et al.*, no date). Some examples of CDRMs include afforestation, reforestation, and improved forest management; soil carbon sequestration, such as biochar; bioenergy with carbon capture and storage (BECCS); direct carbon capture and storage (DACCS); enhanced rock weathering; and the restoration of peatlands and wetlands. While these existing technologies and methodologies present promising solutions for CO₂ removal and storage, they each have their respective technical, economic and ecological challenges that make them less efficient in some ways.

Table 1: From IPCC AR6 WGIII: CDR Factsheet lists and describes different CDRMs.

CDR METHOD	STORAGE TIMESCALE	FINANCIAL COST (\$ per tonne CO ₂)	RISKS/DISADVANTAGES
------------	----------------------	---	---------------------

<p>Afforestation, reforestation, and improved forest management</p>	<p>Decades to centuries (in vegetation, buildings, soils)</p>	<p>Afforestation /reforestation: \$0-\$24</p> <p>Agroforestry and forest management: not enough data</p>	<p>Afforestation /reforestation: Inappropriate deployment at large scales can cause an increase in competition for land (limiting land for biodiversity conservation and food security issues)</p> <p>Forest management: if fertilizers and several new species are introduced/involved, risks include reduced biodiversity, increased eutrophication and upstream GHG emissions</p>
<p>Soil carbon sequestration (usually through agricultural practices and pasture management)</p>	<p>Decades to centuries (in soils, sediments)</p>	<p>to \$45-\$100</p>	<p>•Increased carbon sequestration can occur at the expense of production.</p> <p>Sequestration contribution per hectare is small and hard to monitor.</p>
<p>Biochar</p>	<p>Centuries to millennia (in soils and sediments)</p>	<p>to \$10-\$345</p>	<p>Negative impacts from dust.</p> <p>Competition for biomass.</p>

Bioenergy with carbon capture and storage (BECCS) 10,000+ years (in \$50-\$200 geological formations)

Growing energy crops increases competition for land (limiting land for biodiversity conservation and food security issues)

Direct carbon capture and storage (DACCS) 10,000+ years (in \$100-\$300 geological formations)

High energy requirements (associated with the use of energy-intensive blowers/fans) could lead to growing competition for low-carbon energy or increased GHG emissions. Some DACCS processes require water.

Enhanced rock weathering 10,000+ years (in \$50-\$200 minerals)

Dust emissions

Potential for increased GHG emissions

from energy generation.

Restoration of peatlands and wetlands	Decades to centuries (in soils, vegetation, and sediments)	Not enough data	Some peat lands are used for food production, which could result in competition for land.
--	--	-----------------	---

1.5 Direct Air Capture (DAC) through passive carbonation

Considering the CDRMs and their respective challenges in Table 1, an alternative CDRM has been proposed, the Passive Direct Air Capture (PDAC) system. The system's engineering relies on passive carbonation, which is less energy-intensive and a much more economically feasible alternative (Abanades, Criado and Fernández, 2020). Passive carbonation, also referred to as mineral carbonation, occurs naturally within the environment. It is a chemical process where certain elements from rocks naturally react with CO₂ to form carbonate minerals, removing it from the atmosphere. This usually occurs over a geological timescale; however, the process can be accelerated with the aid of technology into a shorter time frame, possibly days. To do this, minerals containing alkaline divalent metal ions such as Ca²⁺ and Mg²⁺ (found within the chemical structures of rocks), CO₂ and a suitable nonacidic environment must be available or present within the technology. The amount of divalent metal ions within the rocks determines the amount of CO₂ captured; in addition to that, the structure of the metals and the rock from which they are extracted determines how much of these divalent metals can be extracted for reaction with CO₂. Research shows that the most suitable sources for divalent metals to be used for engineered CO₂ capture or mineral carbonation include:

- Natural minerals – including olivine, serpentine, and wollastonite
- Tailings – from mines including chrysotile, nickel, kimberlite, platinum group metals
- Metallurgical slags – including steel and nickel refining slags

These are all forms of industrial waste, which is a huge problem worldwide (*What is Mineral Carbonation?* - *Exterra*, no date; Kelemen *et al.*, 2020; Bullock *et al.*, 2021).

1.6 Use of Industrial By-Products in Carbon Capture

Europe produces about 18.4 million tons of steel slag, with Sweden producing about >300kton/year (Rydén, Hanning and Lind, 2018). Out of 18 million tons produced 85.6% is utilized for purposes such as cement or concrete production, road construction, and sometimes reused within the steelmaking process, however the remainder is landfilled or stored in giant piles usually outside of steel factories (*Stainless-steel slag treat acidic*

wastewater | KTH, no date; O'Connor *et al.*, 2021; Kieush *et al.*, 2024). These slags often contain high concentrations of elements and compounds with potentially severe impacts on ecosystems and human health that stem from the leaching of potentially toxic elements into local waterways, ground water and surface water (Piatak, 2018; C.M.G, V. I and I.C., 2019). Utilizing these alkaline waste materials can contribute to environmental remediation and resource efficiency. This approach not only supports the idea of a circular economy by repurposing industrial waste but also helps reduce the massive volumes of industrial waste produced by these activities.

1.7 Extraction of $\text{Ca}(\text{OH})_2$

The backbone of this analysis is a study conducted by Julian Scheer (Scheer, no date), who investigated the extraction of $\text{Ca}(\text{OH})_2$ from industrial alkaline waste products. The method involved 2-3 main stages of extraction processes as detailed below.

1.7.1 Stage 1: Calcium Extraction

Three main industrial waste products used were steel converter slag (LD-Slag), blast furnace slag (Petrit T), and mine tailings from Tara mining. These by-products were ground into a fine powder form, with a particle size distribution of 90–250 μm . This particle size was chosen based on literature studies detailing that calcium content in finer particles is higher and would benefit the process (Mattila, Grigaliūnaitė and Zevenhoven, 2012). After the desired particle size is achieved, it is then treated with either hydrochloric acid (HCl) or ammonium chloride (NH_4Cl) at 2 mol/L. The mixture was stirred for 20 minutes, filtered, and analyzed to collect dissolved calcium ions for further processing. NH_4Cl showed higher selectivity for calcium, while HCl extracted more total calcium but co-extracted impurities.

1.7.2 Stage 2: Impurity Removal for filtrate produced using HCl

Impurities such as iron, aluminium, and magnesium were precipitated by adjusting the filtrate pH with ammonium hydroxide (NH_4OH) to 9.5. The solid residues were separated and analyzed, leaving a purified calcium-rich solution. NH_4Cl typically required little additional purification due to its selectivity and hence did not require this step.

1.7.3 Stage 3: Precipitation of $\text{Ca}(\text{OH})_2$

Calcium hydroxide was precipitated by raising the pH to 13 using sodium hydroxide (NaOH). The resulting solid was filtered, dried, and confirmed as pure $\text{Ca}(\text{OH})_2$ by X-ray diffraction and gravimetric analysis.

1.7.4 Difference between HCl and NH_4Cl

HCl extracts Ca^{2+} more efficiently than NH_4Cl ; however, HCl does not selectively extract Ca^{2+} but does so with impurities from the slag, such as Fe/Al/Mg, which calls for the need of impurity extraction to obtain pure enough Ca^{2+} (Scheer, no date).

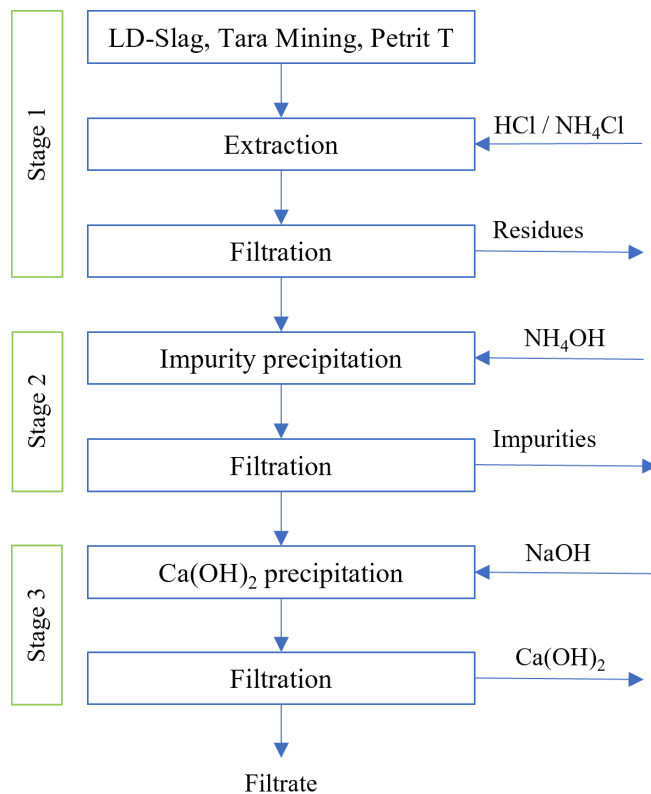


Fig 2. Flow diagram outlining the procedure for extracting Ca(OH)_2 using both HCl and NH_4Cl chemical solvents (Scheer, no date)

After Ca(OH)_2 has been extracted, it is meant to be used in the construction of porous materials, which are then used to absorb CO_2 from the atmosphere.

1.8 Life Cycle Assessment (LCA) in CO_2 Capture

1.8.1 Definition and importance of LCA

A Life Cycle Assessment (LCA) is a systematic approach to evaluating the environmental aspects and potential impacts associated with a product, process or service. An LCA provides a detailed view of the environmental interaction that a product or service has throughout its life cycle, which could be from the extraction of raw material, through production, use, to disposal or recycling (Bruijn *et al.*, 2004). An LCA is conducted according to a framework or a set of principles; this framework was established by the International Organization for Standardization (ISO) 14040. ISO14040 just established the framework and did not go into detail about the specific methods to use in conducting an LCA study; this was addressed by ISO 14044. ISO 14044 builds on ISO14040 and includes a specification for how to conduct a study, including choosing impact categories, category indicators, and characterization models, ensuring the LCA is thorough (*Understanding LCA Standards: ISO 14040/14044* | *cove.tool Help Center*, no date).

This assessment method enables a comprehensive analysis of all interactions within the Ca(OH)_2 extraction process, providing a deeper understanding of potential environmental impacts and effectively evaluating the environmental feasibility of the study.

1.8.2 Types of LCA approaches

LCAs can be commonly grouped by their temporal scope, the stage of development of the technology being assessed (technology maturity), and the type of environmental impacts considered (causality).

- **Time (Temporal Scope)**

Retrospective LCA: Examines past or current systems, analyzing what has already happened. This is also often called an accounting LCA.

Prospective LCA: Investigates the potential future environmental impacts of proposed changes or new technologies that are not yet mature (Arvidsson, Sandén and Svanström, no date a). This is also often called a change-oriented LCA.

- **Technology Maturity**

Ex-post LCA: Studies technologies that have already reached a high level of maturity.

Ex-ante LCA (related to Prospective LCA): Focuses on immature technologies and models them as they might exist in the future once they have matured.

Lab-scale LCA: An LCA performed on technology in its early, immature, lab-scale phase often suggests improvements to developers (De Souza *et al.*, 2023).

- **Causality (Purpose)**

Attributional LCA: Determines the environmental impacts of a product or process by looking at its causes, essentially contributing to a global impact share.

Consequential LCA: Assesses the effects of a decision on a product system, considering the resulting impacts on the environment. This type of LCA is forward-looking and aims to understand the real-world consequences of actions (Arvidsson, Sandén and Svanström, no date b).

The study is a combination of an attributional LCA and a Lab-scale LCA; this is because the study is based on the scaling up of a laboratory conducted extraction process to see how it will perform when fully developed. It also aims at determining and understanding the process's direct emissions.

1.9 Components of a Life Cycle Assessment

The ISO14040 and ISO14044 Frameworks detail an iterative four-phase approach as explained below:

1. Goal and Scope definition: This is the most important step of the study because it involves establishing clear objectives and the intended application of the LCA. This is

also the stage where there is a need to set up the functional unit of a study. The functional unit of the study is a specific quantitative value that serves as the reference for the system and everything else in the study (inputs and outputs), including the calculations revolving around this (Baumann and Tillman, 2004). In this stage, there is a need to set a clear boundary for the system, which basically refers to the processes included in the study, and could also include geographical and temporal boundaries.

2. Life Cycle Inventory Analysis (LCI): This is the data collection part of the study, which involves gathering information on the inputs and outputs of the system being analyzed. The methodological choices of the study must be clearly decided, such as the approach for data collection and allocation methods. (*Understanding LCA Standards: ISO 14040/14044 | cove.tool Help Center*, no date).
3. Life Cycle Impact Assessment (LCIA): the goal here is to quantify or measure all the inputs and outputs of the system, assessing their magnitude and their contribution to overall environmental impact (Quist, 2024). It is important in this stage to select environmental impact categories which typically include Ozone depletion potential, Acidification, Resource consumption, global warming potential and eutrophication.
4. Life Cycle Interpretation: The final step involves the analysis of the qualitative results in relation to the study objectives. This also involves presenting findings in a clear, concise manner with a summary that has important insights from the study.

The process detailed above can be very long and involve some technical calculations. To streamline it, there are LCA software tools available, including integrated databases from accredited researchers, simplifying data input and analysis.

2. Methodology

2.1 Goal and Scope

The study evaluates the environmental feasibility of various $\text{Ca}(\text{OH})_2$ extraction methods. The study is a cradle-to-gate study, which means that the system boundary starts when the industrial by-product enters the system and ends when the $\text{Ca}(\text{OH})_2$ has been produced and is ready to be used for porous materials. The system's boundary also accounts for the transportation of waste residues from the process to the waste facility; everything after that is out of the study's scope.

2.2 Functional Unit (FU)

Considering the goal is to use the extracted $\text{Ca}(\text{OH})_2$ to create a porous material which will then be used for carbon capture, the functional unit of the system is set as 1 tonne of CO_2 captured by the passive Direct Air Capture (DAC) system.

This functional unit allows for the comparison of the proposed DAC system with other CDRMs, and it also quantifies the environmental impacts of the system, simplifying result communication.

2.3 Linz-Donawitz slag (LD-Slag)

LD-slag, which was obtained from SSAB, is the chosen industrial waste product for this study because of the availability of lab data covering all areas necessary for an LCA.

LD-slag is sometimes referred to as steel converter slag or Blast Oxygen Furnace slag (BOF slag). This is a by-product from the steelmaking process and comes from slag-formers such as burned lime/ dolomite and from oxidizing of silica, iron and others when refining the iron into steel in the LD-Furnace ("LD - slag - SSAB," no date).

Table 2: A detailed description of the typical elemental composition of LD-slag (Rydén, Hanning and Lind, 2018).

Element	Ca	Fe	Mg	Si	Mn	V	Al	S	K	Cr	P
Percentage %	31.7	17.1	5.9	5.6	2.6	1.5	0.8	0.10	0.05	0.2	0.25

2.4 Flow diagram:

Figures 3 and 4 are the flow diagram of the analysis, which is basically a visual representation of the modelled system and an insight into what went into the model. There are two flow diagrams which represent the extraction process using HCl and NH₄Cl, with the red outline representing the system's boundary. The green arrows in the flow diagram represent every input to the system, with the red dashed arrows representing all the outputs from the system; the yellow boxes represent the waste procedure in the extraction process.

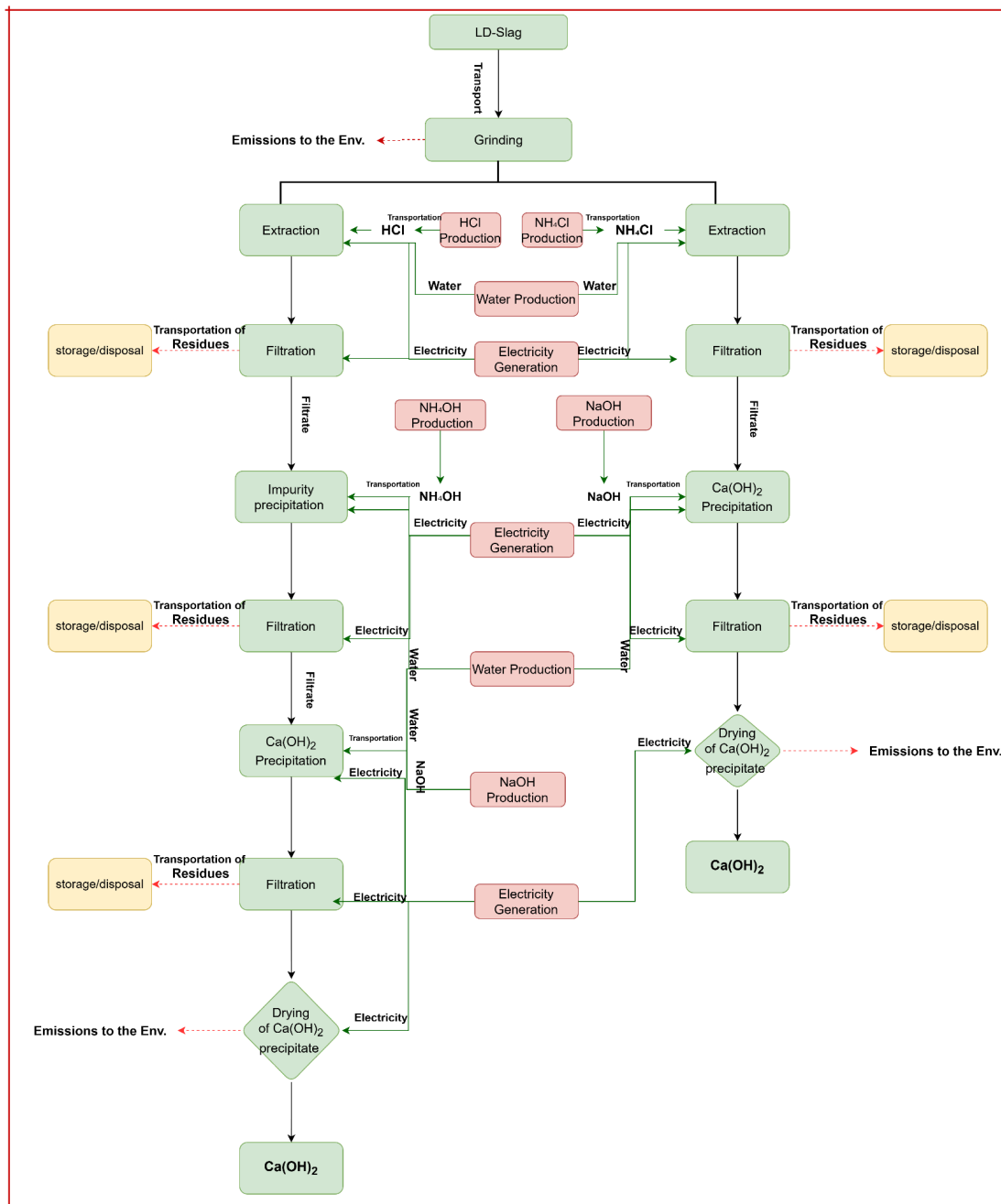


Fig. 3: Flow diagram for the extraction of Ca(OH)_2 using both HCl and NH_4Cl solvents.

2.5 Life Cycle Inventory (LCI):

2.5.1 Data collection:

Data sources and quality:

In an LCA, different data sources can lead to different outcomes and conclusions. For a data set to be of high quality, it must be reliable, relevant to the study in terms of geography, and when the data is collected, it also must be accessible (Flemström and Pålsson, no date). The ideal form of data is one that is directly obtained from the plant or system being analyzed, often known as primary data.

Depending on the study, primary data may not always be easily available; in such instances, to build a model for an LCA, generic data or estimations can be used.

The main types of data sources within the model are detailed below:

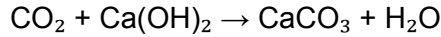
- **Foreground Data:** This describes a type of data within the model that is collected directly for the modelled system, and it is usually the part that can be influenced or controlled (“Explained: Data in LCA Ecochain Technologies Help Center,” no date). This includes the lab data for the extraction process, industry averages and published studies. The foreground data in the study are represented by the green boxes in the flow chart.
- **Background Data:** This refers to data that covers the processes outside of the system, usually referring to larger supply chain systems that cannot be influenced or controlled. This could be CO₂ emissions, electricity generation or water production/treatment and transportation within the model (“Explained: Data in LCA Ecochain Technologies Help Center,” no date). The background data in the study is represented by the red boxes in the flow chart.
- **Estimated data:** this refers to data that is not directly measured but approximated based on available information. Some part of the model’s data was obtained from calculations, consultation with experts and from Ecoinvent, which is an LCA database used in the LCA open software tool (Tampubolon *et al.*, 2021).

Model calculations were based on primary data from the lab experiment; the functional unit (FU) is 1 tonne of CO₂ captured by the passive Direct Air Capture (DAC) system, which represents the scaled-up system. All the primary figures from the lab data had to be multiplied using a scale factor for it to match the set functional unit. To calculate the scale factor, an initial calculation of how much Ca(OH)₂ is needed to capture 1 tonne of CO₂ was done.

2.5.2 Calculation of how much Ca(OH)_2 is needed to capture 1 tonne of CO_2

To capture 1 tonne (1,000 kg) of CO_2 using calcium hydroxide (Ca(OH)_2).

Chemical Reaction:



This equation indicates that one mole of CO_2 reacts with one mole of Ca(OH)_2 to produce one mole of calcium carbonate (CaCO_3) and water.

Molar Masses:

- CO_2 : 44 grams per mole
- Ca(OH)_2 : 74 grams per mole

Calculations:

1. **Determining Moles of CO_2 to Capture:**
 - 1 tonne of CO_2 = 1,000,000 grams
 - Moles of CO_2 = 1,000,000 grams / 44 grams per mole = 22,727 moles
2. **Calculating Required Ca(OH)_2 :**
 - Moles of Ca(OH)_2 needed = Moles of CO_2 = 22,727 moles
 - Mass of Ca(OH)_2 = 22,727 moles \times 74 grams per mole = 1,681,818 grams
 - Converting to kilograms: 1,681,818 grams / 1,000 = 1,682 kg

Therefore, approximately **1,682 kg of Ca(OH)_2** is required to capture **1 tonne of CO_2** .

