GREEN HYDROGEN
SOUTH AFRICA

Life Cycle Assessment of green ammonia produced at a coastal facility in South Africa and utilised for heavy-duty transport in Germany

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Life Cycle Assessment of green ammonia produced at a coastal facility in South Africa and utilised for heavy-duty transport in Germany

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ACRONYMS

COP	Conference of the Parties
CFC	Chlorofluorocarbon
DALY	Disability-Adjusted Life Years
DC	Direct Current
DEA	Department Environment Affairs (now DFFE)
DFFE	Department of Forestry, Fisheries and the Environment
e-Fuels	Electro-fuels are electricity-based fuels produced by PtX
EoL	End of Life
ES	Ecosystems
ETS	Emissions Trading System
EU	European Union
FCEV	Fuel-Cell Electric Vehicles
GH_2	Green Hydrogen
GHG	Greenhouse Gases
GLO	Global Market
GNH_3	Green Ammonia
GWh	Gigawatt Hour
GWP	Global Warming Potential
H_2	Hydrogen
H2.SA	Green Hydrogen South Africa
HCFC	Hydrochlorofluorocarbon
HH	Human Health
ICCT	International Council on Clean Transportation
IPCC	Intergovernmental Panel on Climate Change
IPHE	International Partnership for Hydrogen and Fuel Cells in the Economy
ISO	International Organization for Standardization
KA	Kiloampere
Kg	Kilograms
Km	Kilometres
kPa	Kilopascal
Kt	Kilotonnes

ACRONYMS

kV	Kilovolt
KWh	Kilowatt-Hour
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
LCI	Life Cycle Impact
m^2	Square Metre
m^3	Cubic Metre
MJ	Megajoule
MPa	Megapascal
MVA	Megavolt Ampere
MW	Megawatt
NDC	Nationally Determined Contributions
NOx	Nitrogen Oxide
PDF	Potential Disappeared Fraction of Species
PM	Fine Particulate Matter
PtX	Power-to-X (Power-to-Liquids and Power-to-Gas)
PV	Photovoltaic
RE	Renewable energy
ReCIPe	RIVM and Radboud University, CML, and PRé Consultants
REDZ	Renewable Energy Development Zone
RES	Resources
RoW	Rest of the World
SO_2	Sulphur Dioxide
Species*yr	Actual Species Lost Per Year
SWRO	Sea Water Reverse Osmosis
t	Tonnes
tkm	Tonne-kilometres
UNFCCC	United Nations Framework Convention on Climate Change
USD/$	United States Dollar
YLL	Years of Life Lost
ZA	South Africa

Executive Summary

Context

The transition to low-carbon fuels such as green hydrogen (GH_2) is critical to mitigate climate change. Countries with abundant sources of solar and wind resources, such as South Africa, are well positioned to help fulfil growing global demands. While GH_2 fuel is a promising alternative to the carbon-intensive fossil fuels used for power and transport, there are challenges. GH_2 has a low energy density by volume, which makes it unfeasible to transport over long distances and high-pressure storage systems are costly and energy intensive. One solution to improve the volumetric energy density and ease of storage and transport is to convert GH_2 into green ammonia (GNH_3).

This report is part of the project 'Promoting a South African Green Hydrogen Economy (H2.SA)', which is funded by the *Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH* and aims to support the South African public and private sectors in realizing the potential of a sustainable GH_2 economy. This report is an assessment of the environmental impacts of a GNH_3 plant at Saldanha bay[1] with an annual production capacity of 280 000 tonnes. Renewable energy from wind and solar photovoltaics (PV) is used to desalinate seawater, produce GH_2 and synthesise GNH_3 fuel. The GNH_3 produced could be used in several markets for different end uses, but this study assumed export with the transport of green ammonia to Europe, cracking to green hydrogen and distribution to Germany for powering fuel-cell driven heavy duty transport.

Life Cycle Assessment (LCA) is a standard and systematic approach to assess the environmental impacts of a product throughout lifecycle – from extraction of raw materials through manufacturing, use and final disposal. Therefore, two LCAs were carried out to assess the environmental impacts of GNH_3; cradle-to-production gate and cradle-to-grave, as shown by points A and B in the Figure below. The functional unit for the cradle-to-gate is per kg GNH_3, while the functional unit of cradle-to-gate is per km travelled.

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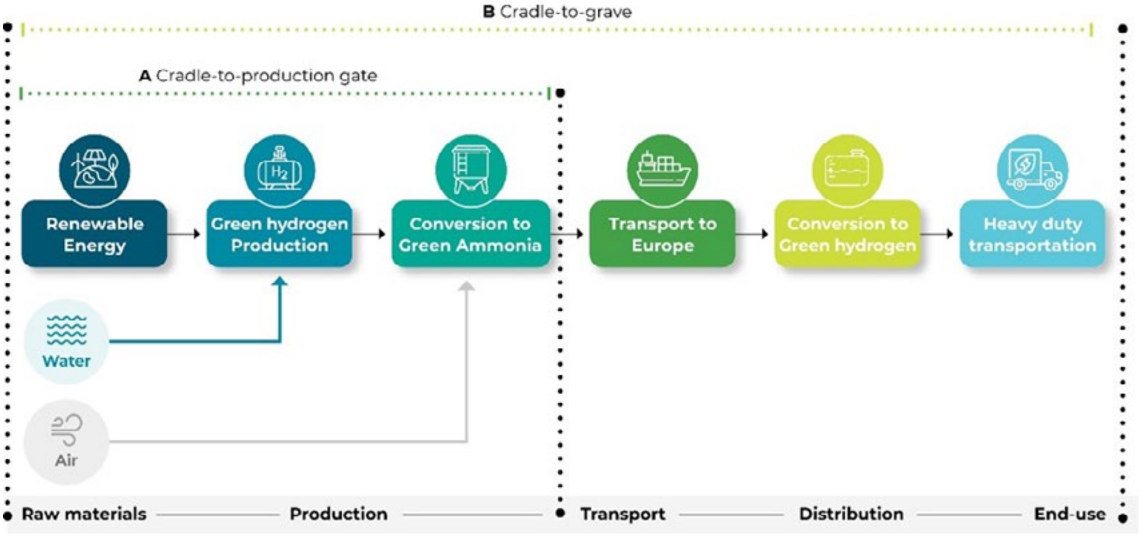
[1] *The 'Pre-Feasibility Study on Lighthouse Technology Ammonia' serves as a guide for developers to consider technical, financial, environmental, and social aspects in the development of GNH_3 projects and explores Saldanha bay as a case study. The study is available at H2.SA.*



A: Cradle-to-production gate: Production and storage of GNH_3 at the port of Saldanha bay, South Africa.

B: Cradle-to-grave: Extending the LCA beyond production at Saldanha bay to include transport of the green ammonia to Europe, cracking to hydrogen and distribution to Germany for use in heavy-duty transport.

The assessments evaluated the environmental impacts of GNH_3 production using the ReCiPe 2016 method with 18 indicators of environmental impacts (mid points); determined the damage to areas of protection concerning human-health, ecosystems and resources (end points); as well as estimated the total environmental impacts (single score). Although all impact categories were analysed, the initial analysis was focused on greenhouse gases (GHG) and the Global Warming Potential (GWP) impact categories to improve the understanding of production pathways that can provide low-carbon fuels to achieve global carbon emissions reduction targets in the transport sector.

Since the standards for GH_2 are still developing and there are several certification schemes and standards with different thresholds, boundary and scope, the assessment also explores how the environmental impacts of GNH_3 production and end-use are influenced by the assessment in terms of different definitions of the scope; such as whether the energy supply system (and its associated environmental impacts) is included in the system boundary, and whether co-products (electricity, argon and oxygen) are included.

Therefore, to understand how results are affected by different boundaries and scope, three scenarios were considered, namely:

- **Scenario 1 –** Renewable energy (solar PV and wind power) to produce green hydrogen from electrolysis of seawater, and synthesis of green ammonia as the only product. The extended LCA includes transport of ammonia to Europe, cracking to hydrogen and distribution to Germany for powering fuel-cell driven transport.
- **Scenario 2 –** Renewable energy (solar PV and wind power) for the production of green hydrogen from electrolysis of seawater, synthesis of green ammonia product and co-products of electricity, oxygen and argon. The extended LCA includes transport of green ammonia to Europe, cracking to hydrogen and distribution to Germany for powering fuel-cell driven heavy-duty transport.
- **Scenario 3 –** Renewable energy (solar PV and wind power) to produce green hydrogen from electrolysis of seawater, and synthesis of green ammonia as the only product. The embodied emissions associated with the capital infrastructure of the energy supply system excluded (cut-off), and therefore renewable energy supply has zero emissions. This approach is the recommended methodology for the certification of hydrogen as a low carbon fuel (IPHE, 2023).

This study aims to help inform project design and the development of harmonised standards for the certification of green hydrogen and its derivatives as low-carbon fuels. In addition, this research and its findings are informing the development of a green hydrogen certification standard for South Africa that is being led by the Department of Forestry, Fisheries and the Environment (DFFE).

Results of the Life Cycle Assessments

A. Cradle-to-production gate Life Cycle Assessment

The cradle-to-production gate global warming potential (GWP) for GNH_3 produced and stored at Saldanha bay port was 0.790 kilograms (kg) CO_2-eqivalent (eq)/kg GNH_3. If oxygen, argon and excess electricity are sold to market and allocated a portion of greenhouse gas (GHG) emissions, then the GWP of ammonia is 0.276 kg CO_2-eq/kg. If embodied emissions associated with the capital infrastructure of the energy supply system are excluded in accordance with the **recommended methodology for the certification of hydrogen as a low-carbon fuel,** then the GWP is **0.106 kg CO_2-eq/kg ammonia or 0.598 kg CO_2-eq/kg hydrogen** when expressed in terms of hydrogen content of ammonia[2].

The global ambition to mitigate climate change by 1.5 ^{0}C requires that near zero carbon fuels (< 1 kg CO_2-eq/kg) are achieved by 2050, but the certification systems and carbon intensity thresholds for hydrogen fuels to be classed as low-carbon are still developing. Thresholds for the certification as a low-carbon fuel range from 0.45 to 5.04 kg CO_2-eq/kg hydrogen, with several certification systems having a threshold <4 kg CO_2/kg hydrogen. For example, the Japan Hydrogen Association, European Union RED-II standard specify a 70% reduction compared to grey hydrogen from natural gas, which represents a threshold of 3.4 kg CO_2-eq/kg hydrogen. **Therefore, GNH_3 produced from coastal production in South Africa in the given case are within these thresholds and will achieve certification as a low-carbon fuel.**

In terms of other environment impacts for cradle-to-production gate, GNH_3 has greater impacts than grey and/or black ammonia in some categories, notably eco-toxicity (human, freshwater and marine), human toxicity (carcinogenic and non-carcinogenic), land-use, eutrophication (freshwater and marine) and acidification which could be a concern. However, when these environment impact indicators are normalised and aggregated to express the damage to areas of protection, GNH_3 **has reduced damage to human health, ecosystems and resources.** GNH_3 has a reduced damage to human health (0.21×10^{-05}; 0.04×10^{-05} and 0.04×10^{-05} DALY[3] for scenario 1, 2 and 3 respectively), compared to black ammonia (1.19×10^{-05} DALY) or grey ammonia (0.28×10^{-05} DALY); a reduced damage to ecosystems for scenario 1, 2 and 3 (0.67×10^{-08}; 0.12×10^{-08} and 0.11×10^{-08} species.yr[4] for scenario 1, 2 and 3 respectively), compared to black ammonia (2.92×10^{-08} species.yr) and grey ammonia (0.81×10^{-08} species.yr); and reduced damage to resources

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[2] *The hydrogen content of ammonia is 17.65%. Therefore, 1 kg hydrogen = 5.67 kg ammonia*

[3] *Loss of life and productivity, measure as Disability-Adjusted Life Years (DALY)*

[4] *Biodiversity loss, measured as species lost over time (species.yr)*

($0.49x10^{-01}$; $0.09x10^{-01}$ and $0.06x10^{-01}$ USD2013[5] for scenario 1, 2 and 3 respectively), compared to black ammonia ($2.35x10^{-01}$ USD2013) or grey ammonia ($2.86x10^{-01}$ USD2013).

A contribution analysis indicates that the most significant **impact categories contributing to the total environmental impact of GNH_3 production are particulate matter (55%), followed by GWP (33%)** and **water (4%).** These impacts are related to the embodied emissions from fossil fuels (coal, oil, and natural gas) that were used to generate electricity for the manufacturing of infrastructure in the GNH_3 value chain. In addition, the **processes or lifecycle stages contributing to the total environmental impact of GNH_3 production** are **electrolysis (68%), air separation (15%) and ammonia synthesis (13%),** which reflects the energy intensity of these processes.

B. Cradle-to-grave Life Cycle Assessment

The extended life cycle included transport, distribution and use in heavy duty transport in Germany. The **cradle-to-grave** GWP of GNH_3 was 0.097 kg CO_2-eq/km travelled (scenario 1). If oxygen, argon, and excess electricity are sold and allocated a portion of GWP on a mass basis, then the GWP of GNH_3 is 0.047 kg CO_2-eq/km travelled (scenario 2). If the GWP from renewable energy infrastructure is assumed zero, as proposed by the methodology for certification of hydrogen (scenario 3), then the GNH_3 carbon emissions are 0.043 kg CO_2-eq/km travelled[6]; which is 81% reduction compared to grey ammonia (0.221 kg CO_2-eq/km) and 92% reduction compared to black ammonia (0.508 kg CO_2-eq/km). However, if the cradle-to-grave emissions are compared to the current business-as-usual heavy-duty vehicles using diesel fuel, which have carbon emission intensity of approximately 0.789 kg CO_2-eq/km (ICCT, 2021), then the carbon emission reductions of GNH_3 are of 95%. Therefore, GNH_3 produced from coastal facilities in South Africa and used for heavy duty transport in Germany, shows a carbon emission reduction of >70% when compared to heavy duty transport using grey ammonia, black ammonia or diesel fuel, and will likely receive certification as a low-carbon fuel.

In terms of other environment impacts for cradle-to-grave, GNH_3 has greater impacts than grey and/or black ammonia in some categories, notably eco-toxicity (human, freshwater and marine), human toxicity (carcinogenic and non-carcinogenic), land-use, eutrophication (freshwater and marine) and acidification which could be a concern. However, when these environment impact indicators are normalised and aggregated to express the damage to areas of protection, GNH_3 **has reduced damage to human health, ecosystems and resources.** GNH_3 has a reduced damage to human-health ($2.23x10^{-07}$; $0.88x10^{-07}$ and $0.87x10^{-07}$ DALY for scenario 1, 2 and 3 respectively), compared to black ammonia ($9.62x10^{-07}$ DALY) or grey ammonia ($2.80x10^{-07}$ DALY); reduced damage

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[5] *Impacts to Resources leading to resource depletion and increasing costs of extraction, measure in US dollars in 2013 (USD2013)*

[6] *The functional unit for the cradle-to-gate is per km travelled. The 0.0427 kg CO_2-eq/km travelled can be converted to hydrogen fuel equivalents at the re-fueling station, which amounts to 4.12 kg CO_2-eq/kg of H_3 equivalent*

to ecosystems for scenario 1, 2 and 3 ($0.72x10^{-09}$; $0.28x10^{-09}$ and $0.27x10^{-09}$ species.yr for scenario 1, 2 and 3 respectively), compared to black ammonia ($2.54x10^{-09}$ species.yr) and grey ammonia ($0.83x10^{-09}$ species.yr); and reduced damage to resources ($0.52x10^{-02}$; $0.19x10^{-02}$ and $0.17x10^{-02}$ USD2013 for scenario 1, 2 and 3 respectively), compared to black ammonia ($2.02x10^{-02}$USD2013) or grey ammonia ($2.44x10^{-02}$ USD2013).