1,682 kg of Ca(OH)_2 was then used to calculate the scale factor for both HCl and NH_4Cl .

2.5.3 Scale factor calculation for HCl

According to the lab data provided, the amount of calcium hydroxide (Ca(OH)_2) extracted at the end of the process for LD-slag were: 4.40g for HCl and 1.13g for NH_4Cl , the difference in the amounts of Ca(OH)_2 yield is due to the difference in HCl's Calcium extraction efficiency, it is higher in initial extraction of calcium ions from the raw materials and often results in a more substantial final yield of Ca(OH)_2 precipitate (Scheer, no date b).

The final yield provided by the lab data is then used to divide the prospective yield of **Ca(OH)_2 to capture CO_2** and then multiplied by 1000 to find the scale factor.

- **LD Slag (HCl extraction):** 1,682 kg / 4.40 g (Converted to kg) = 382.27 X 1000
Therefore, the scale factor for HCl: **382270**
- **LD Slag (NH_4Cl extraction):** 1,682 kg / 1.13 g (Converted to kg) = 1488.50 X 1000
Therefore, the scale factor for NH_4Cl : **1488500**

These scale factors are then used to calculate the rest of the lab data, as evident in the tables below (some of the figures in the table are scaled up directly from the lab data, others are retrieved from literature and estimated):

Table 3.1: Material and energy flows for the extraction process using HCl

		INPUTS	FIGURES	OUTPUTS	FIGURES
STAGE 1	Grinding	Electricity kWh for grinding	98.24339	Grounded material (kg)	3822.7
		LD-SLAG (kg)	3822.7		
		Transportation of LD slag to the plant site	178.3km * 4 t		
	Extraction	HCl (kg)	2787.51284	Stage 1 Residue (kg)	711.63383
		Grounded LD-SLAG (kg)	3822.7		
		Water (kg)	38227		
		Transportation of HCl to the plant site (car)	357 km * 3tons		
		Electricity for stirring (kWh)	4.052		
	Filtration	Transportation of filter cake residue for storage/disposal	9.8 km * 1 ton	Stage 1 Filtrate (L)	22936.2
		Electricity for filtering (kWh)	109.4		
STAGE 2	Impurity Precipitation	Stage 1 Filtrate (L)	22936.2	Impurities(kg)	2298.245467
		Electricity for stirring (kWh)	4.052		
		NH ₄ OH (L)	9537.6365	Stage 2 Filtrate (L)	22936.2
		Transportation of NH ₄ OH to the plant site (car)	357 km * 10 tons		
	Filtration	Electricity for filtering (kWh)	116.5	Stage 2 Filtrate (L)	22936.2
		Transportation of filter cake residue for storage/disposal	9.8 km * 3ton		
STAGE 3	Ca(OH) ₂ Precipitation	Electricity for stirring (kWh)	2.67436092	Final Waste (kg)	1587.490856
		Stage 2 Filtrate (L)	22936.2		
		NaOH (kg)	2618.5495	Final Ca(OH) ₂ (kg)	1,682
		Transportation of NaOH to the plant site (car)	357 km * 2 tons		
	Filtration	Electricity for filtering (kWh)	61.5		
		Transportation of filter cake residue for storage/disposal	9.8 km* 2 tons		
	Drying	Electricity for drying (kWh)	0.0525		

Table 3.2 Material and energy flows for the extraction process using NH_4Cl .

		INPUTS	FIGURES	OUTPUTS	FIGURES
STAGE 1	Grinding	Electricity	38.25445	Grounded material (kg)	14885
		LD-SLAG (kg)	14876.1 (14.9T)		
		Transportation of LD slag to the plant site	178.3 km* 15tons		
	Extraction	NH_4Cl (kg)	15926.95	Stage 1 Residue (kg)	10502.707 15
		Water (kg)	148850		
		Transportation of NH_4Cl to the plant site (car)	357 km*16tons		
		Grinded material	14885		
		Electricity (for stirring) (kWh)	15.7781		
	Filtration	Transportation of filter cake residue for storage/disposal	9.8 km*1ton	Stage 1 Filtrate (L)	89310
		Electricity	168.5		
STAGE 2	$Ca(OH)_2$ Precipitation	Electricity (for stirring)	15.7781	Final Waste (kg)	2249.7189
		Stage 1 Filtrate (L)	89310		
		NaOH (kg)	9915.94045		
		Transportation of NaOH to the plant site (car)	357km*11tons		
		Water (kg)	237982.5708		
	Filtration	Electricity for filtering (kWh)	369	Final $Ca(OH)_2$ (kg)	1,682
		Transportation of filter cake residue for storage/disposal	9.8 km* 3 tons		
Drying	Electricity for drying (kWh)	0.1602			

2.5.3 Allocation

This is the part of an LCA that calculates the partitioning of the environmental loads of a process that yields multiple products (Ekvall, 1999). Allocation can be done in three main ways: based on mass, physical properties (e.g. energy used in the process) and allocation based on economic value. The allocation method heavily impacts the outcome of the LCA, and it is therefore crucial that the reasons for choosing a particular allocation method are documented and explained ("Explained: Life Cycle Impact Assessment (LCIA) phase Ecochain Technologies Help Center," no date). In this study, allocation is avoided, and the

environmental burden of the process is therefore attributed entirely to the main output, which is the dried $\text{Ca}(\text{OH})_2$. The system can be expanded to include recovery of metals from waste residues from the extraction process and environmental burden allocated in subsequent studies; however, that is not within the assessment scope for this LCA. This decision is in alignment with the ISO14044, which states that the first preference for allocation in an LCA is to avoid allocation together by either expanding the system (to include the additional process related to the secondary co-products) or dividing the process into subdivisions (where the data for the subprocesses are collected separately) (for Standardization (ISO), 2006).

3 ■ Modelling and Sensitivity Analysis

The model was built on the extraction process of $\text{Ca}(\text{OH})_2$, and to correctly model the transportation, a hypothetical base location for the proposed plant site was chosen. The consideration for choosing this location was to choose a site that captures average transport distances across Sweden, has industrial or transport relevance and is helpful for modal split analysis for an LCA. The location choice was Örebro (**Latitude (59.2741° N), Longitude (15.2066° E)**), which is located between the two largest cities in Sweden, and that makes it a central position in the country's transport network, ensuring that the modelled transport distances are a good representation of average national distances. The transport model includes distances to the waste facility (9.8 km), from the chemical producer (1,428 km) and delivery distance for the LD-slag to be delivered to the proposed plant site (178.3 km).

An individual model was then built around this for the extraction process using HCl or NH_4Cl . All three to four stages were modelled, with four scenarios. The varying factor between the scenarios is the type of electricity, and the varying factor between the two cases is the provider of the chemicals within the extraction process.

3.1 Sensitivity Analysis:

When building an LCA model, there is a need to pick a data provider for each background dataset. For example, specifying whether the electricity is supplied from a Swedish grid mix, a European average, or a global 'rest of world' mix. The choice of provider influences how representative the dataset is of the study region, including emission intensities, transportation distances, and production methods, which ultimately influences the outcome of the analysis.

Scenario 1: Market Chemicals + Market Electricity (Standard Baseline)

In this scenario, all the chemicals used in the extraction process are modelled using the standard market data set with market providers. A market data set reflects the global or regional average of a product, incorporating various standard production processes, average transportation distances, and distribution losses ("ReCiPe," 2016).

The electricity used is also derived from a market data set and is specified as medium voltage electricity, representative of industrial connections typically ranging from 1 to 24 kilovolts (kV) (*Explained: Life Cycle Impact Assessment (LCIA) phase | Ecochain Technologies Help Center*, no date). This scenario serves as a baseline for comparison, using conventional datasets for both chemicals and electricity.

Scenario 2: Specific Chemicals + Market Electricity

This scenario employs specific chemical production methods from specific providers with reduced environmental impact data sets. These datasets focus on the emissions and losses associated exclusively with the chemical manufacturing process, excluding distribution and transportation, which must be modelled separately. The specific low environmental impact chemical production datasets chosen for the model are the following :

HCl: allyl chloride production, reaction of propylene and chlorine to form hydrochloric acid.

NH₄Cl: ammonium chloride is a byproduct of the production of hexamethyldisilane using the amination of chlorisane.

NH₄OH: ammonium hydroxide used/ produced in cobalt production.

NaOH: chlor-alkali electrolysis in a membrane cell to produce sodium hydroxide.

The chemical suppliers for the model: for NaOH, HCl, and NH₄Cl, the supplier is Brenntag AB (from their facility in Lotsgatan 1, 392 31 Kalmar); however, Brenntag AB does not supply or produce ammonia anhydrous liquid, which is used to produce NH₄OH within the model. An external supplier was sourced, Yara AB (from their facility in Nya Hamnvägen 14, 731 36 Köping), a company that deals particularly in nitrogen-based industrial chemicals (ammonia, urea, nitric acid, nitrates). The electricity used remains consistent with Scenario 1 in terms of **medium voltage (1–24 kV)** and is sourced from a **regular market data set**.

Scenario 3: Market Chemicals + Renewable Electricity

In this scenario, the chemicals are modelled using the **standard market data set** (as in Scenario 1), reflecting average global or regional production practices along with typical distribution and transport assumptions.

However, the electricity used in this scenario is sourced from renewable energy. It remains at medium voltage (1–24 kV) but utilizes a renewables-based electricity data set, introducing a variation in energy source while maintaining baseline chemical data.

Scenario 4: Specific Chemicals + Renewable Electricity

This scenario combines specific, low-impact chemical production data sets (as in Scenario 2) with renewable electricity. It represents the most environmentally optimized model, focusing both on minimizing emissions in chemical manufacturing and the use of clean energy.

Electricity is modelled at medium voltage (1–24 kV) and is derived from a renewables-based data set, replacing the standard market electricity used in Scenarios 1 and 2.

Purpose of Scenarios in Sensitivity Analysis

These four scenarios are designed to perform a sensitivity analysis, testing the robustness of the environmental impact results under different assumptions. This approach helps identify:

- Key contributors (hot spots) to the total environmental impact.
- The influence of energy source vs. chemical production method.
- The potential benefits of switching to cleaner technologies or datasets.

3.2 Additional Sensitivity Analysis: Transport Distance Variations

To further assess the robustness of the environmental impact results, an additional sensitivity analysis is performed by varying the transport distances within the model. Of our four scenarios, the most impacted by differences in distance would be scenarios that use specific chemical production data sets (Scenario 4). Unlike market datasets, specific production datasets do not include transportation, requiring explicit modelling of this component; however, there is still a little bit of transportation in those scenarios stemming from the delivery of LD-slag and waste procedures. The distances used in the model are the averages of possible distances within the extraction process.

Transport Distance Cases

Three different transport distance cases are considered:

- **Case A – the proposed plant site will be in Göteborg**

Transportation is modelled with a Euro 6 truck. The transportation within this model includes the distance from the chemical producer or supplier (**350.5 km total**), the distance that the waste residues travel to the waste facility (**7.07 km**) and the distance from SSAB to our proposed plant site for the delivery of LD slag (**410.7 km**).

- **Case B – the proposed plant site will be in Kiruna**

Transportation is modelled with a Euro 6 truck. The transportation within this model includes the distance from the chemical producer or supplier (**1,646 km total**), the distance that the waste residues travel to the waste facility (**7,9 km**) and the distance from SSAB to our proposed plant site for the delivery of LD slag (**1,348 km**).

- **Case C –the proposed plant site will be in Umeå**

Transportation is modelled with a Euro 6 truck. The transportation within this model includes the distance from the chemical producer or supplier (**1041.5 km total**), the distance that the waste residues travel to the waste facility (**13,4 km**) and the distance from SSAB to our proposed plant site for the delivery of LD slag (**768 km**).

Table 4: Proposed plant site cities and coordinates.

City	Central Logistics Point Coordinates
Kiruna	67.8558° N, 20.2253° E
Umeå	63.8365° N, 20.2444° E
Gothenburg	57.7089° N, 11.9746° E

Note: All transport is assumed to occur via **diesel-powered Euro 6 trucks**.

Application to Scenarios

These transport cases are applied to the following scenarios:

- **Scenario 1:** Market data set for chemical production methods + Market Electricity data set
- **Scenario 2:** Specific Chemicals production method dataset + Market Electricity data set

This analysis helps to quantify the impact of transport relative to chemical production.

Table 4.2 Chemical and Energy Scenario Dataset (Grouped by Distance Variants)

Scenario + Case	Chemical Data Set Type	Electricity Source
1A	Specific	Market
1B	Specific	Market
1C	Specific	Market
2A	Specific	Market
2B	Specific	Market
2C	Specific	Market

4. Life Cycle Assessment Impact (LCIA)

This is the stage where all the inventory data (the inputs and outputs of the modelled system, including background and foreground data) are quantified and assessed to determine the model's actual environmental impacts. This can be done using life cycle assessment Impact methods; there are several LCIA methods, and selecting said methods is dependent on several factors such as the goal of the LCA study, the industry standards, regulatory requirements and availability of data[38]. For this study, the impact assessment method chosen was Recipe 2016, which is an impact assessment method that comes with the recent ecoinvent database version 3_10.

Recipe 2016 was chosen because it is a highly detailed and standard assessment method designed with a dual-level approach, which allows for the option to choose a detailed analysis using midpoint or endpoint indicators/ categories. Midpoint categories measure specific environmental issues such as climate change, acidification, etc., while end point categories summarize or collate the midpoint categories into three main areas (effects on human health, ecosystem quality and resource availability[39] to show broader impact. The assessment for this study employs both endpoint and midpoint factors.

The Impact Categories chosen for this method are:

- **Climate Change (kg CO₂-Eq):** This assesses a product's contribution to global warming by measuring its greenhouse gas (GHG) emissions. Various GHGs are converted into a single standard unit, CO₂-equivalent (CO₂-eq), to account for their different warming potentials.
- **Terrestrial acidification (kg SO₂-Eq):** This category is an indicator of the potential change in acidity of soils due to releases of gases such as nitrous oxides and sulphur oxides.
- **Human toxicity: carcinogenic (kg 1,4-DCB-Eq):** This category reflects the impacts of toxic emissions on human health.
- **Freshwater ecotoxicity (kg 1,4-DCB-Eq):** This category assesses the impact that toxic emissions have on freshwater habitats and the organisms within them.
- **Fresh Water Eutrophication (kg P-Eq):** This category assesses the impact that toxic emissions have on freshwater habitats and the organisms within them.

- **Mineral resources (kg Cu-Eq):** Indicator of the depletion of natural non-fossil resources.
- **Stratospheric ozone depletion (kg CFC-11-eq):** This category is an indicator of emissions into the air that destroy the stratospheric ozone layer.

The recipe 2016 impact assessment method allows the option to generate results from 3 cultural perspectives. These perspectives are Individualist (I), Hierarchist (H), and Egalitarian(E). The choice between these perspectives is dependent on the goal and scope of the assessment or study. For this assessment, the cultural perspective for the generated results is the Hierarchist (H) perspective. This was chosen because it is the most used perspective in LCA studies accepted by scientists (“ReCiPe,” 2016).

Table 5: A table describing the difference between the Recipe 2016 perspectives(“ReCiPe,” 2016).

Recipe 2016 Perspective	Time perspective	Manageability	Required level of evidence
Individualist (I)	Short time	Technology can avoid many problems	Only proven effects
Hierarchist (H)	Balance between short and long term	Proper policy can avoid many problems	Inclusion based on consensus
Egalitarian(E)	Very long term	Problems can lead to catastrophe	All possible effects

4.1 Characterization:

This process in LCIA transforms a study’s elementary flows from both the inputs and outputs in the model into a common unit (e.g., CO₂-eq, DCB eq, kg N-eq, etc.).This common unit is obtained by multiplying standard characterization factors (CF) derived from scientific models and databases with the quantified inventory results for each substance associated with a particular impact category (*Explained: Life Cycle Impact Assessment (LCIA) phase | Ecochain Technologies Help Center, no date*)

An example:

- For GWP (100 years):
- CO₂ has a CF of 1
- CH₄ has a CF of 28

- N₂O has a CF of 265

So, if a system emits

1 kg CO₂ → 1 kg CO₂-eq

1 kg CH₄ → 28 kg CO₂-eq

1 kg N₂O → 265 kg CO₂-eq

Total GWP = 294 kg CO₂-eq.

Since the assessment for this study is done using Recipe 2016 and the open LCA tool, the characterization is done within the app when the results are being generated for the chosen endpoint and midpoint categories.

4.2 Normalization

This is an optional stage within an LCIA that allows for the comparison of results from the chosen Impact categories; here, the characterized results are compared to a norm, allowing for easy understanding of environmental impacts. The norm is usually the damage caused to the environment by the average person per year. An example is known that the average person produces 7tons of CO₂ in a year if the impact categories are in CO₂ eq, that result number can then be divided by 7tons to determine how many people the extraction process climate impact is equivalent to in a year.

5. Results and Discussion

With all the environmental burdens allocated to the extracted $\text{Ca}(\text{OH})_2$, the results below depict the environmental consequences associated with the system being studied across various impact categories.

5.1 HCl vs NH_4Cl

Below are results from the comparison of HCl and NH_4Cl baseline (scenario 1) extraction methods in the study, where:

Scenario 1: represents market chemicals (market-average datasets) and market-average grid electricity

5.1.1 Midpoint

The results show that the NH_4Cl extraction procedure emits more across all the impact categories than the HCl extraction procedure does. This high emission for NH_4Cl can be attributed to upstream production processes and supply chain processes, which are then magnified by the amount of NH_4Cl needed in the extraction because of its low efficiency in extracting Ca^{2+} ions, which means more of NH_4Cl is needed to extract as efficiently as HCl.

Acidification

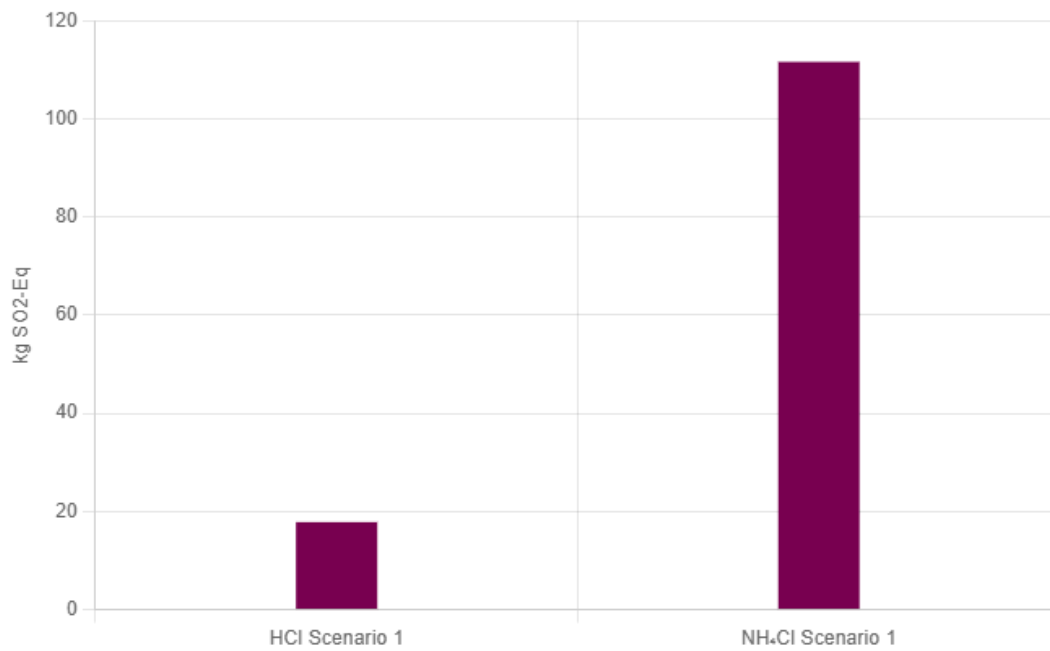


Fig. 4: A figure comparing the acidification impacts between the HCl and NH₄Cl baseline scenarios.

Climate change

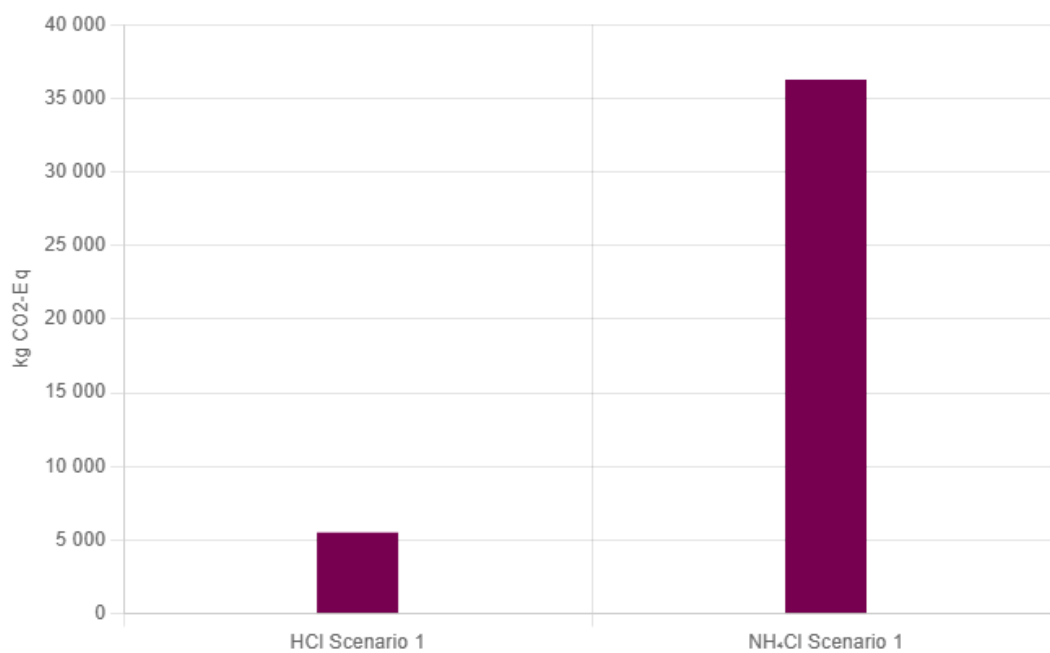


Fig. 5: A figure comparing the climate change impacts between the HCl and NH₄Cl baseline scenarios.