The most significant **impact categories contributing to the overall environmental impact** for GNH_3 cradle-to-grave lifecycle are particulate matter (51%), GWP (39%), and water (3%). These impacts are related to the fossil fuel combustion systems used to generate electricity. In addition, the stages/process contributing to the overall environmental impact for GNH_3 cradle-to-grave lifecycle are electrolysis (37%), cracking (16%), compression and storage (15%) and air separation process (8%). It is noteworthy that considerable impacts of the cradle-to-grave assessment of GNH_3 are related to the transport, cracking and distribution to end users in Germany, due to the loss of hydrogen in cracking (15%) and the energy intensity of compression and storage. While the GWP for cradle-to-production gate is 0.598 kg CO_2-eq/kg hydrogen, the transportation, cracking, distribution and use in heavy duty vehicles incurs additional carbon emissions of 3.522 kg CO_2-eq/kg hydrogen. The emissions and energy intensity of GNH_3 cracking, transport and distribution to refuelling stations for heavy duty transport may negate the carbon savings of GNH_3 production and pose a risk for the certification as a low-carbon fuel.

In conclusion, the just energy transition from fossil fuels, such as coal and natural gas, to GH_2/GNH_3 fuels can reduce GHG emissions in the heavy-duty transport sector and help to mitigate climate change. In addition, compared to fossil fuels such as coal and natural gas, GH_2/GNH_3 shows lower environment impacts in most impact categories and can thereby reduce the damage to human health, ecosystems and resource depletion.

Introduction

The global energy landscape is undergoing a significant transformation, driven by the urgent need to mitigate climate change and reduce greenhouse gas (GHG) emissions. Renewable energy sources, such as wind and solar power, are increasingly being harnessed to meet supply low-carbon energy and transition to a more sustainable development path. However, the intermittent nature and unequal distribution of renewable energy resources necessitates the development of efficient energy storage and energy carrier systems. Energy carriers such as low-carbon fuels have the potential to play a crucial role in the energy transition by serving as an energy carrier for the storage and transportation of renewable energy; particularly from regions with abundant renewable resources, but distant energy markets (Brown *et al*., 2021).

In this context, green ammonia (GNH_3) has emerged as a promising low-carbon energy carrier due to its high energy density and ease of storage and transport (IEA 2019 and IEA 2013a; Jones *et al*., 2019; Smith *et al*., 2020; Milkovits *et al*. 2021). Ammonia is an energy carrier that can be used for electricity, industrial process heat and cooling, and as a transportation fuel. Ammonia is easily liquefied by compression at 1 megapascal (MPa) and 25°C, which simplifies storage and transportation, while hydrogen requires extreme low-temperature and high-pressure conditions. Ammonia also has a volumetric hydrogen density of approximately 123 $kg\text{-}H_2/m^3$ at 1 MPa, which surpasses metal hydrides (25 $kg\text{-}H_2/m^3$), liquefied hydrogen (71 $kg\text{-}H_2/m^3$), and methanol (99 $kg\text{-}H_2/m^3$), enabling it to store more hydrogen in a given volume (Smith *et al*., 2020). The established ammonia industry, with extensive storage, transportation, and distribution networks enables the integration into current energy systems. Moreover, its high chemical stability and low flammability compared to pure hydrogen, enhances safety.

South Africa offers excellent opportunities for hydrogen (H_2) and ammonia (NH_3) production, with coastal regions that have abundant wind and solar resources, making them ideal locations to produce GNH_3 from renewable resources. However, the environmental implications of GNH_3 production and use are not yet fully understood, necessitating comprehensive Life Cycle Assessment (LCA) studies to evaluate its potential as a sustainable energy carrier. More specifically, the carbon certification systems for green hydrogen (GH_2) are still emerging and have discrepancies in how “green” is defined in terms of a carbon intensity thresholds and where the boundaries are drawn within the supply chain for emissions accounting. These discrepancies could lead to certification schemes not being recognised between exporting and importing jurisdictions, which would hamper the investment and trade of GH_2 and its derivatives, such as GNH_3.

Since the transport sector currently accounts for 20% of global GHG emissions, the transition to low-carbon fuels offers opportunities to reduce emissions, particularly in heavy-duty trucks, shipping and aviation. In a future net-zero emissions scenario, global hydrogen and hydrogen derivatives are expected to contribute more than 25% of total transport energy by 2050, with a substantial growth in fuel-cell electric vehicles (DST 2021, IEA 2021).

This study is part of the project 'Promoting a South African Green Hydrogen Economy (H2.SA)' implemented by the *Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ), GmbH* to support the South African public and private sectors in realising the potential of a sustainable GH_2 economy. This study aims to contribute to the ongoing discourse on renewable energy strategies and the Just Energy Transition in South Africa by providing a detailed LCA of the environmental impacts of GNH_3 produced in South Africa and exported to Germany for use in fuel-cell electric vehicles for heavy duty transport. To that end, the study may also guide the identification of low-carbon production pathway(s) and facilitate the design of the GH_2/GNH_3 production process and associated value chains in order to meet the requirements and specifications that potential importers, such as the European Union (EU), have set as part of their decarbonisation regulatory framework and dedicated Power-to-X (PtX) funding instruments. In particular, the German government decided to put a price on GHG emissions in the transport sector from 2021 as a key instrument to help reach its climate targets and has recently supported the EU's 2040 target of reducing heavy-duty vehicle emissions by 90% with the *proviso* that it includes PtX fuels or e-fuels (Euractiv 2024, and Clean Energy Wire 2024).

Furthermore, the findings from this study are contributing to the current development of a South African certification system for GH_2 with ongoing information provided to an expert working group under the auspices of the Department of Forestry, Fisheries and the Environment (DFFE). It is against this background that the LCA facilitates the design of PtX production pathways in the country and the associated supply chains, which, in turn, can meet the market requirements and thresholds for low-carbon fuels.

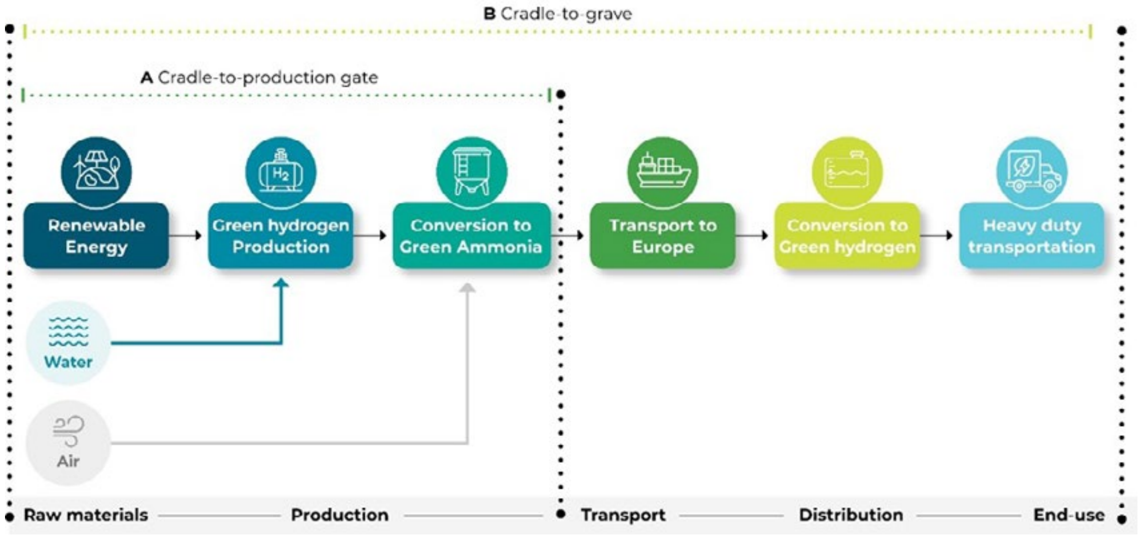

Figure 1: Lifecycle of green ammonia and the cradle-to-production gate and cradle-to-grave boundaries for the two LCAs carried out in this study.