Ecotoxicity freshwater

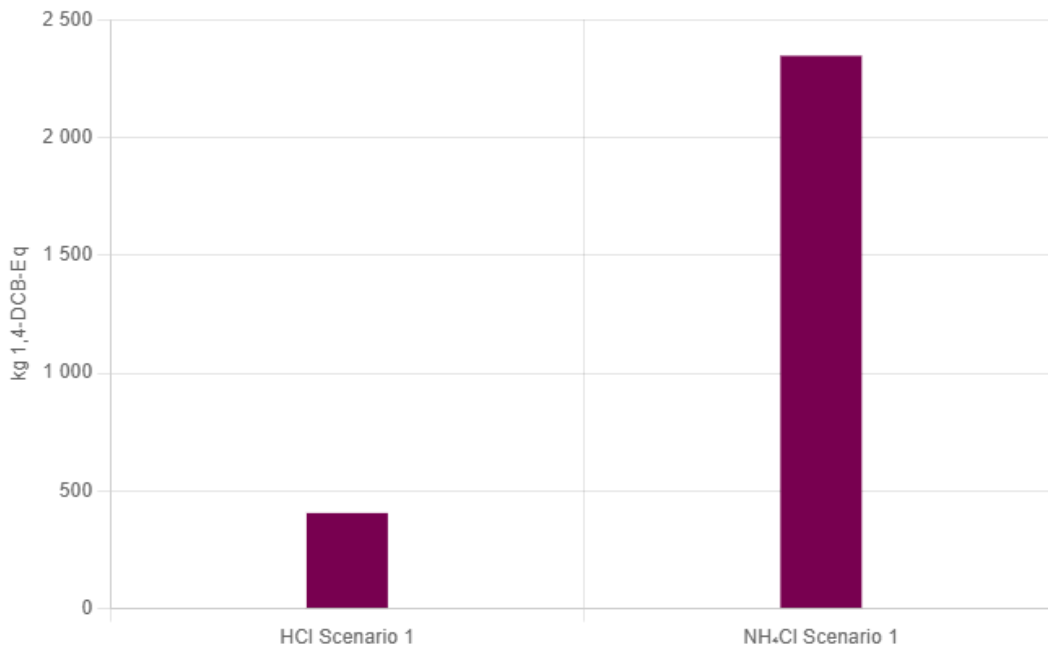


Fig. 6: A figure comparing the freshwater ecotoxicity impacts between the HCl and NH₄Cl baseline scenarios.

Freshwater eutrophication

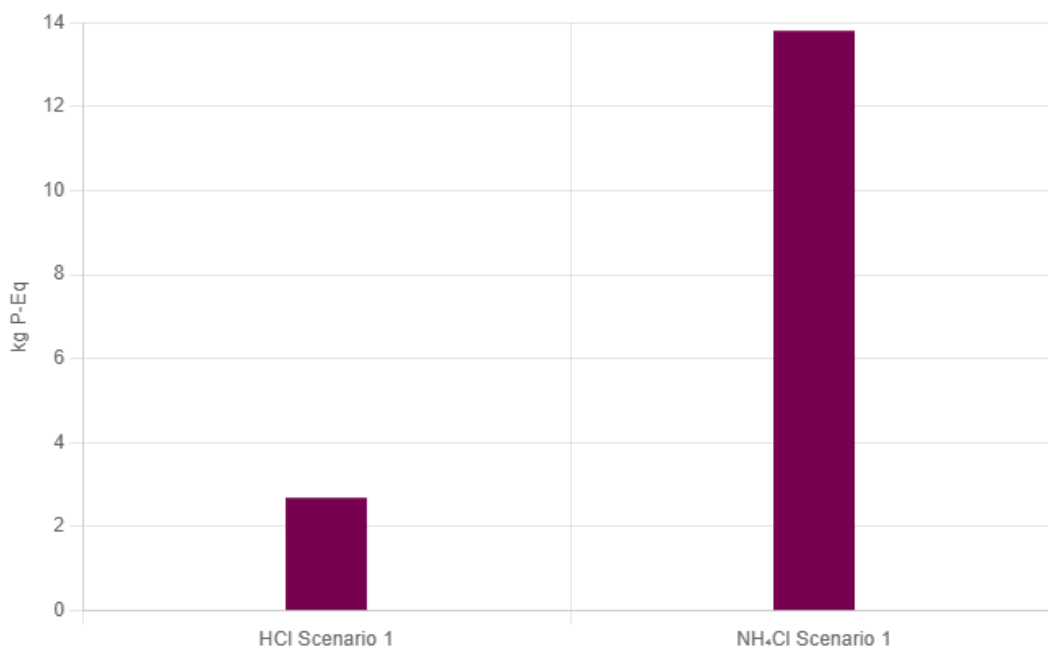


Fig. 7: A figure comparing the freshwater eutrophication impacts between the HCl and NH₄Cl baseline scenarios.

Ozone depletion

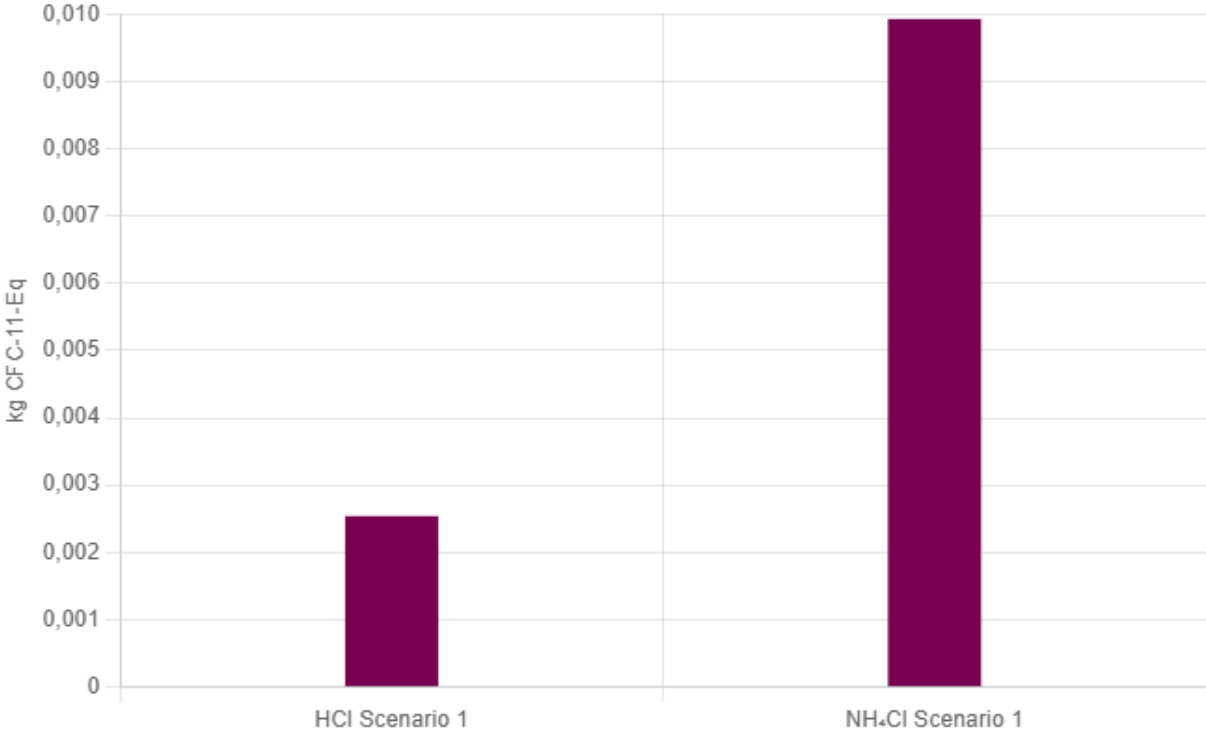


Fig. 8: A figure comparing the ozone depletion impacts between the HCl and NH₄Cl baseline scenarios.

Human toxicity carcinogenic

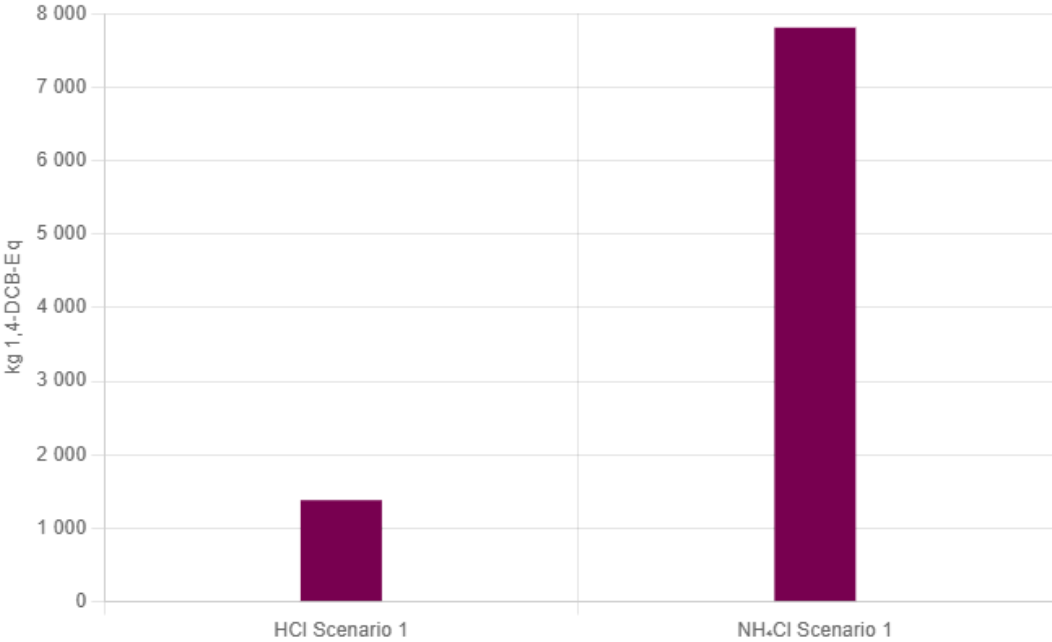


Fig. 9: A figure comparing the carcinogenic impacts between the HCl and NH₄Cl baseline scenarios.

Mineral resources

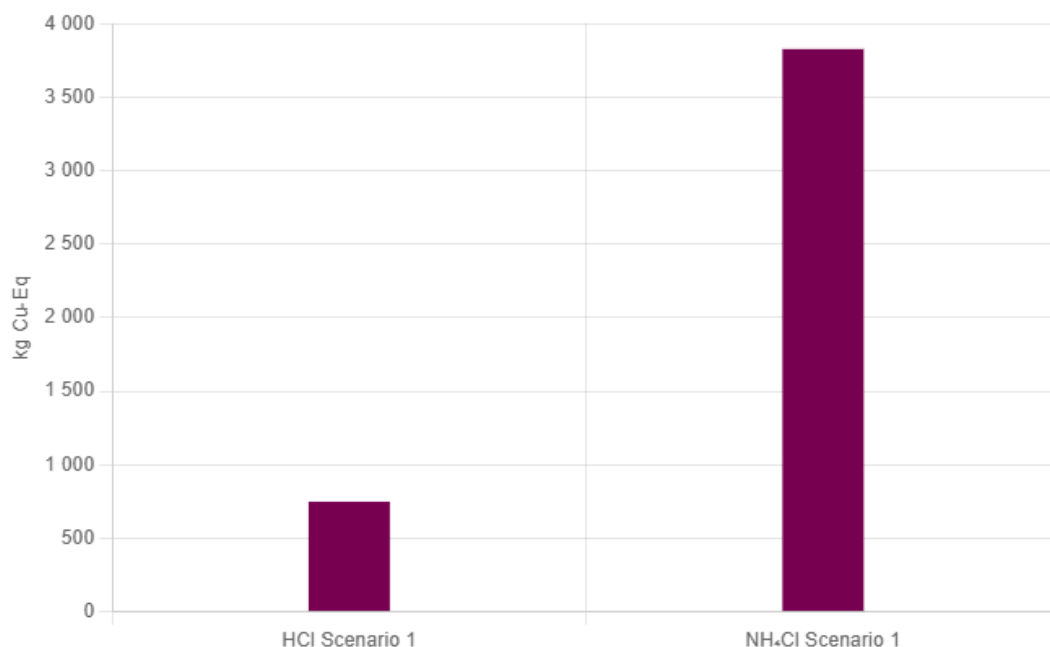


Fig. 10: A figure comparing the material use (minerals and metals) impacts between the HCl and NH₄Cl baseline scenarios.

Table 6: A table comparing the difference between the HCl and NH₄Cl extraction scenarios.

Impact Category	HCl Scenario 1	NH ₄ Cl Scenario 1	Relative Difference (NH ₄ Cl ÷ HCl)
Acidification: terrestrial (kg SO ₂ -Eq)	17.85	111.59	6.3× higher
Climate change (kg CO ₂ -Eq)	5,514	36,261	6.6× higher
Ecotoxicity: freshwater (kg 1,4-DCB-Eq)	406	2,346	5.8× higher
Eutrophication: freshwater (kg P-Eq)	2.69	13.81	5.1× higher
Human toxicity: carcinogenic (kg 1,4-DCB-Eq)	1,382	7,809	5.6× higher

Material resources: metals/minerals (kg Cu-Eq)	748	3,827	5.1× higher
Ozone depletion (kg CFC-11-Eq)	0.00254	0.00993	3.9× higher

5.2 Results for HCl Scenario 1 *Baseline*.

5.2.1 Midpoint results

Acidification

The life cycle contribution analysis for HCl case 1, Örebro, shows a total acidification potential expressed as SO₂-equivalents of 17.85 kg SO₂-eq. The highest environmental burdens can be linked to Stage 4: impurity precipitation and Stage 2: extraction stages contribute 58.0 % and 52.9 % of the system total, respectively (10.36 and 9.45 kg SO₂-eq). Upstream chemical production is a major hotspot: the market dataset for hydrochloric acid and its production routes (Mannheim process and reaction of H₂ with Cl₂) together account for a substantial share (51.7 % for the overall HCl market dataset; Mannheim process alone contributes 4.98 kg SO₂-eq). Sulfuric acid (market and production datasets) is also an important upstream source (3.78 and 3.73 kg SO₂-eq, respectively), which indicates that the supply of acid feedstocks is a key driver of SO₂-equivalent emissions in the studied system. Sodium hydroxide (NaOH) production used in stage 4 is another major contributor (7.30 kg SO₂-eq; 40.9 % of the system total), primarily driven by chlor-alkali electrolysis and its electricity and raw-material demand. Most individual processes report near-zero direct SO₂ emissions because the impact is borne by upstream processes (chemical manufacture and electricity generation). Notably, sulfuric acid production shows a measurable direct contribution (1.98 kg SO₂-eq); it shows up as an upstream elementary flow for many of the chemicals used in the process.

Climate Change

The life cycle contribution analysis for the functional unit (HCl case 1, Örebro) shows a total climate change potential of 5514.50 kg CO₂-eq. The hotspots in this impact category are again the stages where chemicals are used during Ca(OH)₂ extraction, these are stages 2,3, and 4. The biggest upstream contributor in this category is the production process of Sodium hydroxide (NaOH). The market dataset for NaOH contributes 2373 kg CO₂-eq (43.0 %). Much of this burden stems from the chlor-alkali electrolysis process (2350.7 kg CO₂-eq), which in turn has high electricity and heat demand and significant upstream raw-material demands (NaCl(sodium chloride), etc.). Electricity supplied from conventional grids is itself a major contributor: the electricity input under NaOH production contributes 669.1 kg CO₂-eq (12.1 %) of the total impact of stage 3. HCl supply chain (market HCl datasets and production routes) is also crucial; it contributes about 33 % (1,836.97 kg CO₂-eq) to the entire climate change impact. Within the market data set, the production route with the highest impact is the production of HCl through the reaction of H₂ + Cl₂, contributing

about 1,229.31 kg CO₂-eq. These include burdens from chlorine and hydrogen production, which are energy-intensive and often electrochemical (chlor-alkali) or fossil-fuel driven. Other upstream chemicals and energy consumption also contribute to the total impact; ammonia (NH₄OH) production used in stage 3 contributes 955.73 kg CO₂-eq (17.3 %). Sulfuric acid, steam/heat and other commodity chemicals appear as mid-sized contributors and are relevant to feedstock supply decisions. Transport and small material flows are minor in comparison to the major chemical procedures within the study, contributing relatively little (<1 % each in most cases)

Ecotoxicity freshwater

The life cycle assessment of the HCl production process for scenario 1 reveals the distribution of potential toxicity impacts in terms of 1,4-dichlorobenzene (1,4-DCB) equivalents. The results highlight both direct process contributions and upstream supply chain impacts.

The total 1,4-DCB equivalent for the functional unit considered (production of Ca(OH)₂ via HCl process) is 406.05 kg 1,4-DCB-Eq, distributed across several stages, with varying contribution magnitudes. The dominant contributor here stems from sodium hydroxide production (NaOH) used in stage 4. Market-based production of NaOH contributes 207.71 kg 1,4-DCB-Eq, representing approximately 51% of the total toxicity impact. The impact is primarily indirect, arising from the energy-intensive chlor-alkali electrolysis process, highlighting the environmental burden of NaCl production. The next big contributor is the Hydrochloric acid production and supply chain, like in earlier categories, the market dataset, specifically the reaction of hydrogen and chlorine (Mannheim process and other related production routes), contributes 45–164 kg 1,4-DCB-Eq to the entire toxicity impact.

Other minor impact contributions can be attributed to electricity supply, transport and ammonia production, which collectively contribute between 0.77- 16.78 kg 1,4-DCB-Eq. With the range provided, the ammonia production process contributes the most, but still plays a secondary role in toxicity potential in comparison with the other chemical components within the study.

Ozone depletion

The total ozone depletion potential for the model is approximately 0.002540627 kg CFC-11-eq. Overall, the ozone depletion emission for the model is relatively small; most of the emissions are embedded in the production of the chemicals, which are the background or upstream processes within the model. The most prominent contributor is the production process of HCl, which contributes about **0.00122 kg CFC-11-Eq** of the total impact amount, stemming from the market data set of production methods. The same goes for NaOH being the second biggest contributor, emitting a total of 0,00104 kg CFC-11-Eq, which can also be attributed to the market data set encompassing the various methods of production, specifically the chlor-alkali process, which alone emits about 0,00103 kg CFC-11-Eq of the total amount associated with NaOH production. Ammonia production does not have as high

an impact in this category, emitting a small fraction of the total impact (9.85E-05kg CFC-11-Eq). The rest of the impact is made by minor contributors, such as transport activities and the actual electricity used in the extraction process.

Human Toxicity

The life-cycle characterization for HCl Case 1 yields a total of 1381.92 kg 1,4-DCB-Eq. Most of the impact on human health is attributed to upstream background processes, with the biggest contributor being the NaOH / chlor-alkali chain (market NaOH, chlor-alkali electrolysis and NaCl). This process contributes 640.0687482 kg 1,4-DCB-Eq with the chlor alkali process specifically emitting 635.30342 kg 1,4-DCB-Eq. The second largest contributor is the market data set for HCl, which includes the production and acquisition of HCl, emitting a total of 490.56664 kg 1,4-DCB-Eq. Of this amount, 311.33327kg 1,4-DCB-Eq comes directly from producing HCl from the reaction of hydrogen with chlorine; this amount results largely from the actual production of chlorine, which accounts for 184,55654 kg 1,4-DCB-Eq of the emission impact from reacting hydrogen with chlorine to produce HCl.

There are other minor contributors to the total impact results, such as ammonia anhydrous liquid production, which amounts to about 78.69580kg 1,4-DCB-Eq to the total impact amount, as well as transport within the model's waste procedure.

Freshwater Eutrophication:

The life cycle assessment of the HCl production process Scenario 1 reveals the distribution of eutrophication potential impacts in terms of kilograms of phosphorus equivalents (kg P-Eq). The total emission amount is 2.6896 kg P-Eq, with contributions coming from several upstream processes. The dominant contributor is the market-based production of sodium hydroxide, especially its chlor-alkali electrolysis pathway. This alone contributes 1.68046 kg P-Eq, representing over 60% of the total eutrophication potential. Much of this arises via emissions of nitrogenous compounds (e.g. NO_x, NH₃, from electricity generation, chemical process emissions) embedded in the NaOH supply chain. The next-largest sources are the HCl supply chain, which emits 0.9154 kg P-Eq, of which the market for HCl (34%) and its hydrogen-chlorine reaction route make up significant shares. This indicates that HCl production (as used in the Ca(OH)₂ process) is also a major driver of freshwater eutrophication. Other smaller contributions stem from transport (e.g. road freight), ammonia production, tap water use, process waste (supernatant), etc. While none of these individually approach the magnitude of NaOH or HCl supply chain emissions, in sum, they contribute about 2% to the overall eutrophication impact.

Mineral resources:

The life cycle assessment reveals the distribution of resource scarcity/metal depletion impacts in terms of kilograms of copper equivalents (kg Cu-Eq). The total impact amount is 748.48 kg Cu-Eq. Again, as seen throughout other impact categories, the major contributors are the upstream processes within the model. The dominant contributor is sodium hydroxide

(NaOH) production, particularly via the chlor-alkali electrolysis process. NaOH used in stage 4 contributes 486.74 kg Cu-Eq, which is about 65% of the total metal-resource depletion / copper-equivalent impact. A large fraction of this comes from the production of the sodium chloride feedstock (NaCl), whose mining, processing, and purification have a high copper-equivalent burden because they require substantial material extraction and associated environmental impacts. The next largest source is the hydrochloric acid supply chain. The HCl market (30%) contributes 243.76 kg Cu-Eq (32-33%), with its hydrogen-chlorine reaction route contributing 145.58 kg Cu-Eq, and chlorine production itself a sizable share of that. Additional inputs such as electricity (especially from regions with high intensity for copper-equivalent or mineral resource scarcity) and heat make smaller but non-negligible contributions (on the order of single-digit to tens of kg Cu-Eq).

Other medium to minor contributors includes water deionised, transport, and ammonia production. These each contribute relatively small fractions of the total, but in sum, represent the remainder (5–10%) of the Cu-Eq burden.

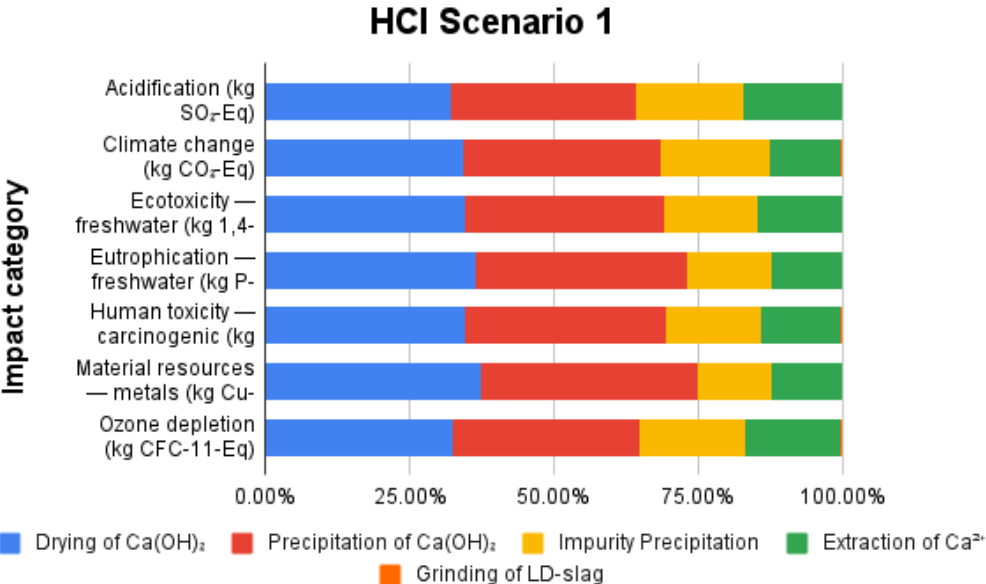


Fig 11: A chart mapping each environmental impact category to its dominant contributors within the HCl extraction process.

5.2.2 Endpoint results

Natural resources

With HCl scenario 1, about natural resource depletion, the total impact of the model amounts to 643.95 USD (2013). This figure represents the monetized cost of resource depletion (e.g. extraction of fossil fuels, metals, and minerals) within the entire model. Many individual processes contribute to this final amount, with the top ones being heavily centered around background processes. The most noticeable contributor is stage 3: Impurity Precipitation,

which contributes 368.7 USD (2013) to the entire resource depletion amount, accounting for about 57%. This is a result of the ammonium hydroxide used to precipitate out the impurities, which contributes about 17.7% to the stage 3 impact amount. The production process of anhydrous ammonia liquid requires a lot of resources that span from natural gas, electricity for production, waste procedures, nickel, water, transportation (which calls for the use of crude oil) and other solvents within the production of anhydrous ammonia liquid. The waste procedure within stage 3 also contributes about 2.4% (15.4 USD), which can be wholly attributed to the transport of the waste from the plant site to the waste facility. Another big contributor to natural resource depletion here is hydrochloric acid production, which is used in stage 2: Extraction of Ca⁺ carries about 34.5% of the entire impact burden. The noticeable upstream driver here is the consolidation of various HCl production methods within the market data set. The hotspot areas here are the production methods and processes that span from chlorine and hydrogen production and acquisition (including electricity and transport), as well as waste procedures within the said dataset. Sodium Hydroxide used in Stage 4: Ca(OH)₂ Precipitation also contributes about 40,84% (about 263 USD (2013)) to the entire impact on natural resource depletion. This huge impact stems mainly from the production of NaOH using the chlor-alkali electrolysis. This electrolysis process is electricity-intensive, but the biggest upstream driver here is the market data set for sodium chloride, which amounts to about 23.6% (150.4 USD (2013)) of the total stage 4 impact. The sodium chloride market data includes transportation within the production process, and rare earth oxide production and acquisition.

The other Endpoint categories, ecosystem quality and human health, are not as impacted by Scenario 1 as the natural resource depletion. Ecosystem quality's impact result is much lower, about 2.597E-5 species.yr (which is an indicator of the risk of species loss over time). With the biggest contributors being stage 3: Impurity Precipitation, Stage 4: Ca (OH)₂ Precipitation and stage 2: Extraction of Ca ++. Stage 3 however over here contributes a little bit less about 53.8% (1.40E-05 species.yr), the biggest contributor here still is as a result of the elements within the ammonium hydroxide production process however the contribution of the production process lies at about 12.98% (3.37E-06 species.yr) with a slight reduction in impact amount within the anhydrous liquid ammonia production process. In this endpoint category, Stage 2 emits about 38.88% (1.01E-05 species.yr), which is slightly more than that of natural resource depletion. This stems from an increase in the impact amount within the market data set of consolidated HCl production methods. Stage 3 also has a slightly bigger impact amount of 53.76% (1.40E-05 species.yr), also attributed to the elements within the production process of anhydrous ammonia liquid.

Human Health Endpoint Category

This category is measured in Disability-Adjusted Life Years and is an indicator of the overall impact the studied process has on human health, with an impact value of 1.61E-02 DALYs. The biggest contributor in this category is HCl production, and that is due to the processes involved in the production of the acid used for calcium ion extraction in stage 2. It contributes about 38.56% of stage two's entire impact. The production of sodium hydroxide is also yet again a big upstream contributor to the overall impact on human health, with an impact value of about 45.2% (7.26E-03 DALYs) of stage 3's entire impact (51.84% = 6.62E-03 DALYs).

Overall, for scenario 1, the most critical environmental impact in the endpoint category is natural resource depletion, which has higher impact numbers in relation to human health and ecosystem quality.

In conclusion for the HCl scenario 1, the most critical environmental burdens do not lie in the extraction of $\text{Ca}(\text{OH})_2$ but in the upstream supply chains and production process of the chemicals used within the model.

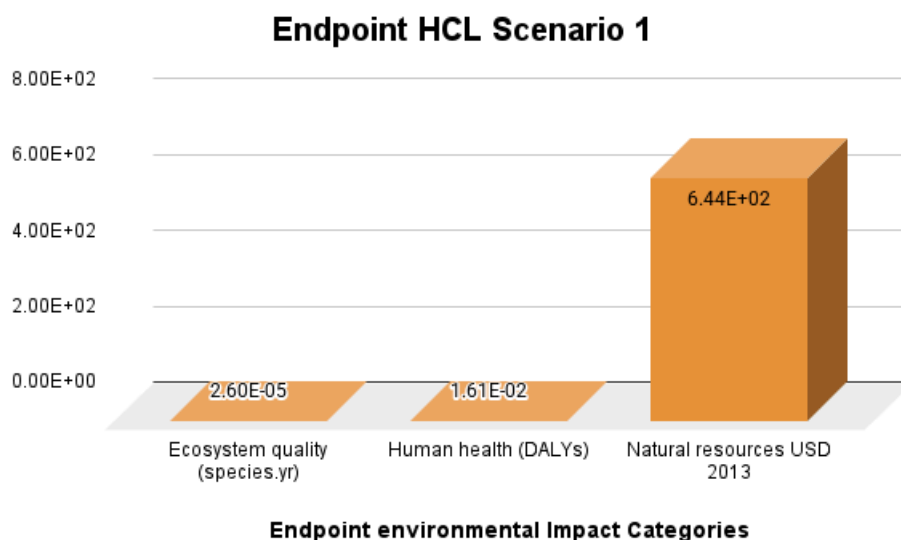


Fig 12: A figure comparing the various Endpoint Impact categories for the HCl extraction process.

5.3 Results for NH_4Cl Scenario 1.

5.3.1 Midpoint

Acidification

This impact category is expressed in $\text{kg SO}_2\text{-eq}$, which measures the potential contribution of emissions to acidification and the associated effects on ecosystems. The total potential impact of the model is 111.59 $\text{kg SO}_2\text{-eq}$, with the most critical hotspot being the production of ammonium chloride. The global market dataset for ammonium chloride contributes approximately 82.46 $\text{kg SO}_2\text{-eq}$, equivalent to 73.9% of the total impact in stage 2. Within this dataset, soda ash production using Hou's process dominates, contributing 66.44 $\text{kg SO}_2\text{-eq}$. This is primarily due to sulfur emissions from energy-intensive reactions, the combustion of fossil fuels, and chemical reactions in soda ash manufacturing.

The actual production of ammonium chloride adds another notable contribution of 11.53 $\text{kg SO}_2\text{-eq}$, driven mainly by fossil energy consumption, ammonia use, and other upstream chemical flows. Transportation within the ammonium chloride supply chain plays a secondary

but measurable role, contributing roughly 1.3 - 1.8 kg SO₂-eq, mainly from freight by sea, lorry, and rail.

Sodium hydroxide used in Stage 3 is also a significant contributor, with a total impact of 27.64 kg SO₂-eq. The chlor-alkali electrolysis process alone contributes 27.42 kg SO₂-eq, driven by electricity consumption, heat generation, and upstream sodium chloride extraction and refining. Minor contributions from sulfuric acid and electricity in different European regions collectively add to the remaining impact.

Other stages, such as the drying of Ca(OH)₂ in Stage 4 and LD-slag grinding in Stage 1, have smaller contributions (0.81–0.11 kg SO₂-eq) but reflect energy use in these processes. Waste management and tap water use also add minor impacts (<0.26 kg SO₂-eq), indicating that ancillary flows are less influential but not negligible.

Climate Change

This midpoint category is expressed in kg CO₂-eq, which measures the model's potential emission contribution to climate change, which also accounts for both direct and upstream GHG emissions across the entire model's elementary flows. The model's total impact is 3.63E+04 kg CO₂-eq, with the biggest hotspot being ammonium chloride production; the market data for NH₄Cl has an impact of 2.63E+04 kg CO₂-eq, which is about 73% of the total impact stage 2 makes. This huge emission amount is due to soda ash production using Hou's process, which has large CO₂ emissions from the energy-intensive chemical reactions. The soda ash production process emits a total of 2.20E+04 kg CO₂-eq of the impact from the market data set. The second biggest contributor is ammonia production, which is used within the soda ash production process, accounting for about 4.71E+03 kg CO₂-eq of the soda ash production impact. Electricity and carbon dioxide used in the soda ash production process collectively emit 6.69E+03 kg CO₂-eq.

The actual ammonium chloride production is another significant contributor to the overall impact, with an impact amount of 3409.816518 kg CO₂-eq driven primarily by the energy use and process emissions in the NH₄Cl synthesis stage.

Sodium hydroxide used in Stage 3 is another key hotspot, with a total contribution of 8,987 kg CO₂-eq. Within this, chlor-alkali electrolysis dominates (8,902 kg CO₂-eq), driven by high electricity consumption, sodium chloride production, and heat input. Other stages, such as LD-slag grinding in Stage 1 and Stage 4, collectively emit 665.447kg CO₂-eq of the entire impact.

Ecotoxicity: freshwater

The total potential impact of the model is 2,346 kg 1,4-DCB-Eq; NH₄Cl production and its upstream supply chain dominate this overall impact amount. It contributes over 1,525 kg 1,4-DCB-Eq, which is about 65% of the total stage 2 impact. This huge amount of emission is due to soda ash production using Hou's process, which has heavy elementary flows and is a bit energy-intensive. Within the Hou process, ammonia is an elementary flow which amounts to a total of 1,319.7 kg 1,4-DCB-E,q, making it the second biggest driver in the NH₄Cl supply chain after soda ash. NaOH production is also another contributor to the overall impact, with

an impact amount of 784.2 kg 1,4-DCB-Eq. The main drivers here are high electricity consumption and sodium chloride mining and refining.

Eutrophication: freshwater

The assessment shows a total eutrophication impact of about 13.81 kg P-eq, which is majorly driven by upstream chemical production and electricity inputs rather than direct emissions from the foreground process of the actual extraction process. The largest single contributors are ammonium chloride (7.31 kg P-eq; 53% of the stage 2 total impact) and sodium hydroxide (6.37 kg P-eq; 46% of the stage 3 total impact). Both are highly energy-intensive chemicals, and their production involves multiple electricity-dependent subprocesses. For ammonium chloride, the Hou's process for soda ash accounts for 6.26 kg P-eq (45%), with major inputs including electricity (1.64 kg P-eq; 11.9%), sodium chloride powder (1.29 kg P-eq; 9.3%), ammonia from various global and regional markets (1.56 kg P-eq; 11%), and CO₂ (0.73 kg P-eq; 5.3%). For sodium hydroxide, almost the entire burden is associated with chlor-alkali electrolysis (6.36 kg P-eq; 46%), where grid electricity dominates the impacts.

In contrast, the contribution of transport processes is relatively small. Combined, freight by lorry, rail, sea, and inland waterways amounts to only 0.14 kg P-eq (1%), indicating that logistics play a secondary role in eutrophication potential. Similarly, supporting flows such as tap water (0.0435 kg P-eq; 0.32%) and wastewater treatment (<0.0045 kg P-eq; <0.05%) are minor in comparison.

Human toxicity: carcinogenic

The assessment shows a total human toxicity impact of approximately 7,809 kg 1,4-DCB-Eq, as with the other midpoint categories, the big drivers are background chemical processes.

A substantial portion of the impact can be traced back to Stage 2: extraction of calcium ions (65.6% contribution, 5,135 kg 1,4-DCB-Eq) and its associated upstream inputs, particularly ammonium chloride production and supply. The production of ammonium chloride via the Hou's process for soda ash emerges as a key upstream driver, contributing over 4,092 kg 1,4-DCB-Eq, primarily due to the energy- and chemical-intensive requirements of this pathway. Supporting activities within NaOH production, such as the production of sodium chloride (1,096 kg 1,4-DCB-Eq), chemical factory infrastructure (1,359 kg 1,4-DCB-Eq), and electricity consumption (416 kg 1,4-DCB-Eq), further exacerbate the total impact.

Energy-related inputs also play a notable role. For instance, chlor-alkali electrolysis for sodium hydroxide contributes nearly 2,406 kg 1,4-DCB-Eq, with significant shares linked to electricity generation. Transportation processes, while present, are relatively minor in comparison to chemical production steps, emitting less than 2% of the total human toxicity impact.

Material resources: metals/minerals

The total impact of the NH₄Cl Scenario 1 is 3,827 kg Cu-Eq. This is largely due to the upstream production processes, particularly the soda ash production via Hou's process and the sourcing of sodium chloride, which contributes significantly to the cumulative

environmental impact (1,653 kg Cu-Eq from NaCl alone), found in the NH₄Cl production process market data set.

Secondary contributions stem from the chlor-alkali electrolysis required for sodium hydroxide production, which represents another substantial fraction (1,841 kg Cu-Eq), emphasizing that the energy-intensive nature of electrolysis is a critical driver of environmental impacts. Other notable contributors, though smaller, include the production of ammonia, carbon dioxide, hydrochloric acid, and various other chemicals (sulfuric acid, platinum, hydrogen peroxide), which together show the complexity of chemical interdependencies in NH₄Cl synthesis.

Transportation impacts, including freight by lorry, train, and ship, account for marginal contributions (<1% each) relative to the dominant chemical production stages. Water usage (tap, deionized, and ultrapure water) and waste handling procedures contribute minimally.

Ozone depletion:

The total impact of the NH₄Cl Scenario 1 is 0.0099256 kg CFC-11-Eq; the extraction of Ca²⁺ ions and ammonium chloride production contribute secondary impacts (0.005925 and 0.001176 kg CFC-11-Eq, respectively), reflecting upstream chemical inputs such as soda ash (Hou's process) and sodium hydroxide production. Within these, electricity consumption across multiple regions and chemical inputs (ammonia, carbon dioxide, and anionic resins) play a minor role in overall ODP contribution, indicating that indirect emissions from energy use are low in comparison to the chemical process itself.

Transportation and logistics covering freight by lorry, train, sea, and barge have negligible impacts (<0.0002 kg CFC-11-Eq), further emphasizing that the ozone depletion potential is largely independent of physical transport and more closely tied to chemical production pathways. Similarly, water consumption and waste handling procedures contribute minimally to ODP, showing that resource use efficiency is well managed.

The chlor-alkali electrolysis for sodium hydroxide production, although a major contributor to other impact categories (like metal equivalents), contributes very little to ODP (0.0039 kg CFC-11-Eq), indicating that electricity generation for this process likely relies on non-ozone-depleting sources.

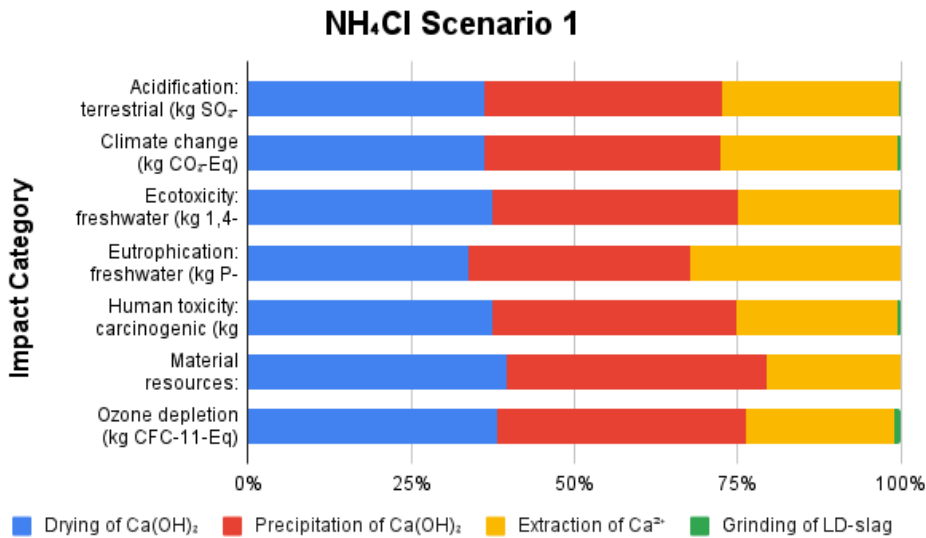


Fig 13: A chart mapping each environmental impact category to its dominant contributors within the NH₄Cl extraction process.

5.3.2 Endpoint

Ecosystem Quality

This impact category is expressed as species.yr, which measures the extent to which ecosystem services, habitats and the organisms within the ecosystem are affected by the model's elementary flows.

The total potential impact of the model on biodiversity is 1.67×10^{-4} species.yr, the most critical hotspot here is the production of ammonium chloride. The market data set to produce NH₄Cl contribute about 1.20×10^{-4} species.yr, which is equivalent to 71.5% of total damage. This is a result of two main processes within the market data, soda ash production using the Hou's process, which emits 9.88×10^{-5} species.yr. This amount can be attributed to energy-intensive reactions, CO₂ emissions and associated habitat modification from resource extraction. This market dataset also has a second hotspot area, which is directly linked to the actual production of NH₄Cl, which adds an impact of 1.57×10^{-5} species.yr. The main cause here is the use of fossil energy and other production elementary flows within NH₄Cl's actual production chain. Within this market data set, transportation is also a secondary but noticeable driver that contributes about 3.9×10^{-6} species.yr.

Sodium Hydroxide used in stage 3 is also another critical hotspot with an impact of 4.34×10^{-5} species.yr; this amount is primarily from the production of NaOH using the chlor-alkali electrolysis process. This process alone emits 4.30×10^{-5} species.yr from the entire NaOH production impact, with the drivers being energy use and mining and refining of NaCl. The transportation of LD-slag within stage 1 also contributes about 1.55% (2.59×10^{-6}) to the total impact.

Human health

This model describes the potential human health impact, and the total impact of the scenario is about 0.1003 DALYs. In this endpoint category, ammonium chloride production (market data set) is the biggest driver, contributing about 0.06944 DALYs of the entire category. The biggest contributor here is the soda ash production in the Hou's process, with about 0.05782 DALYs being emitted from this production process alone, making it the biggest river in the market dataset for NH_4Cl production. A second hotspot here is the market for sodium hydroxide stemming specifically from production using the chlor-alkali process. The market for sodium hydroxide emits 0.02750 DALYs, with the chlor-alkali process emitting 0.02728 DALYs. Other minor contributors here are electricity (contributions across several grids), ammonia production and cumulative transport within the extraction process, all amounting to about 0.019 DALYs.

Natural resources

This impact category is expressed in USD (2013), which measures the monetized cost associated with natural resource depletion caused by the model's elementary flows. The total potential impact of the model on resource depletion is 3,270 USD, with the most critical hotspot being the production of ammonium chloride. The market dataset for ammonium chloride contributes approximately 2,150.91 USD, equivalent to 65.8% of the total impact for stage 2. This is primarily driven by two main processes within the market dataset: dense soda ash production using Hou's process, which contributes 1,783.18 USD due to energy-intensive reactions and material extraction, and sodium chloride feedstock acquisition, contributing 534.83 USD due to resource-intensive mining and purification. Transportation of raw materials within the ammonium chloride supply chain is also a noticeable secondary driver, adding 70.16 USD to the total impact.

Sodium hydroxide used in Stage 4 is another critical hotspot, with a total impact of 995.87 USD. This amount is primarily attributed to the chlor-alkali electrolysis process, which alone contributes 984.28 USD. The key drivers here are high electricity and heating demand, as well as the mining and refining of NaCl. Other minor contributors include regional variations in electricity supply and secondary chemicals, each adding small fractions (<5%) to the total impact.

Stage 3, corresponding to $\text{Ca}(\text{OH})_2$ precipitation, also shows a significant contribution of impact, predominantly due to sodium hydroxide use in precipitation, with a total impact amount of 995.87133 USD (2013). The production of sodium hydroxide (specifically chlor alkali process) is the main driver of this impact (984.27744 USD), with energy-intensive processes, secondary chemicals and natural gas use being the biggest contributors. Minor contributions from waste management, water, and transport add less than 5% in total but still reflect the multi-dimensional nature of the supply chain.