Chapter 1:

Methods

1. Methods

The study followed the ISO 14040 series (ISO, 2006) that define the general framework and requirements to conduct LCA studies. Specifically, the international standard on LCA, ISO 14044:2006, requires that the items in the following subsections be considered and clearly described when defining the goal and scope of an LCA study.

1.1 Life Cycle Assessment

LCA is a systematic approach that evaluates the environmental impacts of a product throughout its entire life cycle (see Figure 2), from extraction of raw materials through to final disposal.

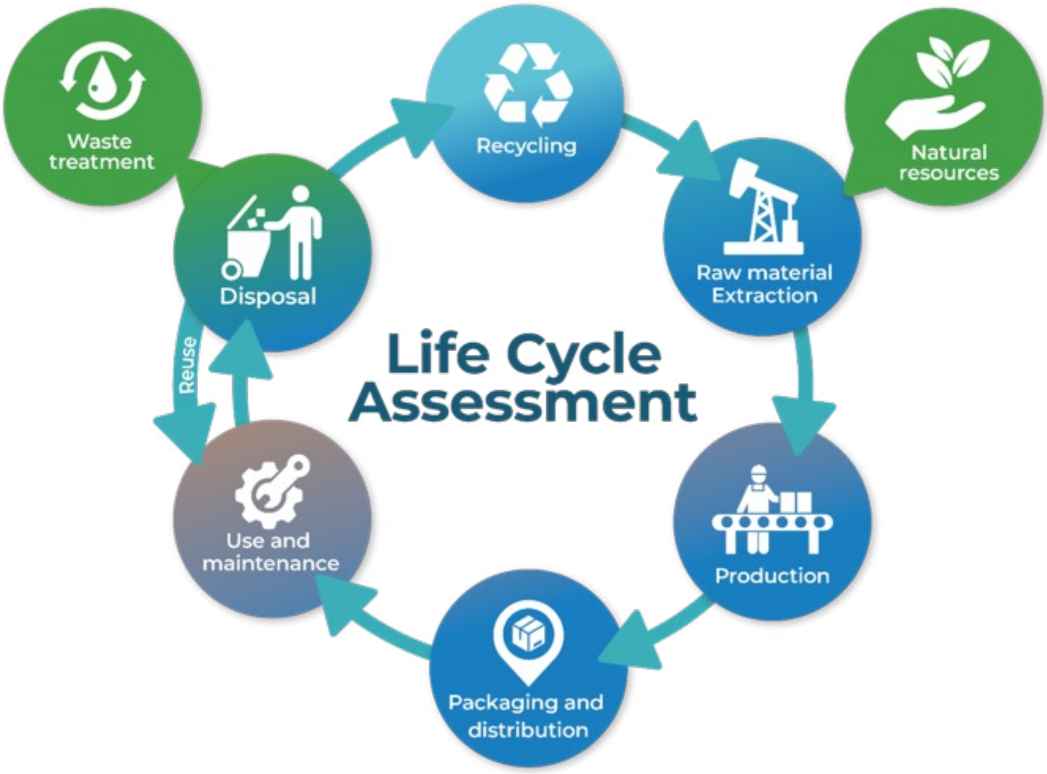

Figure 2: A typical product life cycle[7].

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[7] Source: Swiss Federal Office for the Environment (BAFU) (2022); https://ecoinvent.org/life-cycle-assessment/

LCA quantifies the inputs of material and energy resources, as well as outputs of emissions and waste, throughout a product's life cycle – including raw material extraction, manufacturing, packaging and distribution, use and maintenance, and end-of-life disposal. An LCA considers various environmental impact categories in the assessment; including the consumption of energy, land, water and other resources; as well as various types of emissions to air, water and soil. LCA enables the identification of impact hotspots along the product life cycle; and helps to make informed decisions to minimise environmental impacts, optimise resource efficiency, and promote the transition towards a circular economy.

As per the ISO 14040/14044 standards, the study follows four main stages namely (1) goal and scope definition, (2) life cycle inventory analysis, (3) life cycle impact assessment (LCIA), and (4) interpretation. The first phase consists of defining the aim of the study as well as stating methodological choices for aspects such as the functional unit, system boundaries, relevant impact categories, and data quality requirements. The next stage involves the collection and validation of data in relation to the process units and stated functional unit. For the LCIA stage, inventory results are translated into environmental impacts via Life Cycle Impact Assessment (LCIA) methods, which classify emissions into impact categories and thereafter characterise them to common units. The final stage includes the interpretation of inventory and impact assessment results in accordance with the stated goal and scope.

The SimaPro 9.5 software (Pre', 2022), along with the Ecoinvent 3.9.1 database (Wernet *et al*. 2016) and primary data were used for the LCA modelling. The environmental impacts were assessed using the ReCiPe 2016 method suite (ReCiPe, 2016; Huijbregts *et al*., 2017; Goedkoop *et al*., 2009), which is a widely accepted method for LCA studies (Goedkoop *et al*., 2013) and contains Intergovernmental Panel on Climate Change (IPCC) methodology for calculation of carbon emissions over 100 years (IPCC, 2021).

This process design and associated data were sourced from a techno-economic pre-feasibility study to explore GNH$_3$ production in South Africa, which was prepared as part of the project 'Promoting a South African Green Hydrogen Economy (H2.SA)' and focused on a Saldanha bay case study[8]. The location in Saldanha bay is a Special Economic Zone (SEZ) that is also within a Renewable Energy Development Zone (REDZ). The REDZ is a geographical area identified by the national DFFE as having good wind and solar potential and a lack of sensitive or protected areas so that renewable energy development regulatory processes can be streamlined (REDZ 2019; Global African Network, 2023). In the case scenario, the renewable energy of the GNH$_3$ production plant is connected to the national electricity grid to allow the export and sale of excess electricity, but not allow import from the grid. The plant was designed with

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[8] *The 'Pre-Feasibility Study on Lighthouse Technology Ammonia' serves as a guide for developers to consider technical, financial, environmental, and social aspects in the development of GNH$_3$ projects and explores Saldanha bay as a case study. The study is available at H2.SA.*

379 megawatt (MW) solar PV and 1 515 MW wind power to provide on-site electricity for the annual production of 280 kilotonnes GNH_3. Further details of processes and the life cycle inventory are tabulated in Supplementary information.

1.2 Objective of the study

The objective of the study is to conduct a LCA to determine the environmental footprint of GNH_3 production in South Africa and its utilisation in Germany for heavy-duty transport to help meet its carbon budget the transport sector. The German government decided to put a price on GHG emissions in the transport and building sectors from 2021 as a key instrument to help reach its climate targets and recently supports the EU 2040 target of reducing heavy-duty vehicle emissions by 90% on the proviso that it includes PtX synthetic fuels (Euractiv 2024, and Clean Energy Wire 2024).

The study intends to inform researchers, project developers, certifying bodies and policymakers on the environmental impacts of GH_2 and GNH_3 about its potential for a Just Energy Transition. Since results will be disclosed, this report will be subjected to peer review (ISO 14044, 2006) and the responses and amendments included in the full report available.

1.3 Scope of the study

The study reports on two LCAs with different boundaries:

(A) Production of ammonia to be stored and available at a maritime refilling station Saldanha bay, South Africa (cradle-to-production gate); and

(B) Extending assessment to utilisation and end-use by including transport to Europe, cracking to hydrogen and distribution and use in Germany for heavy-duty transport (cradle-to-grave).

The functional unit for the **cradle-to-production gate** LCA is the production of **1 kilogram (kg) of GNH_3 produced at Saldanha bay, South Africa.** For the **cradle-to-grave** LCA, the functional unit is **1 kilometre (km) travelled.**

The product system boundary entails all the inputs, resources and processes necessary to produce GNH_3 in South Africa at a coastal facility, using renewable energy from wind and solar (cradle-to-production gate), transported and distributed to Germany with use in heavy duty transport (cradle-to-grave). The life cycle stages (Figure 3) include:

- *Raw material extraction* that includes extraction and purification of water for the electrolyser, and air for nitrogen production. It also includes the raw materials for infrastructure and the energy needed for acquiring these raw materials.

- *Renewable electricity generation* from solar and wind resources.
- *Hydrogen production* through water electrolysis using renewable solar and wind energy sources, and *hydrogen storage*.
- *Nitrogen production* in an air separation unit and *nitrogen storage*.
- *Ammonia synthesis and ammonia storage*.
- *Transport of ammonia to Europe, cracking and distribution of hydrogen to refilling stations in Germany*.
- *Use hydrogen for transport (fuel-cell driven heavy-duty vehicles)*.

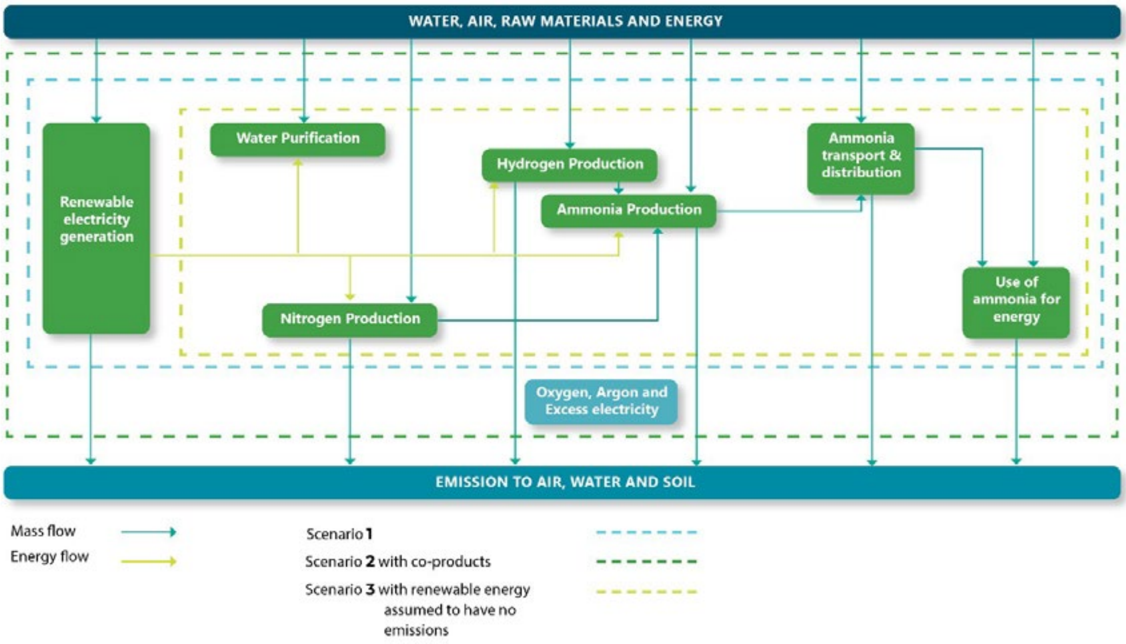

Figure 3: Scope and system boundary of the green ammonia production scenarios 1, 2, and 3

To compare impacts of GNH_3 to established conventional production, the reference fuels were grey ammonia (from natural gas, produced in Asia) and black ammonia (from coal, produced in South Africa).

1.4 The Product System

The product system is based on the Saldanha bay case study and entails all the inputs, resources and processes necessary to produce 280 Kt GNH_3 per annum. The ammonia plant needs to operate at a capacity factor above 95%, which requires the following configuration to achieve lowest cost: (i) an electrolyser oversizing of 100% relative to the ammonia plant; (ii) a renewable energy oversizing of 200% relative to the electrolyser; (iii) a solar fraction of 80% of total renewable energy installed capacity; (iv) an islanded electricity grid with battery storage to improve self-consumption and (v) connected to the national electricity grid to only allow the export of electricity (no import of electricity from the grid). In each case, the product was grid connected but operates in islanded mode to only allow electricity export and sales (no import or supply of electricity from the national grid).

Several scenarios were developed to explore the influence of key assumptions in the boundary and scope on the ammonia carbon emissions. In particular, the inclusion of oxygen as a valuable co-product sold to market, and the cut-off of renewable energy supply (solar and wind assumed zero carbon emissions) was investigated. An assessment with a methodology that has incomplete scope[9] (scope 1, 2 and partial scope 3) is proposed by the Hydrogen Production Analysis Task Force of the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE) whose 'Methodology for Determining the Greenhouse Gas Emissions Associated with the Production of Hydrogen' states: *"GHG impact of electricity used for H_2 production shall be restricted to Scope 1 and 2 emissions, and partial Scope 3 assumptions (not including emissions associated with manufacturing of power generation facilities). As a result of this assumption, the GHG impact of electricity generation from wind, solar photovoltaic, hydropower and geothermal will be assumed to be zero"* (IPHE 2023 and ISO/TS 19870, 2023). The rationale for this scope is that embodied emissions of solar PV and wind infrastructure is strongly influenced by the fossil energy used in manufacturing and, with the decarbonisation of energy systems, these capital infrastructure related emissions are set to decrease in the future. This methodology forms a recent ISO standard - ISO/TS 19870:2023(en):Hydrogen technologies-Methodology for determining the greenhouse gas emissions associated with the production, conditioning and transport of hydrogen to consumption gate[10].

In this study, GNH_3 production was compared to ammonia produced from natural gas and coal (grey and black ammonia, respectively). The GNH_3 production was modelled using scenarios with different boundary and scope, as detailed on the next page:

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[9] *Scope 1, scope 2 and scope 3 emissions are used to classify an organisation's greenhouse gas emissions. Scope 1 are direct emission that results from activities within an organisation; such as fuel combustion, manufacturing and process emissions. Scope 2 refers to indirect emissions from electricity, heat or steam that an organisation purchases and uses. Scope 3 emissions refers to indirect emissions that are a consequence of the company's activities, but do not occur from sources owned or controlled by that company.*

[10] *https://www.iso.org/obp/ui/en/#iso:std:iso:ts:19870:ed-1:v1:en*

- **Scenario 1** – Renewable energy (solar PV and wind power) to produce green hydrogen from electrolysis of seawater, and synthesis of green ammonia as the only product. The extended LCA includes transport of green ammonia to Europe, cracking to green hydrogen and distribution to Germany for powering fuel-cell driven transport.
- **Scenario 2** – Renewable energy (solar PV and wind power) for the production of green hydrogen from electrolysis of seawater, synthesis of green ammonia product and co-products of electricity, oxygen and argon. The extended LCA includes transport of green ammonia to Europe, cracking to green hydrogen and distribution to Germany for powering fuel-cell driven heavy-duty transport.
- **Scenario 3** – Renewable energy (solar PV and wind power) to produce green hydrogen from electrolysis of seawater, and synthesis of green ammonia as the only product. The embodied emissions associated with the capital infrastructure of the energy supply system is excluded (cut-off), and therefore renewable energy supply has zero emissions. This is the methodology for the certification of hydrogen as a low carbon fuel that is being developed into an international standard (ISO/TS 19870 2023 and IPHE 2023).