Finally, Stage 1 (grinding of LD slag) has smaller but non-negligible contributions, with a total impact of 88.38 USD. The main drivers here are the electricity used for grinding.

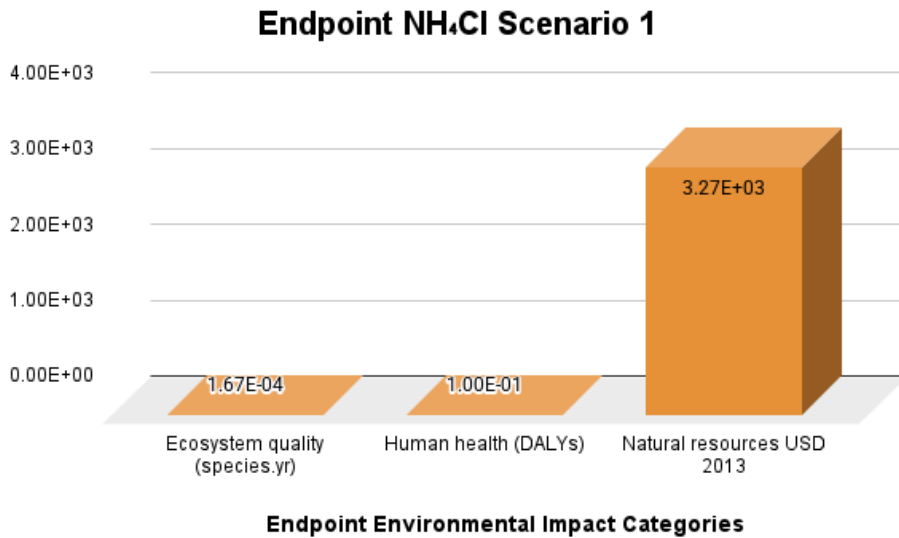


Fig 14: A figure comparing the various Endpoint Impact categories for the NH₄Cl extraction process.

5.4 Sensitivity Analysis 1: HCI Scenario 1 vs HCI Scenario 2

Below are the results from the comparison of HCI Scenarios 1 and 2 in the study, where:
 Scenario 1: represents market chemicals (market-average datasets) and market-average grid electricity

Scenario 2: represents a specific chemical production process and the market-average grid electricity

For each impact category, the results are normalized, the worst-performing case or scenario is set to 100%, and the rest are displayed in relation to the worst performer, which allows for easier comparison across multiple impact categories.

HCL scenario 1's impact outweighs HCI scenario 2, even with scenario 2's added transportation modelling. Most of the impact results are 2-5x higher in scenario than they are in scenario 2. The largest and only difference is in the impact category Ecotoxicity: terrestrial, where scenario 1 has a total impact value of 63,430 kg 1,4-DCB-Eq vs scenario 2's total impact value of 71,526 kg 1,4-DCB-Eq. The reason for this is due to brake wear emission from the added transportation modelling in scenario 2, as seen in Appendix Table A.1.

Table 7: Impact amounts by category for HCl scenarios 1 and 2.

Impact Category	HCl Scenario 1	HCl Scenario 2
Acidification: terrestrial (kg SO ₂ -Eq)	1.78E+01	5.81E+00
Climate change (kg CO ₂ -Eq)	5.51E+03	3.02E+03
Ecotoxicity: freshwater (kg 1,4-DCB-Eq)	4.06E+02	1.46E+02
Ecotoxicity: marine (kg 1,4-DCB-Eq)	5.79E+02	2.50E+02
Ecotoxicity: terrestrial (kg 1,4-DCB-Eq)	6.34E+04	7.15E+04
Energy resources: non-renewable, fossil (kg oil-Eq)	1.61E+03	1.01E+03
Eutrophication: freshwater (kg P-Eq)	2.69E+00	5.05E-01
Eutrophication: marine (kg N-Eq)	3.91E-01	1.25E-01
Human toxicity: carcinogenic (kg 1,4-DCB-Eq)	1.38E+03	6.36E+02
Human toxicity: non-carcinogenic (kg 1,4-DCB-Eq)	8.02E+03	3.66E+03
Ionising radiation (kBq Co-60-Eq)	1.01E+03	3.99E+02
Land use (m ² *a crop-Eq)	1.65E+02	9.56E+01
Material resources: metals/minerals (kg Cu-Eq)	7.48E+02	1.82E+02
Ozone depletion (kg CFC-11-Eq)	2.54E-03	1.33E-03
Particulate matter formation (kg PM _{2.5} -Eq)	6.87E+00	2.52E+00
Photochemical oxidant formation: human health (kg NO _x -Eq)	9.51E+00	4.85E+00
Photochemical oxidant formation: terrestrial ecosystems (kg NO _x -Eq)	1.01E+01	5.48E+00
Water use (m ³)	8.22E+01	5.71E+01

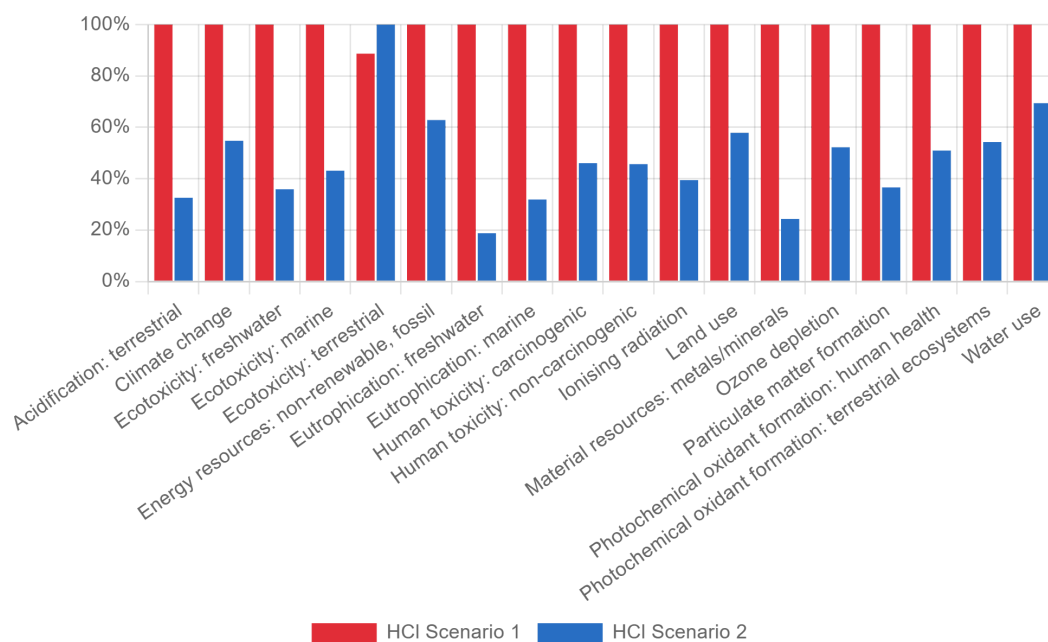


Fig. 15: A normalized comparison of the environmental impacts between HCl Scenario 1 and HCl Scenario 2 across a wide range of Recipe 2016 midpoint impact categories.

5.5 Sensitivity Analysis 1: Scenario 1 vs Scenario 2 NH₄Cl

The results from the comparison of NH₄Cl Scenarios 1 and 2 in the study, where:

Scenario 1: represents market chemicals (market-average datasets) and market-average grid electricity

Scenario 2: represents a specific chemical production process and the market-average grid electricity

For each impact category, the results are normalized, the worst performing case or scenario is set to 100%, and the rest are displayed in relation to the worst performer, which allows for easier comparison across multiple impact categories.

Scenario 1 has much higher environmental impacts across all categories than Scenario 2. This is due to the change in the chemical production data set, which results in changes in upstream processes and overall impact for the two scenarios. For NH₄Cl Scenario 2 in the normalized results most of the impact categories stay below the 40% mark except a few categories: Ozone depletion (where the biggest contributor here is from the transport processes within the model), eutrophication freshwater (with the biggest contributor being waste treatment of spoil from lignite mining in the upstream chemical production processes), land use, material resources and ionising radiation both as result of upstream chemical production processes.

Table 8: Impact amounts by category for NH₄Cl scenarios 1 and 2.

Impact Category	NH ₄ Cl Scenario 1	NH ₄ Cl Scenario 2
Acidification: terrestrial (kg SO ₂ -Eq)	1.12E+02	3.20E+01
Climate change (kg CO ₂ -Eq)	3.63E+04	1.22E+04
Ecotoxicity: freshwater (kg 1,4-DCB-Eq)	2.35E+03	8.74E+02
Ecotoxicity: marine (kg 1,4-DCB-Eq)	3.68E+03	1.28E+03
Ecotoxicity: terrestrial (kg 1,4-DCB-Eq)	7.59E+05	1.77E+05
Energy resources: non-renewable, fossil (kg oil-Eq)	9.13E+03	3.34E+03
Eutrophication: freshwater (kg P-Eq)	1.38E+01	6.67E+00
Eutrophication: marine (kg N-Eq)	2.24E+01	9.59E-01
Human toxicity: carcinogenic (kg 1,4-DCB-Eq)	7.81E+03	3.19E+03
Human toxicity: non-carcinogenic (kg 1,4-DCB-Eq)	4.67E+04	1.85E+04
Ionising radiation (kBq Co-60-Eq)	3.46E+03	2.54E+03
Land use (m ² *a crop-Eq)	8.57E+02	4.21E+02
Material resources: metals/minerals (kg Cu-Eq)	3.83E+03	1.91E+03
Ozone depletion (kg CFC-11-Eq)	9.93E-03	5.41E-03
Particulate matter formation (kg PM _{2.5} -Eq)	4.63E+01	1.36E+01
Photochemical oxidant formation: human health (kg NO _x -Eq)	6.91E+01	2.23E+01
Photochemical oxidant formation: terrestrial ecosystems (kg NO _x -Eq)	7.21E+01	2.37E+01
Water use (m ³)	3.73E+02	9.66E+01

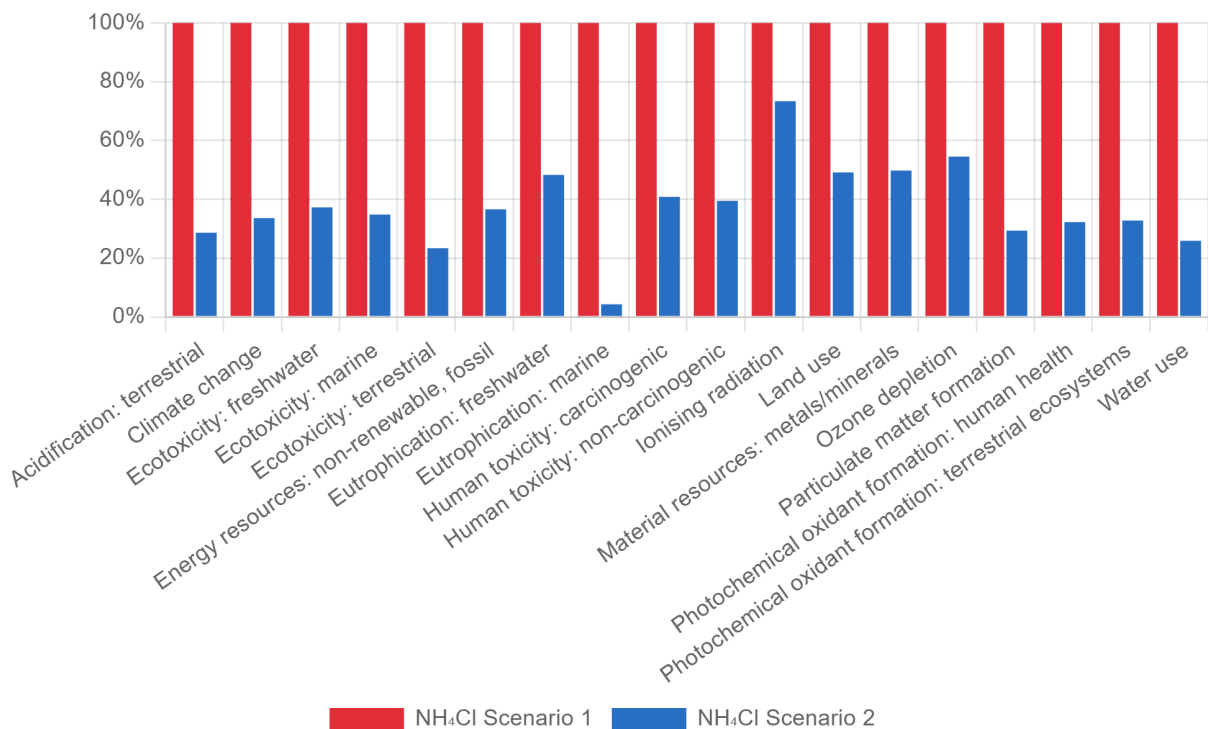


Fig. 16: A normalized comparison of the environmental impacts between NH₄Cl Scenario 1 and NH₄Cl Scenario 2 across a wide range of Recipe 2016 midpoint impact categories

5.6 Transport Sensitivity analysis HCl scenarios

These results detail the environmental impacts associated with varying transport distances within the model. The variations used in the model here are applied to scenarios 1 and 2:

Scenario 1: represents market chemicals (market-average datasets) and market-average grid electricity

Scenario 2: represents specific chemical production processes and the market-average grid electricity.

The variations are represented in cases; case A represents a proposed plant site in Göteborg, case B represents a proposed plant site in Kiruna, and case C represents a proposed plant site in Umeå.

Among the tested cases, all the cases applied to scenario 1 across all the impact categories had a larger environmental impact as compared to scenario 2(which required additional transport modelling), showing that for these cases, the associated environmental burden for the chosen chemical production routes outweighs that of the supply chain impacts. However, within the case variations, case B, specifically 2B, with the proposed plant site located in Kiruna, consistently shows the highest environmental burden. This outcome is directly tied to the modelling of longer transport distances, which outweighs the impact of chemical production.

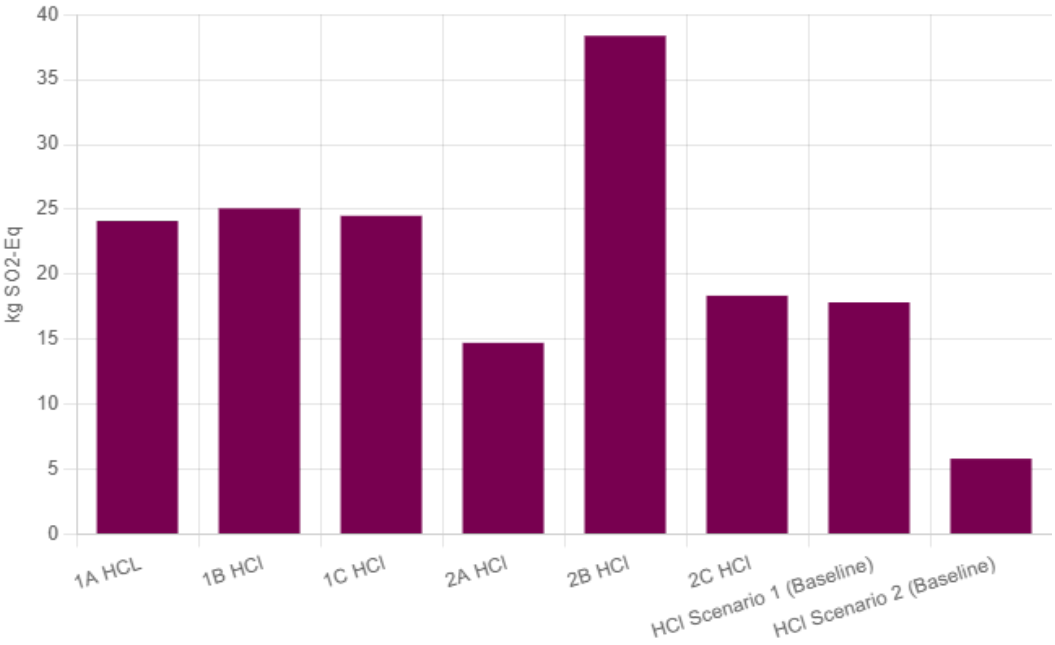


Fig. 17: Comparative results for acidification between all the transport variations relative to the baseline scenarios.

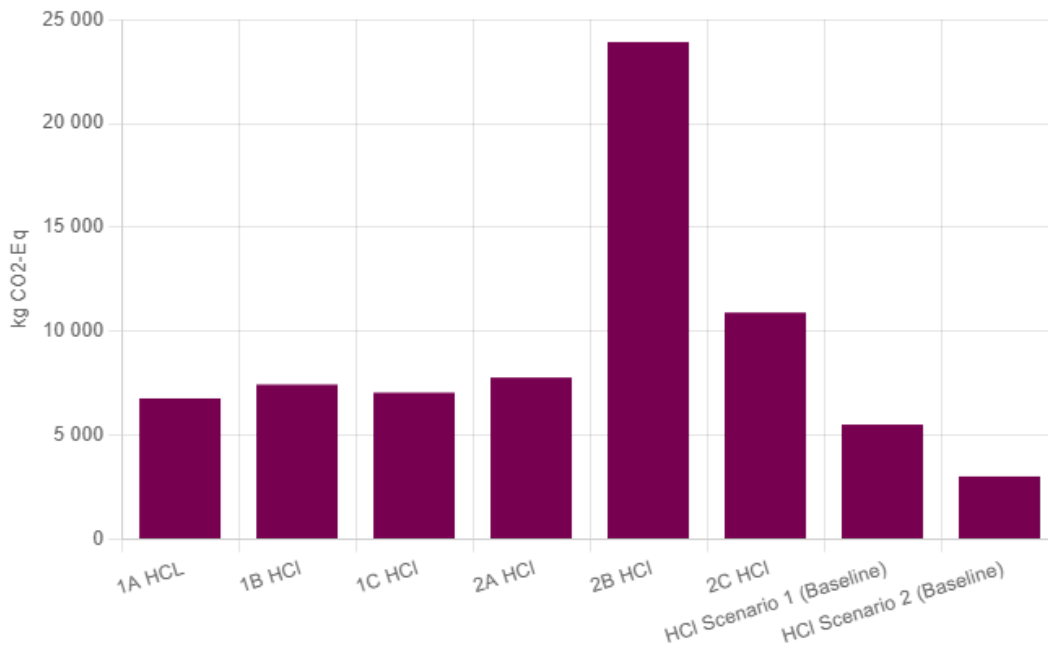


Fig. 18: Comparative results for climate change between all the transport variations relative to the baseline scenarios.

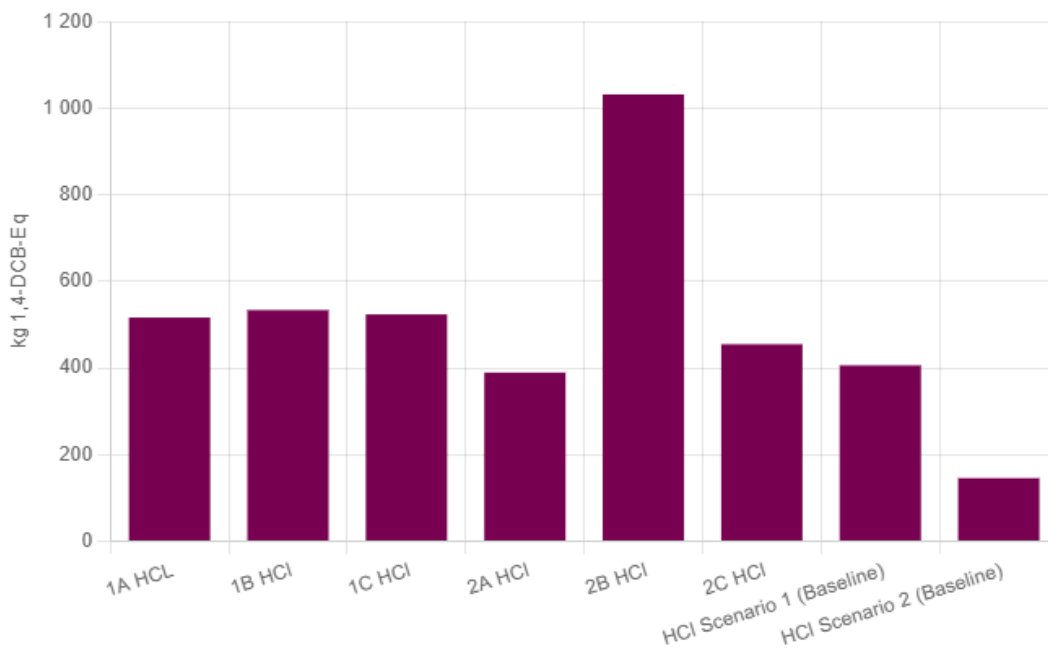


Fig. 19: Comparative results for freshwater ecotoxicity between all the transport variations relative to the baseline scenarios.

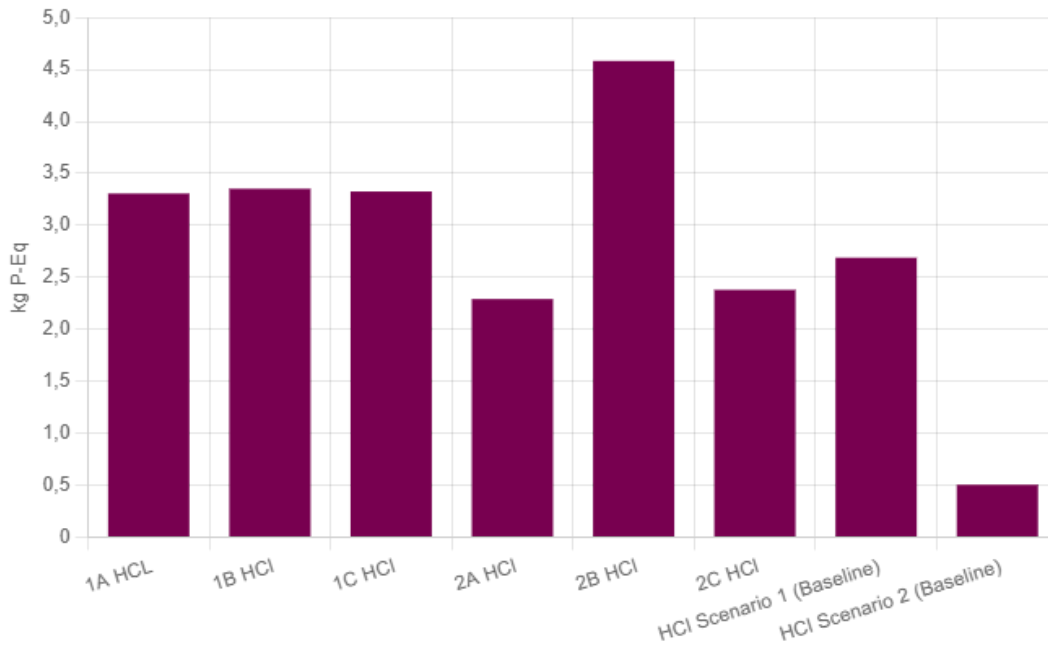


Fig. 20: Comparative results for freshwater eutrophication between all the transport variations relative to the baseline scenarios.

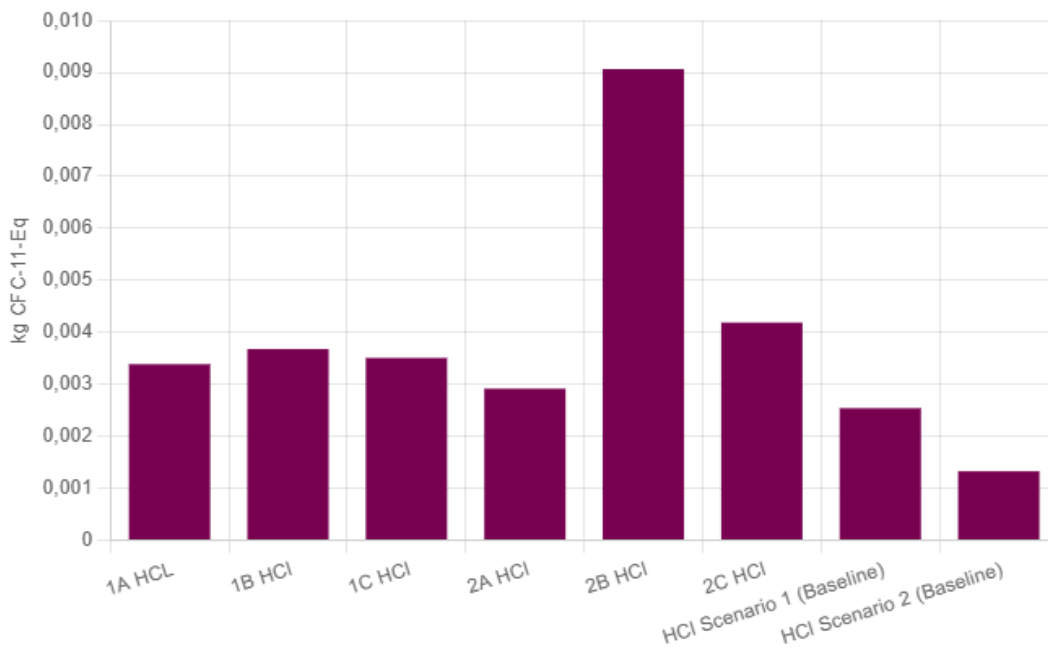


Fig 21: Comparative results for ozone depletion between all the transport variations relative to the baseline scenarios.

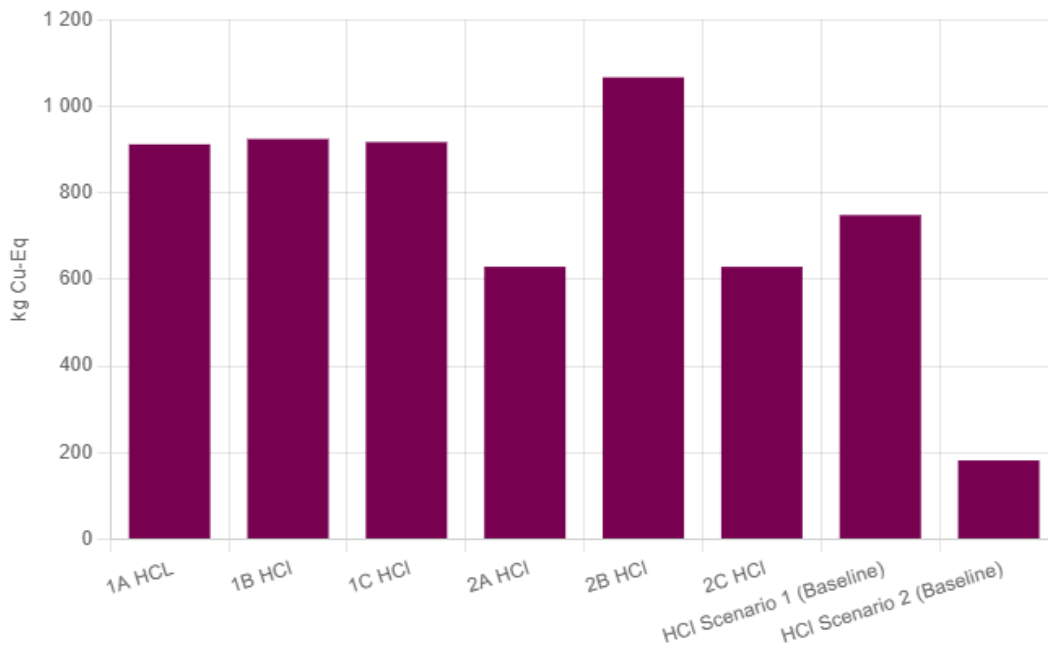


Fig 22: Comparative results for Material resource (minerals and metals) between all the transport variations relative to the baseline scenarios.

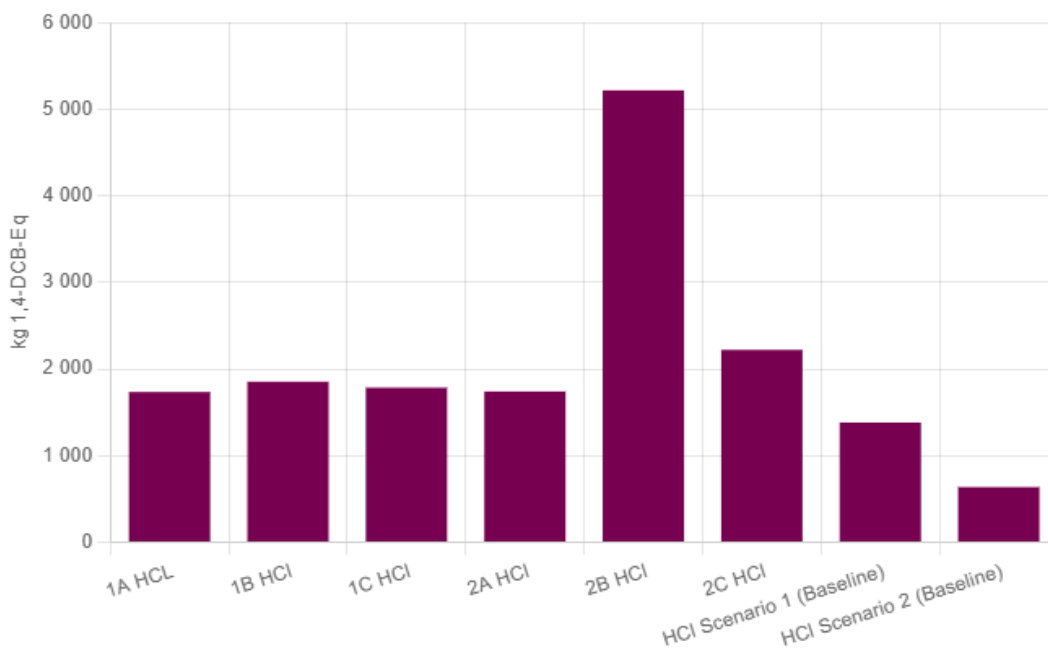


Fig. 23: Comparative results for carcinogenic human toxicity between all the transport variations relative to the baseline scenarios.

5.7 Transport Sensitivity analysis NH₄Cl scenarios

These results detail the environmental impacts associated with varying transport distances within the model. The variations used in the model here are applied to scenarios 1 and 2:

Scenario 1: represents market chemicals (market-average datasets) and market-average grid electricity

Scenario 2: represents specific chemical production processes and the market-average grid electricity.

The variations are represented in cases; case A represents a proposed plant site in Göteborg, case B represents a proposed plant site in Kiruna, and case C represents a proposed plant site in Umeå.

With NH₄Cl, all the cases applied to scenario 1 across all the impact categories had a larger environmental impact as compared to scenario 2 (which required additional transport modelling). With case variations, case B consistently shows the highest environmental burden; however, case 2B is not the most dominant emitter, as the burden is shared among the case variations in scenario 1.

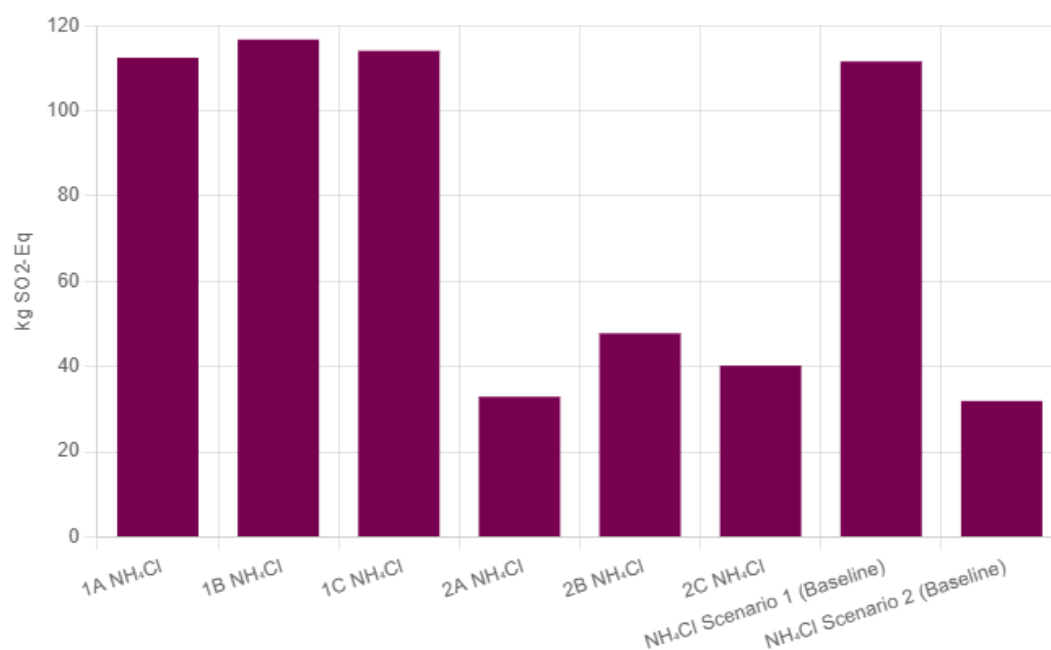


Fig. 24 Comparative results for acidification between all the transport variations relative to the baseline scenarios.

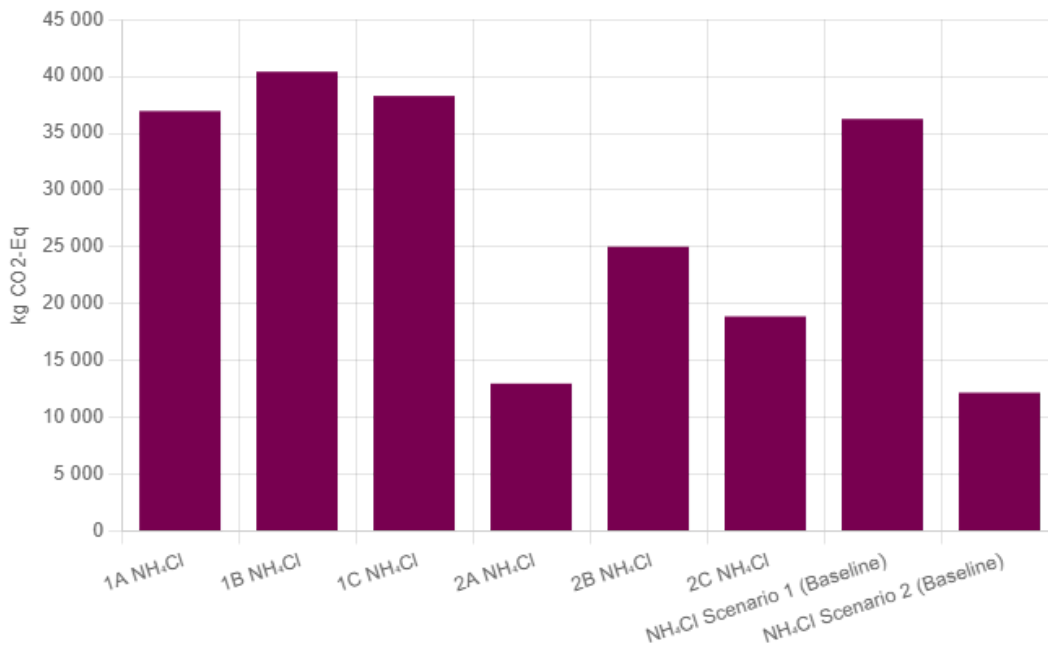


Fig 25: Comparative results for climate change between all the transport variations relative to the baseline scenarios.

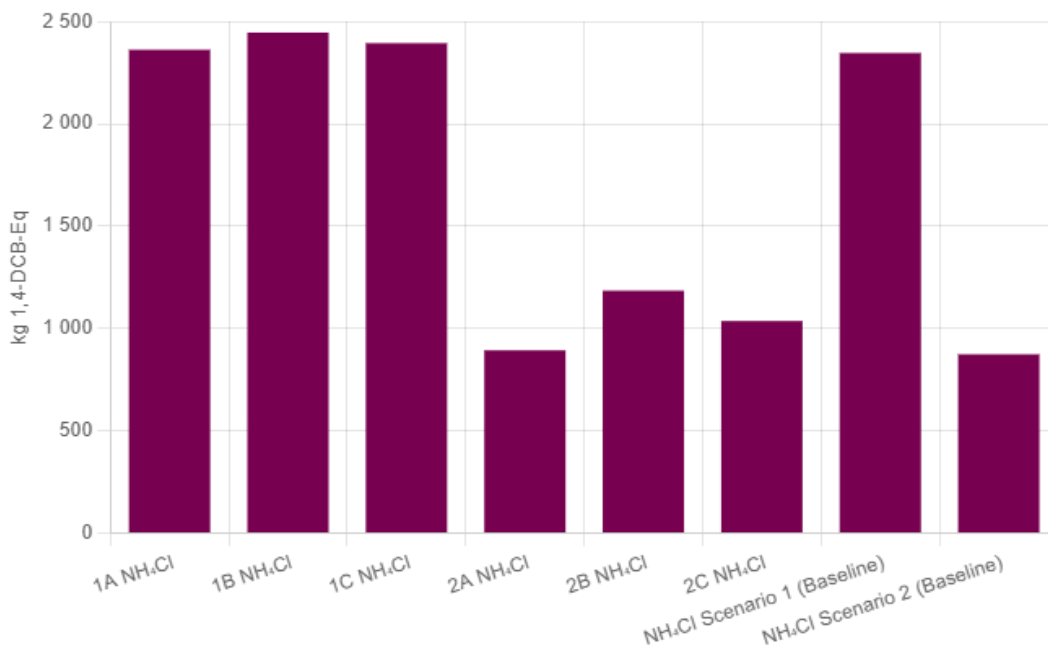


Fig. 26: Comparative results for ecotoxicity in freshwater between all the transport variations relative to the baseline scenarios.

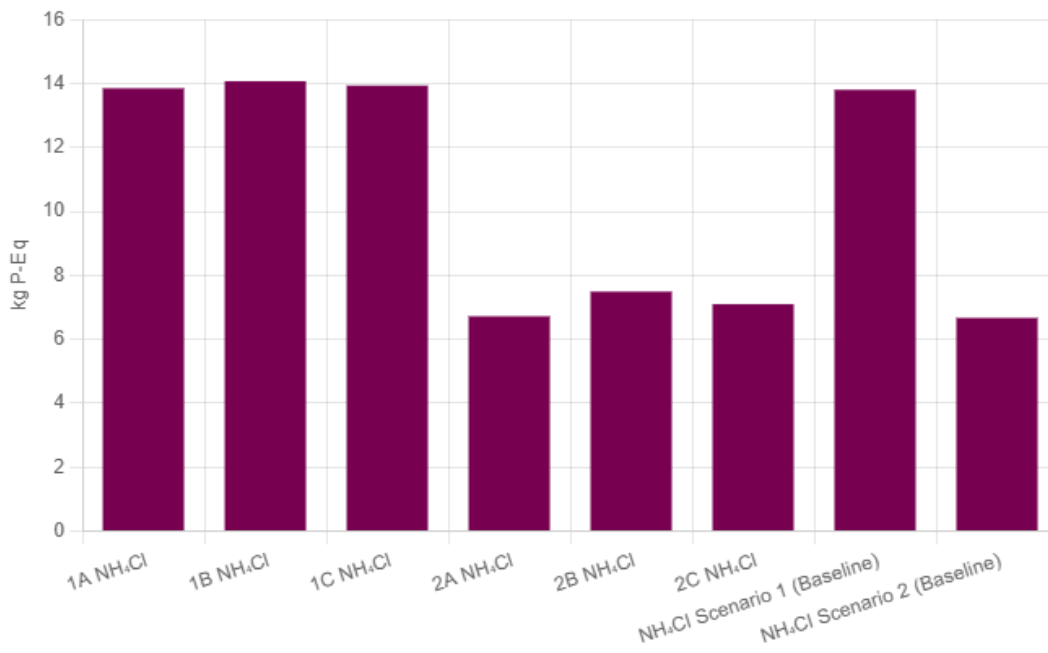


Fig 27: Comparative results for freshwater eutrophication between all the transport variations relative to the baseline scenarios.

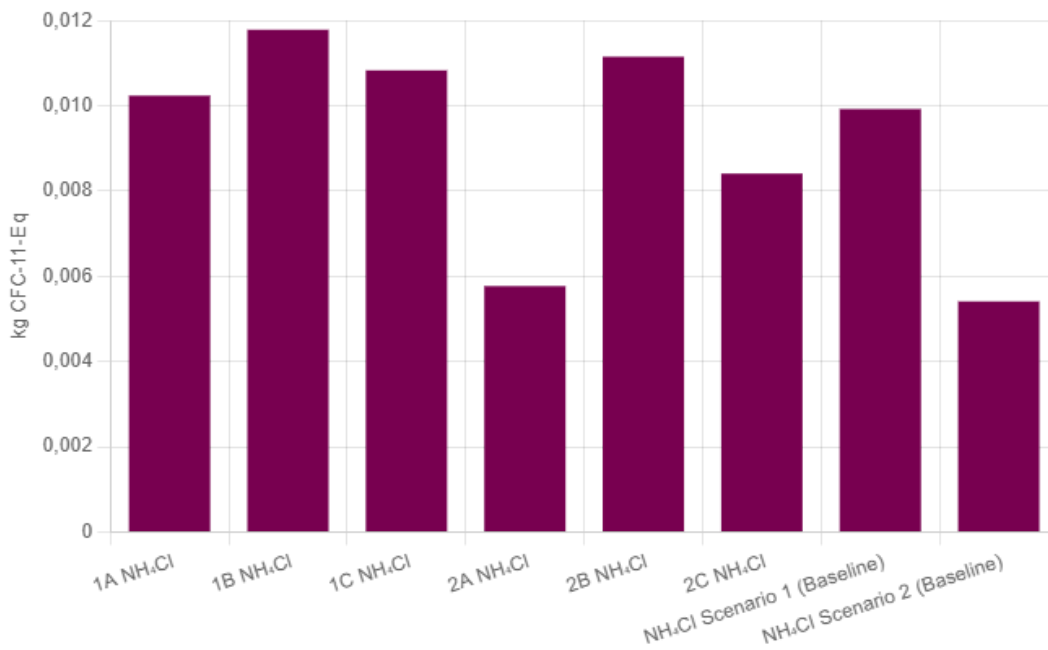


Fig. 28: Comparative results for ozone depletion between all the transport variations relative to the baseline scenarios.