The extended LCA includes transport of green ammonia to Europe, cracking to green hydrogen and distribution to Germany for powering fuel-cell driven heavy-duty transport. The GNH$_3$ was assumed to be shipped from Saldanha bay to the port of Rotterdam (The Netherlands), cracked to produce green hydrogen, then compressed and distributed to Germany to power fuel-cell electric vehicles for heavy-duty transport.

Other assumptions:

- Assume global supply of technology and construction in South Africa. Therefore, material source from global (GLO) market and rest of world (RoW).
- The study includes all infrastructure, with the commissioning, operations and decommissioning, including waste treatment and recycling, as appropriate.
- Recycling of metals (Ni, Cu, Fe and Al) according to established practices and recycling rates in South Africa. The solar PV and wind infrastructure was not recycled as there is no established technology and recycling plants for these components.
- The cradle-to-grave assessment does not include recycling of the vehicle, nor does it include the construction and maintenance of road infrastructure.
- The nitrogen, produced from thermal decomposition (cracking) of green ammonia to hydrogen, was vented to the environment and not considered a co-product.
- The GWP of hydrogen was not included in the impact assessment as this is not an established GHG according to current IPCCC methodology[11].

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[11] *The latest research suggests that hydrogen is an indirect GHG. Compared to carbon dioxide, hydrogen is estimated to have 30 to 40 times more GWP over 20 years and an 8 to 12 greater GWP over 100-year period, see https://www.nature.com/articles/s43247-022-00626-z and https://www.sciencedirect.com/science/article/pii/S0360319922055380*

Chapter 2:

The Life Cycle Mode

2. The Life Cycle Model

2.1 The Life Cycle Inventories

The life cycle for the production and utilisation of GNH_3 were modelled using a combination of background datasets from the Ecoinvent database, adapted to represent the local context, when appropriate, and foreground datasets, that were built to represent specific production process and technologies. Details of processes are described below, with further details provided in the Supplementary information.

Renewable electricity: Renewable energy provided by wind and solar PV capacity is used to optimise the energy generation, reduce supply intermittency, and improve the overall capacity factor. A lithium-ion (Li-ion) battery is installed to provide backup power and further improve the availability of energy (Dai, *et al.* 2018 and 2019). Since the electrolysis unit is less sensitive to power fluctuations, the backup power functions to reduce the downtime of equipment need for water pumping and purification, hydrogen production and storage, air separation, nitrogen storage, ammonia synthesis and ammonia storage. The installed capacity of renewable electricity consists of 80% solar PV (1 515 MW) and 20% wind power (379 MW). Based on the availability of resources at this locality, the combined capacity factor is 26% with 4 311 GWh annual energy produced (of which 862 GWh are from wind and 3 449 GWh are from solar PV with vertical-tilted single-axis solar tracker). The renewable energy was transported from the inland site of electricity generation (Moorreesburg) to the coastal site of ammonia synthesis (Saldanha bay) by means of a 73 km long high voltage electrical transmission grid to convey 751 MW – a High Voltage Direct Current (DC) line or Alternating Current line of either 345 kilovolt (kV) or 765 kV (Miso, 2023). The waste heat from the ammonia synthesis presents an opportunity for electricity generation and dispatchable power, which can complement the intermittent power from wind and solar. Therefore, a power plant with a steam turbine to deliver 0.414 kilowatt hours (KWh) per kilogram of ammonia was added and this generates 116 GWh electricity annually. A utility-scale Li-ion battery, with 120 MW capacity requiring 242 GWh/year to assist with supplying continuous power to the ammonia synthesis unit and air separation unit, was included. The facility is connected to the national electricity grid and excess electricity generated (beyond the demand of the ammonia production) can supply 2 391 gigawatt hours (GWh)/year of electricity to the grid.

Water extraction and purification: Sea water reverse osmosis (SWRO) is the technology utilised for seawater desalination and the daily intake is 4 792 cubic metres (m^3)/day and output of 1 964 m^3/day reaching a recovery rate of 42% to meet the 473 000 m^3 annual water requirement for electrolysis and 82 000 m^3 for cleaning solar panels.

There is also an additional water requirement for cooling of the steam turbine power plant which is met through the reverse osmosis of seawater. Assuming evaporative (wet cooling) is the dominant technology, the water consumption is at least 1.4 litres per KWh electricity generated (WRC, 2021), which results in an additional annual water requirement of 162 kt or 162 000 m^3. The brine-rich wastewater is sent back to the same point of seawater extraction and discharged to sea.

Hydrogen production: Hydrogen production by electrolysis of water, was carried out in an Alkaline electrolyser with a concentrated solution of potassium hydroxide as the electrolyte. The electrolyser uses DC electrical energy and water molecules are reduced at the cathode to form hydrogen gas, while oxygen is generated at the anode. Alkaline electrolysers typically operate at 50-70°C to improve reaction kinetics and have a relatively high efficiency and long history of commercial use, making them suitable for industrial hydrogen production. Oxygen is either vented to the atmosphere or sold to market as a co-product.

Hydrogen storage: The standard storage option is purpose-built hydrogen storage tanks, which are pressurised to 20 megapascal (MPa). The hydrogen storage capacity is 152 tonnes (t), which equals to one day's hydrogen requirement for the ammonia plant to operate at rated capacity. The loss of hydrogen in storage was 0.1% per day (Andersen and Grönkvist 2019) which results in 52 t loss to the environment per annum.

Nitrogen production: The air separation unit separates atmospheric air into its main components, typically nitrogen (78.08%) and oxygen (20.95%), argon (0.93%) and other rare (0.04%) inert gases. Cryogenic separation technology was selected to produce nitrogen. The facility achieves an annual nitrogen production of 247 Kt (98% nitrogen and 2% argon) with an annual power demand of 60 GWh. This process requires tight integration of heat exchangers and separation columns to obtain a good efficiency. The primary process includes the following core steps (i) Ambient air filtration: Dust particles are removed using a filter (ii) Ambient air compression to 600 kilopascal (kPa) (iii) Purification by removal of H_2O and CO_2 (iii) Cooling to -173°C and (iv) Distillation of N_2 at 600 kPa and O_2 enriched air at 140 kPa.

Nitrogen storage: Nitrogen is at -173°C and 600 Kpa while the oxygen is vented to atmosphere. In the co-product scenarios, the oxygen and argon co-products are dried, compressed 20 MPa and stored for sale.

Ammonia synthesis: Ammonia synthesis takes place in a Haber-Bosch reactor using nitrogen and hydrogen gases and an iron catalyst. The gases are recycled in the reactor until a conversion of 97% is achieved. Purging is required to prevent the build-up of gases in the reactor, and this results in 0.0241% of the recycling stream or 16 kt being vented (the purged stream contains 66% nitrogen, 20% argon and 14% hydrogen) (Cheema and Krewer, 2018).

Ammonia storage: Ammonia is stored at -33°C and an atmospheric pressure in a single 150 000 m^3 storage tank and requires a pump station, a reliquification system for boil-off gas, a safety flare and a fire-fighting system (water tank – 10 000 to 15 000 m^3, water pumps for 500 to 800 m^3/h and foam generators). The ammonia was assumed to be stored for 5 days and with boil-off losses of 0.006% per day, which results in 84 t per annum of ammonia vented to the atmosphere. There is also leakage during pumping and storage of 0.02% per day, which results in 56 t per annum of ammonia leaked, which evaporates to the atmosphere (Boero *et al*. 2021).

Ammonia transport and cracking: The ammonia was assumed to be shipped from Saldanha bay to the port of Rotterdam, which is 13 430 km away (Ports.com, 2021). Upon arrival, the ammonia would be reconverted to GH_2 via ammonia cracking, resulting in a 15% loss of hydrogen (Giddey *et al*., 2017).

Green Hydrogen distribution to refilling station (end user): The GH_2 was compressed to a refuelling pressure of 44 MPa. The total energy requirement for the compression was 2.7 kWh/kg of GH_2, and it would be supplied by German grid electricity (Giddey *et al*., 2017). The GH_2 in high pressure cylinders (aluminium body, carbon-fibre wrapped, Patterson *et al*. 2013), was distributed to refuelling stations in major German cities, using Euro 6 heavy-duty trucks with a diesel consumption of 0.0192 kg/tkm (Ecoinvent 2023) and assuming a 450 km average transport distance. Further, with an estimated GH_2 storage of 14 days, and a loss of hydrogen of 0.1% per day (Andersen and Grönkvist 2019), the estimated annual loss of hydrogen in distribution was 1.4% or 592 tonnes.

End use by heavy duty fuel cell vehicles: These heavy duty, fuel-cell electric vehicles (FCEV) are trucks that use GH_2 as fuel to generate electricity for the vehicle's powertrain, with water as the main tailpipe emission. FCEV are a solution to decarbonise the hard-to-abate sectors of heavy-duty trucking, international shipping, and international aviation.

Recycling of infrastructure: The recycling of materials can also be seen as a multi-functional process with waste treatment needed to produce recyclate as a valuable secondary material. The recycling at end-of-life for valuable metals from copper in the electricity transmission line and other electrical components, aluminium in solar PV and other infrastructure, nickel in the electrolyser, and iron in steel infrastructure components was carried out using closed-loop approximation since these metals are recycled without changes in the properties of the material (ISO, 2006).

The process details for GNH_3 production is shown in the Process Flow Diagram that depicts the mass and energy balance (Figure 4).

This study used the APOS (Allocation at Point of Substitution) economic system model. For the production of co-products (scenario 3), energy-based allocation could not be applied since oxygen and argon have no energy value. Therefore, mass-based allocation amongst electricity, argon and oxygen co-products was applied; with the electricity converted to mass using the primary coal demand of national electricity supply company (thermoelectric power plant efficiency of 35%, Eskom, 2021). Mass-based allocation was used instead of economic allocation, since the proportions of the co-products is physically constrained by the production system and cannot be adjusted according to market conditions. In addition, the markets for GH_2/GNH_3 are not yet well-established and the prices uncertain, and also there is uncertainty in the market size and price elasticity of the oxygen and argon co-products.

To compare GH_2/GNH_3 to the current business-as-usual fossil fuels, ammonia produced from coal and ammonia produced natural gas were used (Ecoinvent, 2023); namely:

Ammonia, anhydrous, liquid {ZA}| synthetic fuel production, from coal, high temperature Fisher-Tropsch operations | APOS, U. The synthetic fuels production from coal in South Africa (ZA). This data includes the mining of coal and converting it into synthetic fuels and chemicals through proprietary Fischer-Tropsch technology by Sasol- the largest synfuels producer in and the world, with an annual production of 23 835 m^3/day of crude oil equivalent.

Ammonia, anhydrous, liquid {UN-OCEANIA} |ammonia production, steam reforming, liquid | APOS, U. The production of liquid ammonia using the steam reforming of natural gas from the Oceania region comprising Australia, New Zealand and Pacific. About 85% of the world ammonia production is using steam reforming of natural gas technology.

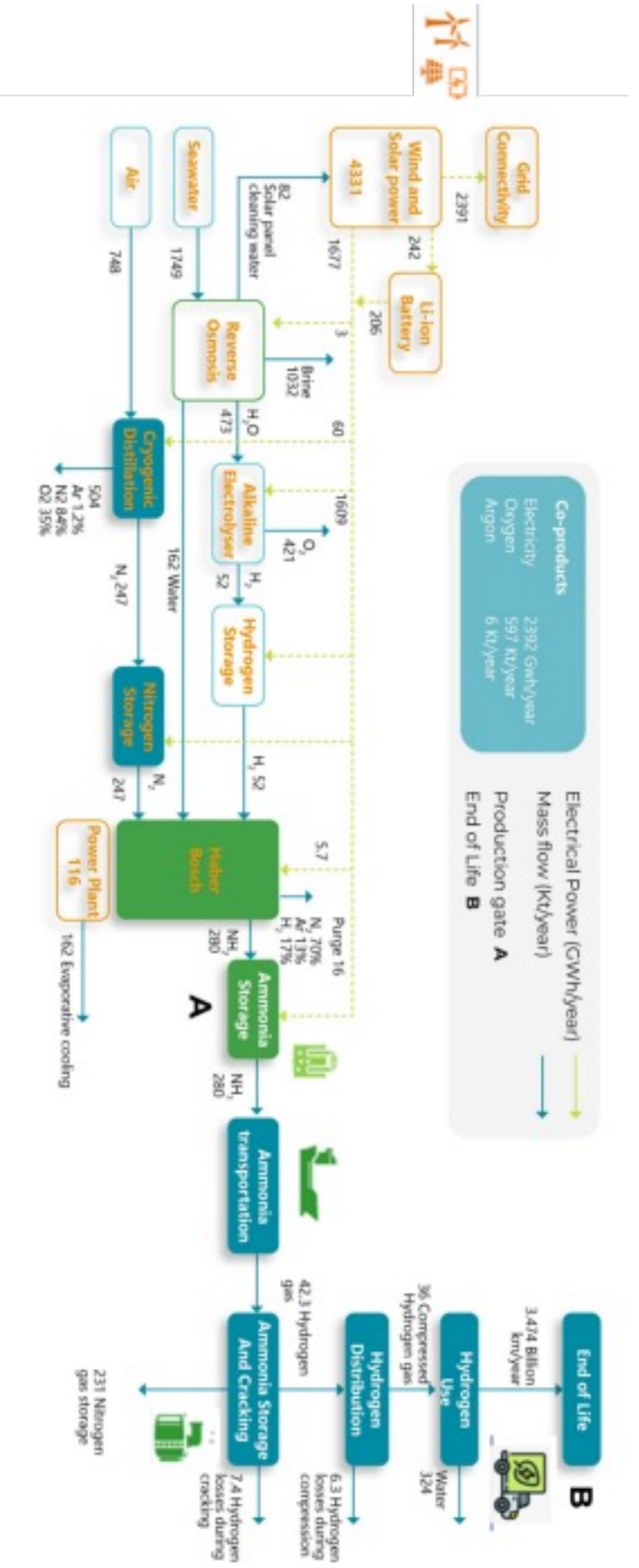


Figure 4: Process flow diagrams showing GNH3 production at Saldanha bay, export to Europe and distribution for use in German heavy duty transport

2.2 Impact Assessment method

The ISO standards do not recommend specific Life Cycle Impact Assessment (LCIA) methods but requires the chosen method to be an internationally accepted one for comparative purposes. For this study, the widely accepted ReCiPe method was chosen, as this method enables a wide spectrum of environmental impacts to be considered. ReCiPe has mid-point impact indicators, end-point damage indicators, and a single score that represents the total environment impacts (ReCiPe, 2016; Huijbregts *et al.*, 2017; Goedkoop *et al.*, 2009) as shown in Figure 5 and Table 1.