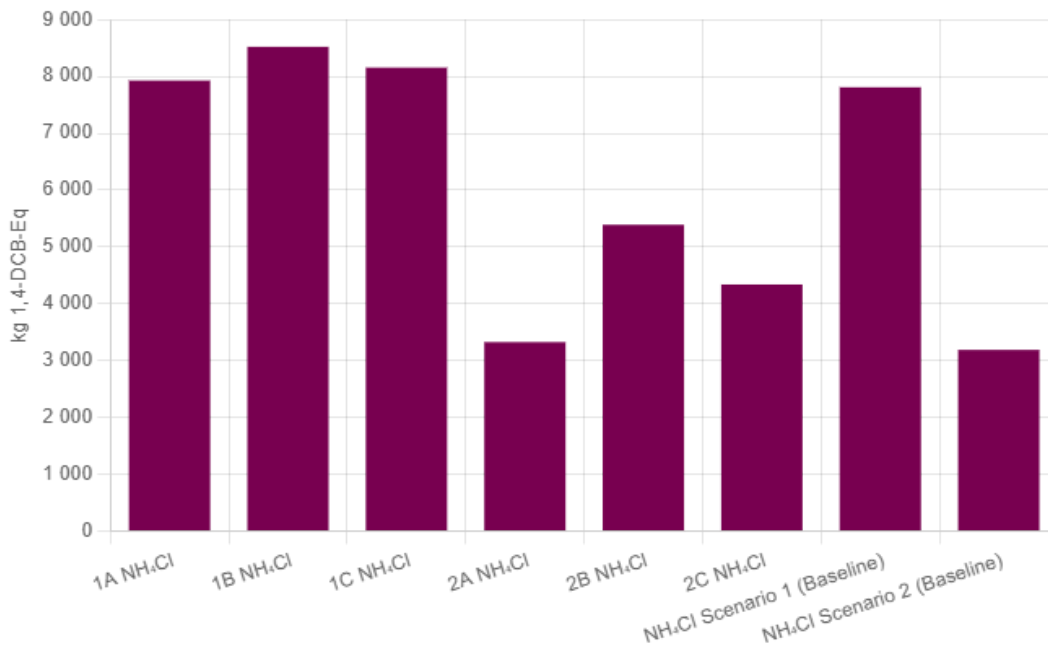


Fig. 29: Comparative results for Human toxicity (carcinogenic) between all the transport variations relative to the baseline scenarios

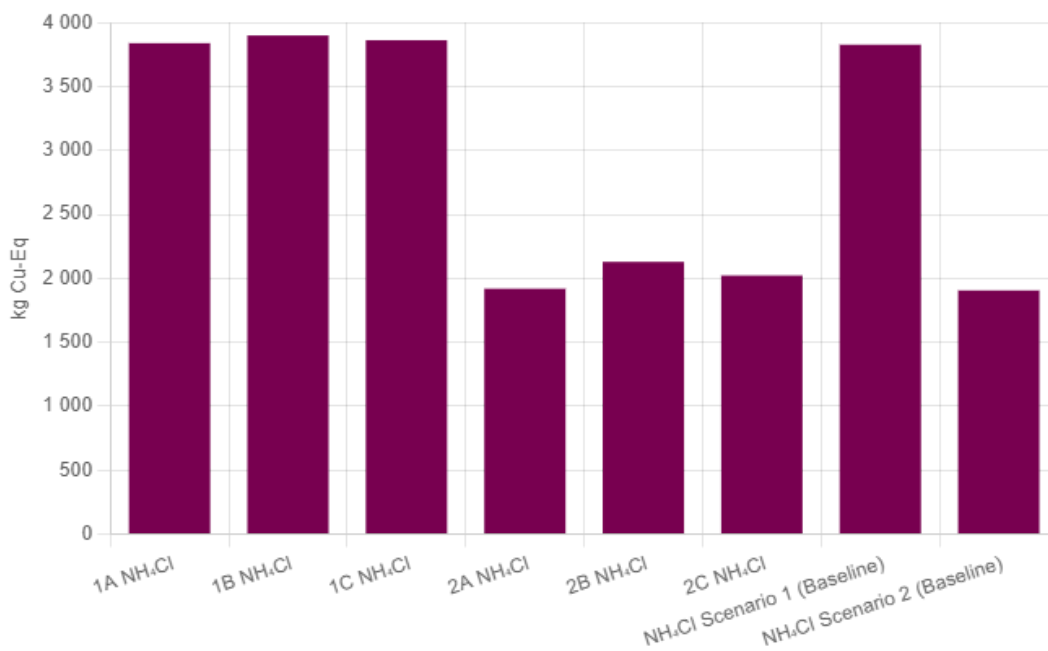


Fig. 30: Comparative results for material resources (minerals and metals) between all the transport variations relative to the baseline scenarios

5.8 Sensitivity analysis on energy type within the model.

This sensitivity analysis assesses how different the model's impacts would be if renewable energy were used instead of the regular market data set. For each impact category, the results are normalized, the worst-performing case or scenario is set to 100%, and the rest are displayed in relation to the worst performer, which allows for easier comparison across multiple impact categories.

The variations used in the model here are applied to scenarios 1 and 2 :

Scenario 1: represents market chemicals (market-average datasets) and market-average grid electricity.

Scenario 2: represents specific chemical production processes and the market-average grid electricity.

Scenario 3 represents market chemicals (market-average datasets) and renewable-based electricity (market datasets).

Scenario 4: represents specific chemical production processes and renewable-based electricity (market datasets).

5.9 HCI Scenario sensitivity analysis varying the electricity source

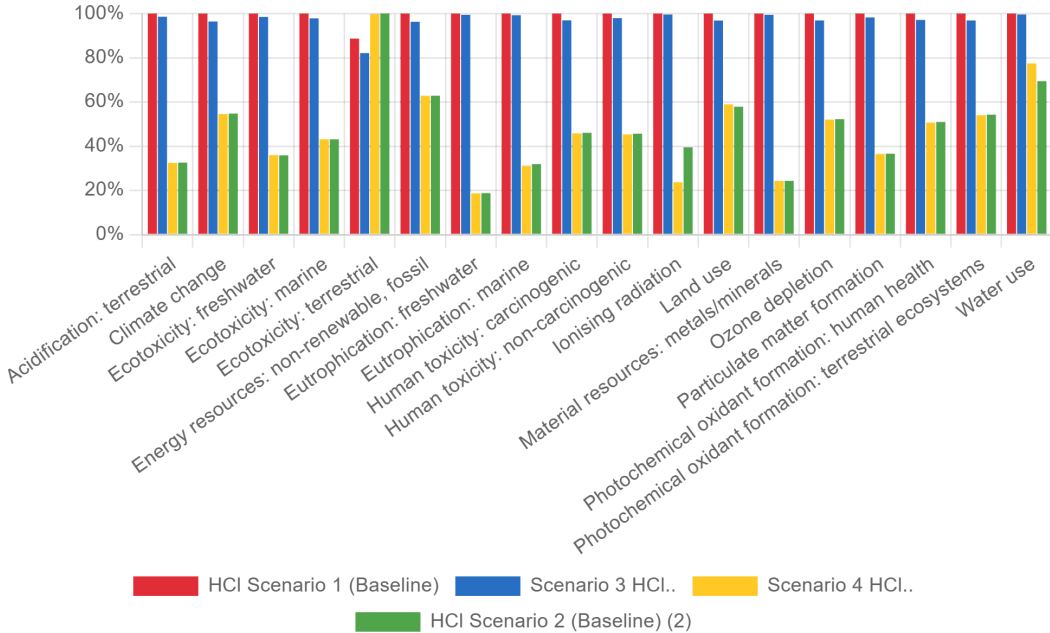


Fig 31: Impact comparison: Baseline vs Renewable-energy sensitivity (HCI scenarios)

Replacing the market data energy source with primarily renewable energy sources in the model produces minute environmental benefits in almost all the impact categories except ecotoxicity: terrestrial. In most categories, Scenario 3 (renewables applied to Scenario 1) and Scenario 4 (renewables applied to Scenario 2) show small reductions in emissions as compared to the baseline they were modelled after. Appendix table A3 gives further details on the precise numerical differences.

5.10 NH₄Cl Scenario sensitivity analysis varying the electricity source

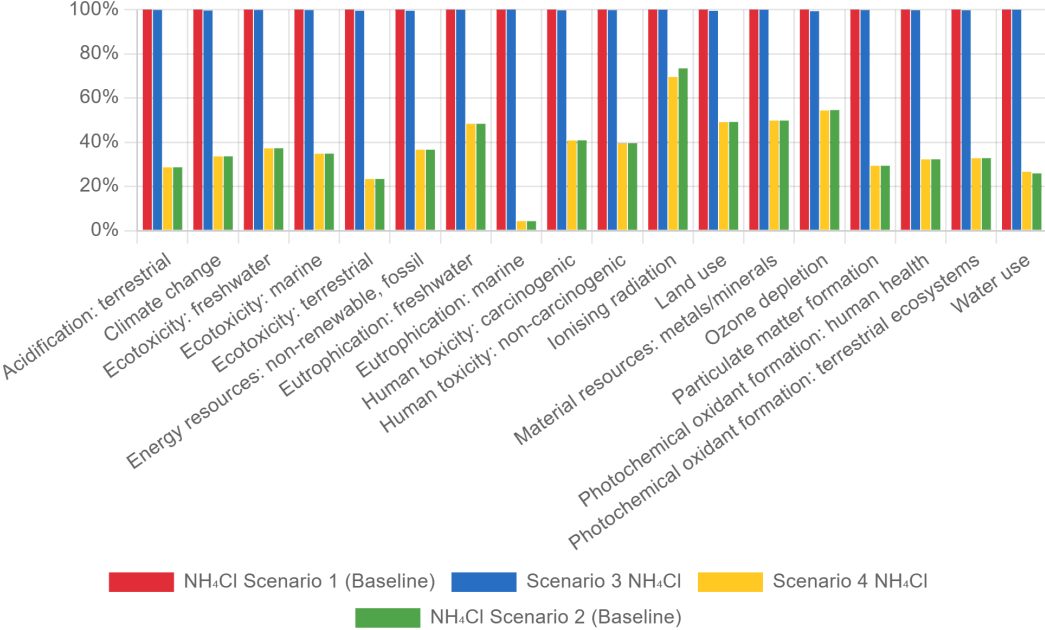


Fig. 32: Impact comparison: Baseline vs Renewable-energy sensitivity (NH₄Cl scenarios).

Between Scenario 3 and Scenario 1, the net change is negligible; Scenario 3 delivers only a marginal reduction (slightly under 1%) in overall emissions. That small improvement reflects the fact that most impacts in this system are dominated by process-level emissions (coke-oven chemistry, metal smelting, ammoniacal liquor, etc.), so substituting renewable electricity removes only a very small slice of the total burden.

6. Conclusions

This study assessed and compared the environmental impacts of $\text{Ca}(\text{OH})_2$ extraction via HCl and NH_4Cl pathways, with detailed life cycle assessments supported by sensitivity analysis.

The results demonstrate that the NH_4Cl pathway is consistently and substantially more environmentally burdensome than the HCl pathway across all midpoint and endpoint categories. NH_4Cl scenarios show impacts 5-7 times higher in climate change, terrestrial acidification, freshwater ecotoxicity, human toxicity, and mineral resource depletion, driven largely by the energy- and material-intensive Hou's soda ash process, ammonia production, and sodium hydroxide production by electrolysis.

For the HCl pathway, impacts are relatively moderate but still significant. The main hotspots are upstream chemical supply chains, particularly sodium hydroxide and hydrochloric acid production, rather than the extraction process itself. Climate change impacts are dominated by NaOH produced through chlor-alkali electrolysis and electricity demand, while natural resource depletion and toxicity categories also trace back to NaOH, HCl, and ammonia supply.

Transport Sensitivity analysis revealed that supply-chain distance and the chemical supply chain both strongly amplify life-cycle impacts, long transport routes increase emissions, and the choice of chemical dataset /production method determines the bulk of upstream burdens.

Renewable energy substitution yielded only minor improvements in HCl scenarios and negligible benefits for NH_4Cl , as process-level emissions outweigh electricity-related burdens.

Overall, in comparison to our functional unit of capturing 1 tonne of CO_2 , the system designed emits approximately 5.5 tonnes more CO_2 -eq (HCl scenario) and about 36 t CO_2 -eq (NH_4Cl scenario), which exceeds the intended capture amount. This imbalance arises from the extraction procedures of $\text{Ca}(\text{OH})_2$, which is very material-intensive, requiring the use of several chemicals that carry large upstream or production emissions that outweigh the intended use of the system. This implies that this procedure is incompatible with the passive DAC method unless the porous materials needed for CO_2 capture can be obtained from low-processing industrial wastes.

7. ■ **Future Work**

This study has revealed that there are many ways to assess the environmental impacts of extracting Ca(OH)_2 from industrial by-products (LD-slag) for use in a passive DAC system. However, there are still varying ways that this LCA can be done to potentially achieve different outcomes:

- A future LCA study can extend the boundaries of the study to include waste treatment procedures and the potential of harvesting important metals from the waste residue. This could then give way to allocation, which could change the result of the study.
- A future study can perform an LCA, including even better chemical providers to further reduce emissions.
- Another LCA can be conducted with different modes of transport, such as trains, etc., to determine if there is an overall change in final emission amounts.
- Another study could focus on extracting Ca(OH)_2 from other industrial by-products to see if there are any changes in emission numbers.

APPENDIX

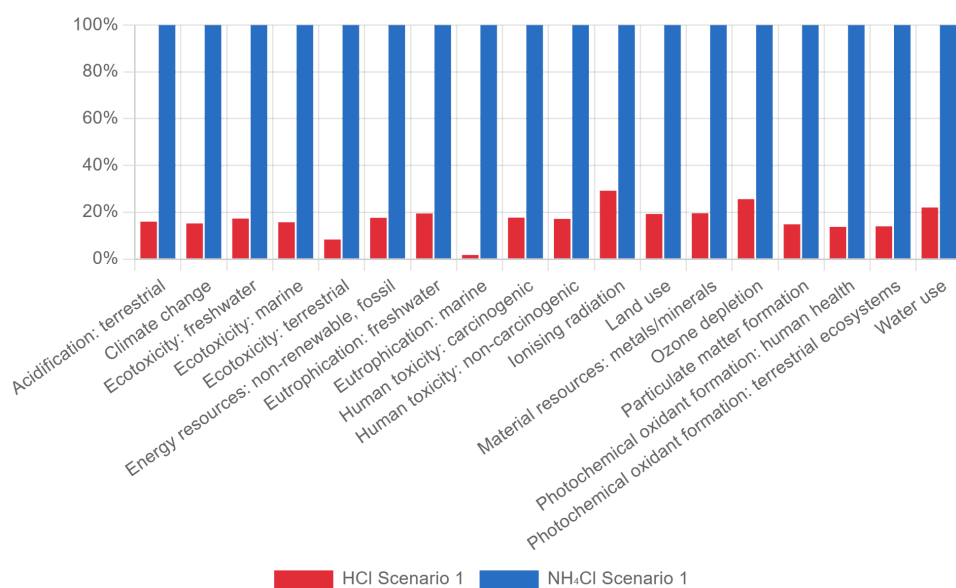


Fig.A.1: Normalized results comparing HCl and NH₄Cl extraction methods.

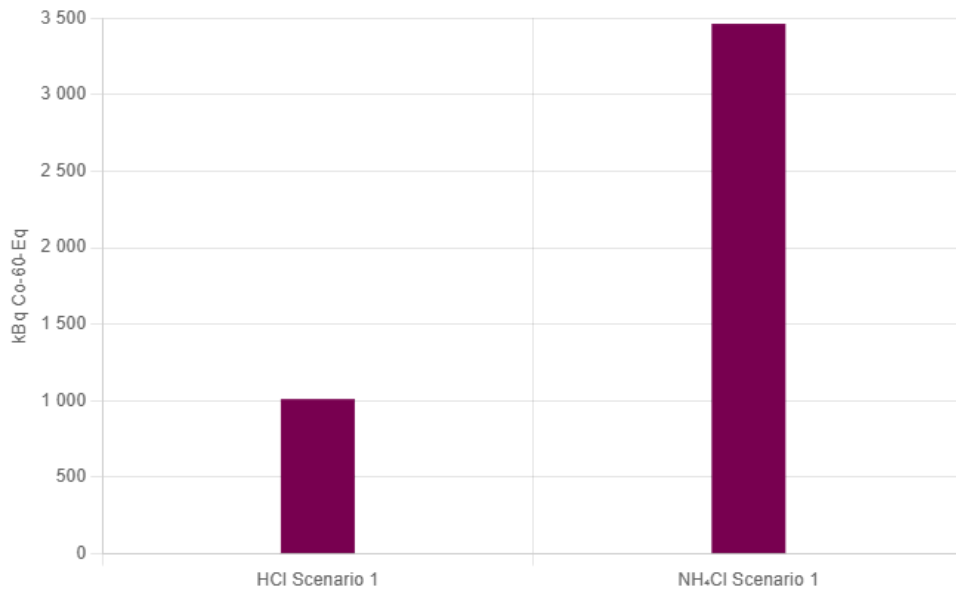


Fig. A.2: A figure comparing the ionising rad. impacts between HCl and NH₄Cl extraction methods.

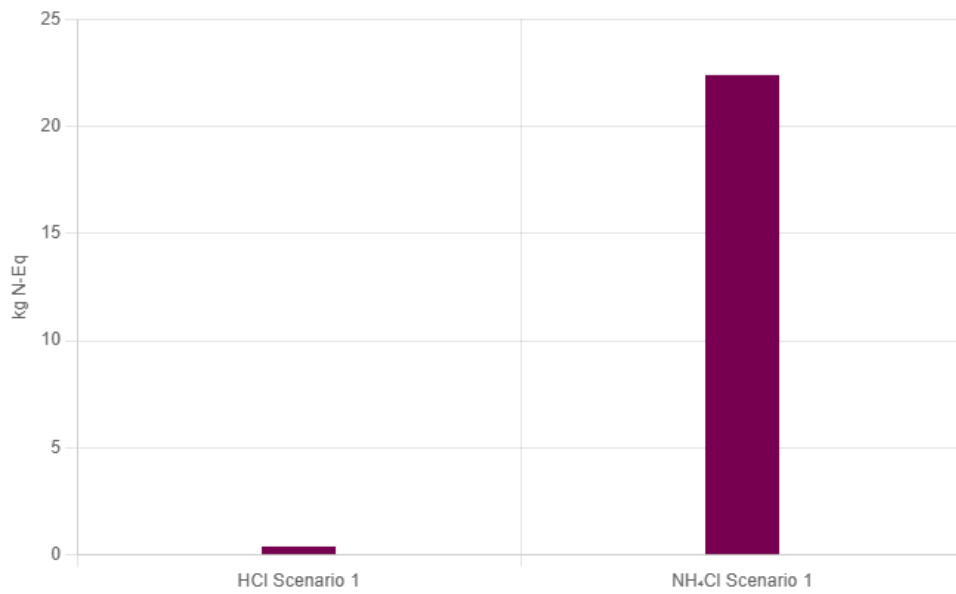


Fig.A.3: A figure comparing the marine eutrophication impacts between HCl and NH₄Cl extraction methods.

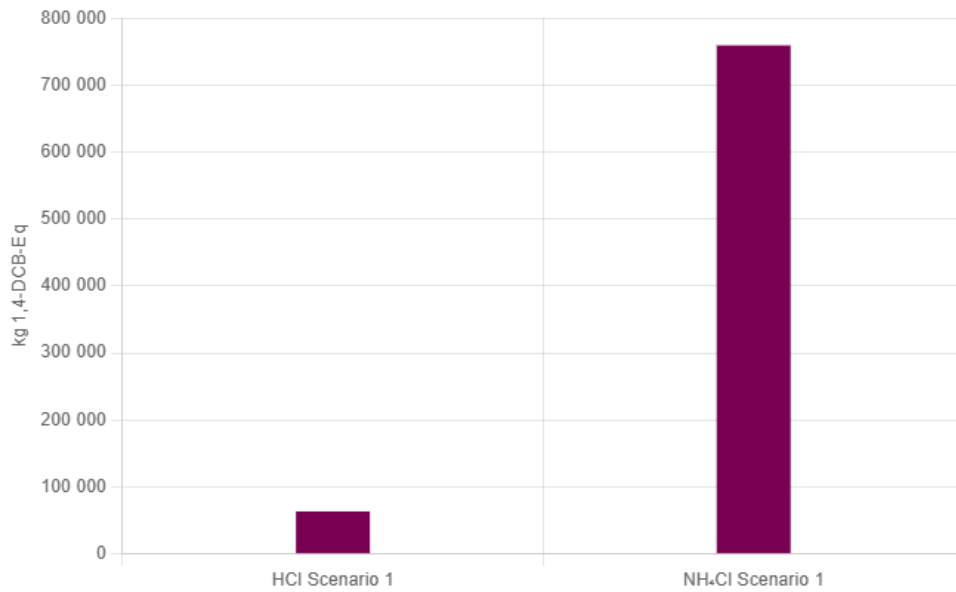


Fig. A.4: A figure comparing the terrestrial ecotoxicity impacts between HCl and NH₄Cl extraction methods.

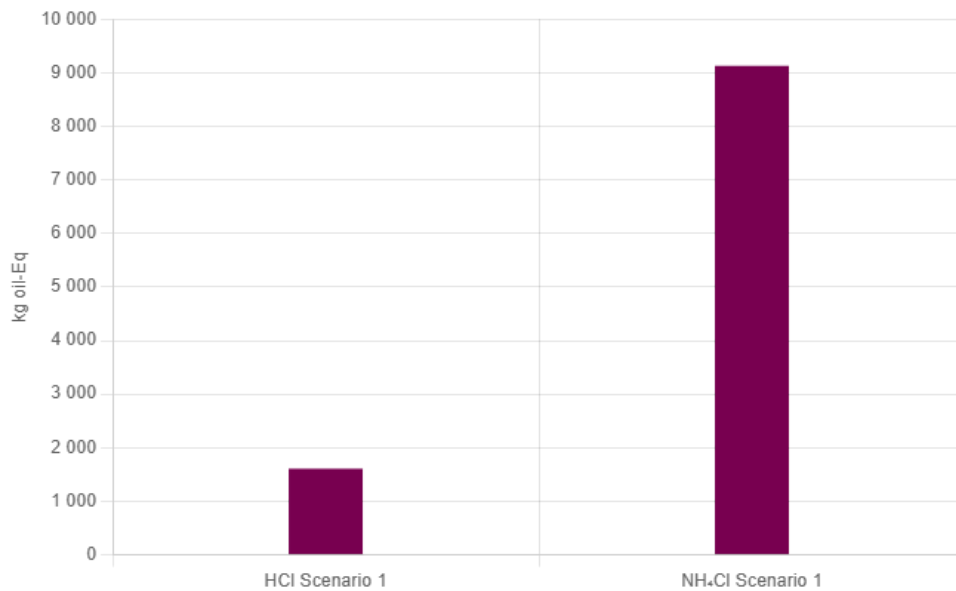


Fig.A.5: A figure comparing the energy resources: non-renewable, fossil impacts between HCl and NH₄Cl extraction methods.

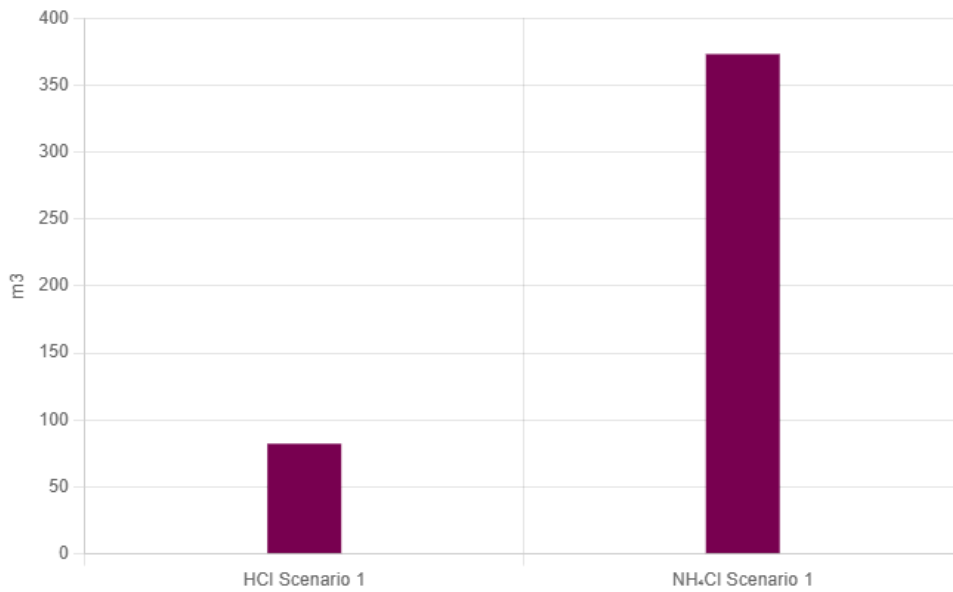


Fig.A.6: A figure comparing the water use impacts between HCl and NH₄Cl extraction methods.

Table A.1: a table describing in detail the top contributors for HCL scenarios 1 and 2.

Scenario	Total (kg 1,4-DCB-Eq)	Top contributor (kg, %)	2nd contributor (kg, %)	3rd contributor (kg, %)	Other notable contributors
Scenario 1 ecotoxicity	63,500	Coke production (wet quenching + standard + coal gas + sulfur): 39,260 (62%)	Others (grouped small sources): 9,430 (15%)	Brake-wear emissions (lorry): 8,000 (12.6%)	Copper smelting (two region entries): 4,470 (7%) ; smaller: ferronickel, zinc monosulfate
Scenario 2 ecotoxicity	71,850	Coke production (regular + wet quenching + coal gas): 29,940 (41.8%) .	Treatment of brake-wear emissions (lorry): 20,400 (28.5%)	Brake-wear emissions (RER entry): 8,290 (11.6%)	Cobalt production (ammonia stream): 7,540 (10.5%) ; Others: 3,450 (4.8%)

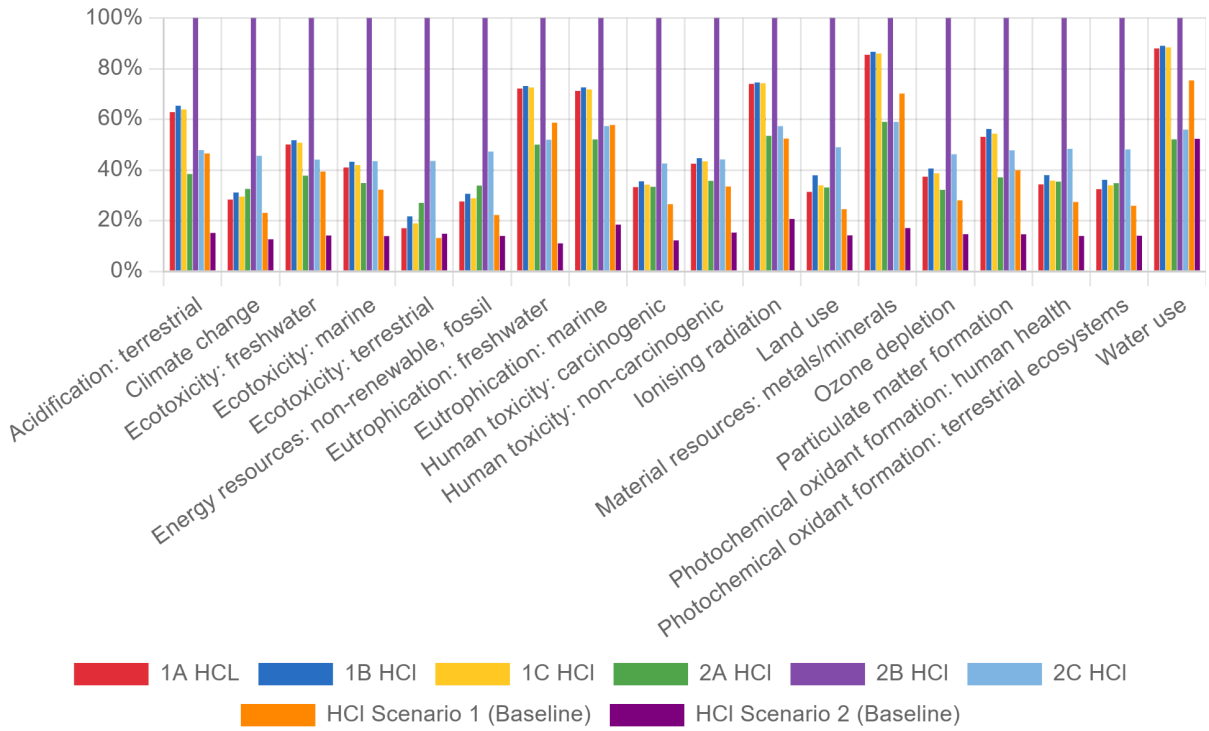


Fig. A.7: Normalized environmental impact of HCl scenario 2, varying the models' transport distances.

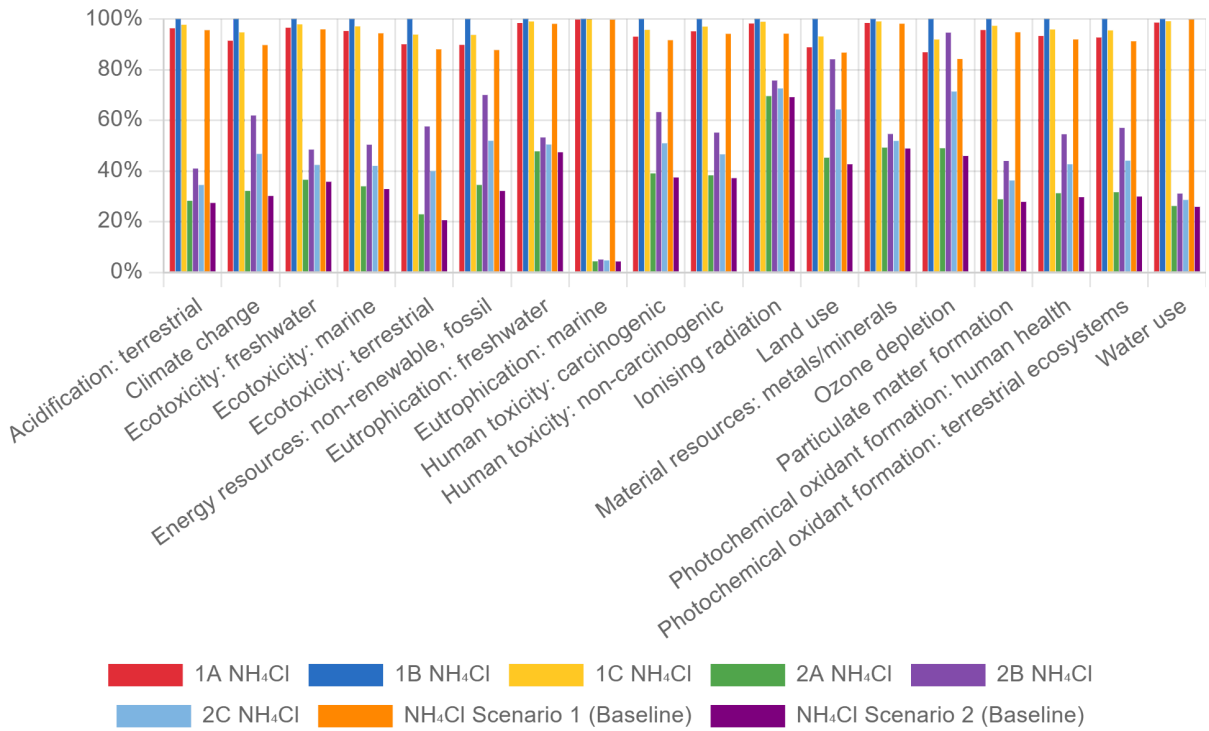


Fig. A.8: Normalized environmental impact of HCl scenario 2, varying the models' transport distances

Table A.2: Impact comparison: Baseline vs Renewable-energy sensitivity (HCl scenarios) comparing the difference in impact amounts

Impact Category	HCL Scenario 1 (Baseline)	HCl Case 1 RnE	HCL Scenario 2 (Baseline)	HCl Case 2 RnE
Acidification: terrestrial (kg SO ₂ -Eq)	17.84853	17.59511	5.81315	5.79208
Climate change (kg CO ₂ -Eq)	5514.49586	5317.62388	3019.99371	3007.85202
Ecotoxicity: freshwater (kg 1,4-DCB-Eq)	406.04551	145.67626	399.96301	145.99037
Eutrophication: freshwater (kg P-Eq)	2.68962	0.50488	2.67428	0.50221
Human toxicity: carcinogenic (kg 1,4-DCB-Eq)	1381.92289	636.41496	1339.59399	632.72739
Material resources: metals/minerals (kg Cu-Eq)	748.47825	182.05222	744.20813	181.75795
Ozone depletion (kg CFC-11-Eq)	0.00254	0.00133	0.00246	0.00132

Table A.3: Impact comparison: Baseline vs Renewable-energy sensitivity (NH₄Cl scenarios) comparing the difference in impact amounts.

Impact Category	NH₄Cl Scenario 1 (Baseline)	NH₄Cl Scenario 2 (Baseline)	Scenario 3 NH₄Cl	Scenario 4 NH₄Cl
Acidification: terrestrial (kg SO ₂ -Eq)	111.5939	31.95539	111.38933	31.92496
Climate change (kg CO ₂ -Eq)	3.63E+04	1.22E+04	3.61E+04	1.22E+04
Ecotoxicity: freshwater (kg 1,4-DCB-Eq)	2346.45987	874.18618	2342.15904	873.0889
Eutrophication: freshwater (kg P-Eq)	13.80556	0.95944	22.38988	0.95683
Human toxicity: carcinogenic (kg 1,4-DCB-Eq)	7809.149	3189.08224	7778.88646	3183.438
Material resources: metals/minerals (kg Cu-Eq)	3827.12642	1905.56847	3824.05954	1905.15457
Ozone depletion (kg CFC-11-Eq)	0.00993	0.00541	0.00985	0.00539

REFERENCES

- Abanades, J.C., Criado, Y.A. and Fernández, J.R. (2020) "An air CO₂ capture system based on the passive carbonation of large Ca(OH)₂ structures," *Sustainable Energy & Fuels*, 4(7), pp. 3409–3417. Available at: <https://doi.org/10.1039/D0SE00094A>.
- Abnett, K. and Abnett, K. (2025) "Europe just had warmest March on record," *Reuters* [Preprint]. Available at: <https://www.reuters.com/sustainability/cop/europe-just-had-warmest-march-record-2025-04-08/>.
- Arvidsson, R., Sandén, B.A. and Svanström, M. (no date a) "Prospective, Anticipatory and Ex-Ante – What's the Difference? Sorting Out Concepts for Time-Related LCA."
- Arvidsson, R., Sandén, B.A. and Svanström, M. (no date b) *Prospective, Anticipatory and Ex-Ante-What's the Difference? Sorting Out Concepts for Time-Related LCA*.
- Babiker Sudan, M. *et al.* (no date) "Oliver Geden (Germany), Veronika Ginzburg (the Russian Federation)," *Jan Christoph Minx* [Preprint]. Available at: <https://doi.org/10.1017/9781009157926.005>.
- Baumann, H. and Tillman, A.-M. (2004) *The hitchhiker's guide to LCA (Life Cycle Assessment): an orientation in Life Cycle Assessment methodology and application*. Studentlitteratur AB. Available at: DOI:
- Bruijn, Hans. *et al.* (2004) *Handbook on Life Cycle Assessment : Operational Guide to the ISO Standards*. Springer Netherlands.

Bullock, L.A. *et al.* (2021) "Global Carbon Dioxide Removal Potential of Waste Materials From Metal and Diamond Mining," *Frontiers in Climate*, 3. Available at: <https://doi.org/10.3389/FCLIM.2021.694175>.

Carbon Dioxide - Earth Indicator - NASA Science (no date). Available at: <https://science.nasa.gov/earth/explore/earth-indicators/carbon-dioxide/> (Accessed: November 18, 2025).

C.M.G, A., V. I, F. and I.C., O. (2019) "MINE WASTE: SOURCES, PROBLEMS AND MITIGATIONS.," *EPH - International Journal of Applied Science*, 5(3), pp. 1–7. Available at: <https://doi.org/10.53555/eijas.v5i3.112>.

CSIRO (no date) "Oceans absorb 30% of our emissions, driven by a huge carbon pump. Tiny marine animals are key to working out its climate impacts."

Effects - NASA Science (no date). Available at: <https://science.nasa.gov/climate-change/effects/> (Accessed: November 18, 2025).

Ekvall, Tomas. (1999) *System expansion and allocation in life cycle assessment: with implications for wastepaper management*. Dept. of Technical Environmental Planning, Chalmers University of Technology.

"Evidence - NASA Science" (2022). Available at: <https://science.nasa.gov/climate-change/evidence/>.

"Explained: Data in LCA Ecochain Technologies Help Center" (no date). Available at: <https://helpcenter.ecochain.com/en/articles/9842753-explained-data-in-lca>.

Explained: Life Cycle Impact Assessment (LCIA) phase | Ecochain Technologies Help Center (no date). Available at: <https://helpcenter.ecochain.com/en/articles/9785060-explained-life-cycle-impact-assessment-lcia-phase> (Accessed: November 18, 2025).

(No date) "Explained: Life Cycle Impact Assessment (LCIA) phase Ecochain Technologies Help Center." Available at: <https://helpcenter.ecochain.com/en/articles/9785060-explained-life-cycle-impact-assessment-lcia-phase>.

Flemström, K. and Pålsson, A.-C. (no date) "Introduction and guide to LCA data documentation using the CPM documentation criteria and the ISO/TS 14048 data documentation format."

for Standardization (ISO), I.O. (2006) "Environmental management — Life cycle assessment — Requirements and guidelines." Geneva, Switzerland: International Organization for Standardization (ISO). Available at: <https://www.iso.org/standard/38498.html>.

"Greenhouse gases" (2023) *World Meteorological Organization* [Preprint]. Available at: <https://wmo.int/topics/greenhouse-gases>.

"IPCC — Intergovernmental Panel on Climate Change" (no date). Available at: <https://www.ipcc.ch/>.

Kelemen, P.B. *et al.* (2020) "Engineered carbon mineralization in ultramafic rocks for CO2 removal from air: Review and new insights," *Chemical Geology*, 550. Available at: <https://doi.org/10.1016/J.CHEMGEO.2020.119628>.

Kieush, L. *et al.* (2024) "Roadmap for recycling practices and resource utilization in the iron and steelmaking industry: a case studies," *Materiaux et Techniques*. EDP Sciences. Available at: <https://doi.org/10.1051/mattech/2024026>.

"LD - slag - SSAB" (no date). Available at: <https://www.merox.se/index.pl/ld-slag>.

Lu, S. (2024) "The Reality of Climate Change: Evidence, Impacts and Engineering Solutions." arXiv. Available at: <https://doi.org/10.48550/arXiv.2410.12412>.

Mattila, H.-P., Grigaliūnaitė, I. and Zevenhoven, R. (2012) "Chemical kinetics modeling and process parameter sensitivity for precipitated calcium carbonate production from steelmaking slags," *Chemical Engineering Journal*, 192, pp. 77–89. Available at: <https://doi.org/10.1016/j.cej.2012.03.068>.

McMichael, A.J., Woodruff, R.E. and Hales, S. (2006) "Climate change and human health: present and future risks," *The Lancet*, 367(9513), pp. 859–869. Available at: [https://doi.org/10.1016/S0140-6736\(06\)68079-3](https://doi.org/10.1016/S0140-6736(06)68079-3).

McNutt, M. (2013) "Climate Change Impacts," *Science* [Preprint]. Available at: https://www.academia.edu/70470968/Climate_Change_Impacts.

O'Connor, J. *et al.* (2021) "Production, characterisation, utilisation, and beneficial soil application of steel slag: A review," *Journal of Hazardous Materials*, 419, p. 126478. Available at: <https://doi.org/10.1016/J.JHAZMAT.2021.126478>.

Piatak, N.M. (2018) "Environmental Characteristics and Utilization Potential of Metallurgical Slag," in *Environmental Geochemistry: Site Characterization, Data Analysis and Case Histories*. Elsevier, pp. 487–519. Available at: <https://doi.org/10.1016/B978-0-444-63763-5.00020-3>.

Pörtner, H.-O. and Roberts, D.C. (no date) "United Kingdom), Susan Crate (USA), Rob Deconto (USA), Chris Derksen (Canada)." Available at: <https://doi.org/10.1017/9781009157964.002>.

Quist, Z. (2024) "Life Cycle Assessment (LCA) - Complete Beginner's Guide," *Ecochain LCA Software* [Preprint]. Available at: <https://ecochain.com/blog/life-cycle-assessment-lca-guide/>.

"ReCiPe" (2016) *PRé Sustainability* [Preprint]. Available at: <https://pre-sustainability.com/articles/recipe/>.

Rydén, M., Hanning, M. and Lind, F. (2018) "Oxygen Carrier Aided Combustion (OCAC) of Wood Chips in a 12 MWth Circulating Fluidized Bed Boiler Using Steel Converter Slag as Bed Material," *Applied Sciences*, 8(12), p. 2657. Available at: <https://doi.org/10.3390/app8122657>.

Scheer, J. (no date) *Extraction of Ca(OH)₂ from industrial by-products for the use in a passive-DAC system for negative emissions*. Available at: www.chalmers.se.

Scheer, J. (no date b) *Extraction of Ca(OH)₂ from industrial by-products for the use in a passive-DAC system for negative emissions*. Available at: www.chalmers.se.

Scheer, J. (no date c) "Extraction of Ca(OH)₂ from industrial by- products for the use in a passive-DAC system for negative emissions."

De Souza, N.R.D. *et al.* (2023) "Integrating ex-ante and prospective life-cycle assessment for advancing the environmental impact analysis of emerging bio-based technologies," *Sustainable Production and Consumption*, 43, pp. 319–332. Available at: <https://doi.org/10.1016/j.spc.2023.11.002>.

Stainless-steel slag treat acidic wastewater | KTH (no date). Available at: <https://www.kth.se/en/om/nyheter/lokala-nyheter/stainless-steel-slag-treat-acidic-wastewater-1.1154691> (Accessed: November 18, 2025).

Tampubolon, F.R.S. *et al.* (2021) "Coal Mining Energy Utilization and Environmental Impact Management Strategy Using the LCA Method," *Nature Environment and Pollution Technology*, 20(5). Available at: <https://doi.org/10.46488/NEPT.2021.v20i05.017>.

The Paris Agreement (2016). Available at: https://treaties.un.org/Pages/ViewDetails.aspx?src=TREATY&mtdsg_no=XXVII-7-.

Understanding LCA Standards: ISO 14040/14044 | cove.tool Help Center (no date). Available at: <https://help.covetool.com/en/articles/8814594-understanding-lca-standards-iso-14040-14044> (Accessed: November 18, 2025).

UNFCCC (no date) *United Nations Framework Convention on Climate Change*. Available at: <http://cdm.unfccc.int/index.html>.

United Nations Framework Convention on Climate Change | UNFCCC (no date). Available at: <https://unfccc.int/process-and-meetings/united-nations-framework-convention-on-climate-change> (Accessed: November 18, 2025).

US EPA, O.A.R. (2016) "Understanding Global Warming Potentials." Available at: <https://www.epa.gov/ghgemissions/understanding-global-warming-potentials>.

Velicogna, I. *et al.* (2020) "Continuity of Ice Sheet Mass Loss in Greenland and Antarctica From the GRACE and GRACE Follow-On Missions," *Geophysical Research Letters*, 47(8), p. e2020GL087291. Available at: <https://doi.org/10.1029/2020GL087291>.

What is Mineral Carbonation? - Exterra (no date). Available at: <https://exterracarbon.com/what-is-mineral-carbonation/> (Accessed: November 18, 2025).

Popular Science summary

There is a continuous increase in atmospheric greenhouse gases such as carbon dioxide (CO₂), which have devastating effects on the planet. Scientists have developed and continue to improve methods to both reduce CO₂ emissions and actively remove CO₂ from the atmosphere in an effort to slow the rapid environmental decline. This thesis questioned whether it was environmentally feasible to use waste from steel production (Slag) to produce materials for passively removing atmospheric CO₂.

The principle of the study is that alkaline materials, specifically calcium hydroxide (Ca(OH)₂), could be extracted from industrial waste such as steel slag, to form porous materials which act as a sponge to absorb atmospheric CO₂. This method could then serve as a low-cost, low-energy alternative carbon dioxide removal method, which also allows for the repurposing of tons of industrial waste.

This study evaluated the environmental feasibility of two methods of extracting Ca(OH)₂, one using hydrochloric acid (HCl), the other using ammonium chloride (NH₄Cl). It then estimated a specific amount of CO₂ likely to be captured with the extracted Ca(OH)₂ and compared this to the overall amount of CO₂ generated during the extraction of the Ca(OH)₂.

The results revealed that the carbon cost of extracting the alkaline material was way higher than the amount of CO₂ the porous materials were estimated to capture. The NH₄Cl process was the worst, emitting 6-7 times more than the HCl procedure.

This means that while the idea of turning steel slag into a CO₂-capturing material sounds promising, it is not an environmentally beneficial option to combat climate change. This highlights the need to consider the whole life cycle of a technology, not just its final purpose.