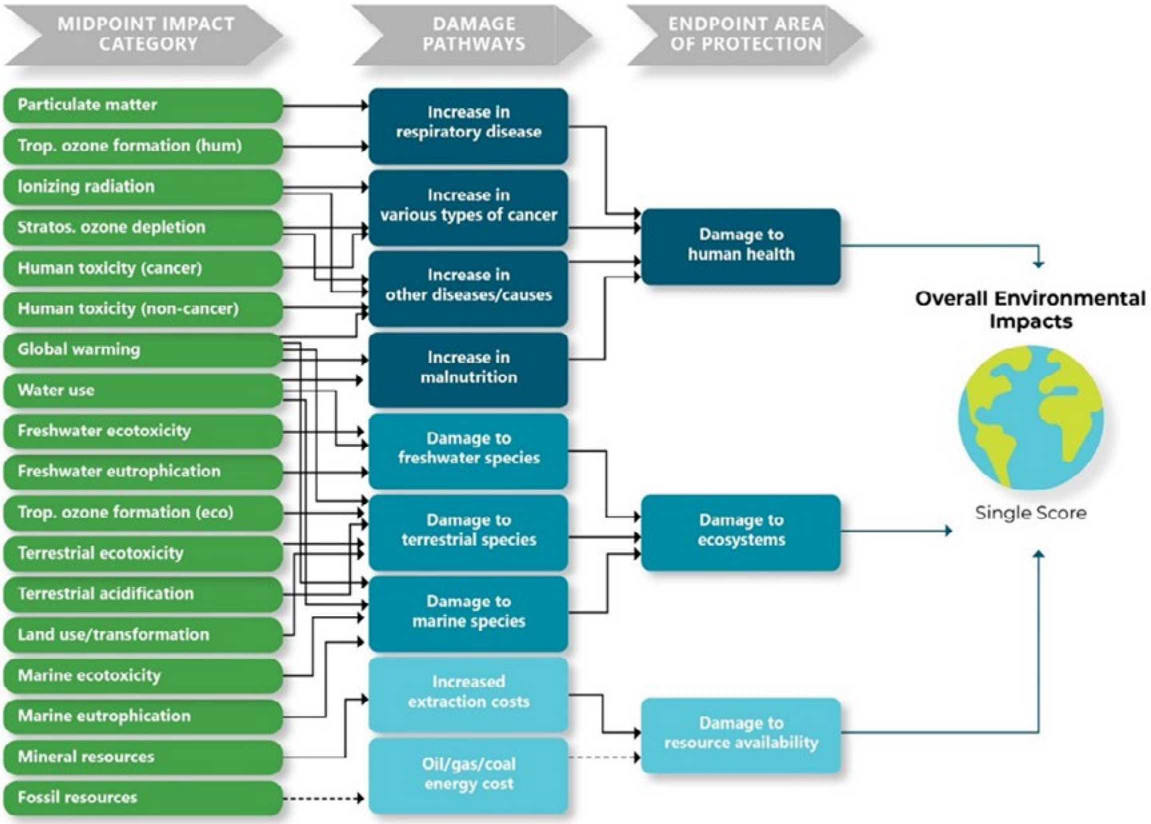


Figure 5: Overview of the impact categories that are covered in the ReCiPe 2016 methodology and their relation to the areas of protection (Huijbregts et al., 2016).

Table 1: ReCiPe 2016 Mid-point, Endpoint and Single Score

Mid-point indicator	Unit	Description
Global Warming Potential	Carbon Dioxide equivalent (Kg CO_2-eq)	Contributions to climate change, primarily through emissions such as CO_2, CH_4, N_2O, etc.
Stratospheric Ozone Depletion	Chlorofluorocarbon-11 equivalent (Kg CFC11-eq)	Damage to the ozone layer from emissions of Chlorofluorocarbons (CFCs), Hydrochlorofluorocarbons (HCFCs), etc., critical for filtering ultraviolet radiation
Ionizing Radiation	Cobalt-60 equivalent (KBq Co-60-eq)	Human and ecosystem exposure to ionizing radiation from emissions
Ozone Formation, Human Health	Nitrogen Oxide equivalent (Kg NOx-eq)	Emissions contributing to ground-level ozone formation affecting respiratory health
Fine Particulate Matter Formation	Particulate Matter <2.5µm (Kg PM2.5-eq)	Emissions of fine particulates causing respiratory and cardiovascular diseases
Ozone Formation, Terrestrial Ecosystem	Nitrogen Oxide equivalent (Kg NOx-eq)	Impact of ground-level ozone on terrestrial ecosystems, including vegetation and biodiversity damage
Terrestrial Acidification	Sulphur Dioxide equivalent (Kg SO_2-eq)	Impacts of acidifying pollutants (SO_2, NOx) on soil and forest ecosystems
Freshwater Eutrophication	Phosphorous equivalent (Kg P-eq)	Measures nutrient (mainly phosphorus) runoff into freshwater bodies causing algae growth and oxygen depletion
Marine Eutrophication	Nitrogen equivalent (Kg N-eq)	Nutrient (mainly nitrogen) runoff into marine environments, which effects water quality
Terrestrial Ecotoxicity	1,4- dichlorobenzene equivalent (Kg 1,4-DCB-eq)	Toxic chemical effects on terrestrial ecosystems, using a comparative toxic unit approach
Freshwater Ecotoxicity	1,4- dichlorobenzene equivalent (Kg 1,4-DCB-eq)	Toxic impacts on freshwater ecosystems, using a comparative toxic unit approach

Mid-point indicator	Unit	Description
Marine Ecotoxicity	1,4- dichlorobenzene equivalent (Kg 1,4-DCB-eq)	Toxic impacts on marine ecosystems, using the same comparative toxic unit approach
Human Carcinogenic Toxicity	1,4- dichlorobenzene equivalent (Kg 1,4-DCB-eq)	Chemicals causing cancer in humans, using comparative toxic units based on known carcinogens
Human Non-Carcinogenic Toxicity	1,4- dichlorobenzene equivalent (Kg 1,4-DCB-eq)	Chemicals to causing non-carcinogenic health effects in humans, like reproductive toxicity
Land use	Square metre per year crop equivalent (m^2/a crop-eq)	Impacts on biodiversity and ecosystem services due to land occupation and transformation, comparing quality and area of land before and after use
Mineral Resources Scarcity	Copper equivalent (Kg Cu-eq)	Evaluates the depletion of abiotic resources (minerals and metals) based on extraction rates versus crustal reserves or concentration
Fossil Resource Scarcity	Oil equivalent (Kg oil-eq)	Depletion of fossil fuels, considering extraction rates in relation to available reserves
Water Consumption	Cubic metres(m^3)	Impacts of water use, considering the volume consumed and local water scarcity

End point indicator	Unit	Area of Protection	Description of impact category
Human Health	DALY	Disability-Adjusted Life Years. One DALY represents the loss of the equivalent of one year of full health	Impacts to human health, expressed in terms of loss of productivity and disability adjusted life years
Ecosystems	Species*yr	Actual species lost per year, based on species density and PDF (Potential Disappeared Fraction of species)	Impacts to ecosystems expressed in terms of biodiversity loss
Resources	USD	US dollars ($)	Impacts to resources that can lead to resource depletion when resources are finite and non-renewable

Single Score	Unit	Total environment impacts	Description of impact category
Single score of total environment impacts	Pt	Points	Total environment impacts

There are different social perspectives and corresponding weighting approaches available in ReCiPe 2016: (a) *Individualist*, which is based on short-term interests, impact types that are undisputed, and technological optimism; (b) *Hierarchist*, which is based on the most common and widely accepted policy principles with regards to time-frame and other issues; and (c) *Egalitarian*, which is precautionary with the longest time-frame and considers impact types that may be disputed.

The results in this study are presented from the perspective of the Hierarchist mid-point, endpoint, and single score. The single score, expressed in points, is calculated by normalisation and weighting of the end-point damage categories of human health, ecosystems, and resources to provide an estimate the total environmental impacts, as shown in Table 2.

Table 2: ReCiPe End Point, Normalisation and Weighting values (World 2010) with Endpoint weighting (H/A)

Damage Category	Normalisation	Weighting
Human Health (HH)	42.1	400
Ecosystems (ES)	1396	400
Resources (RES)	0.0000357	200

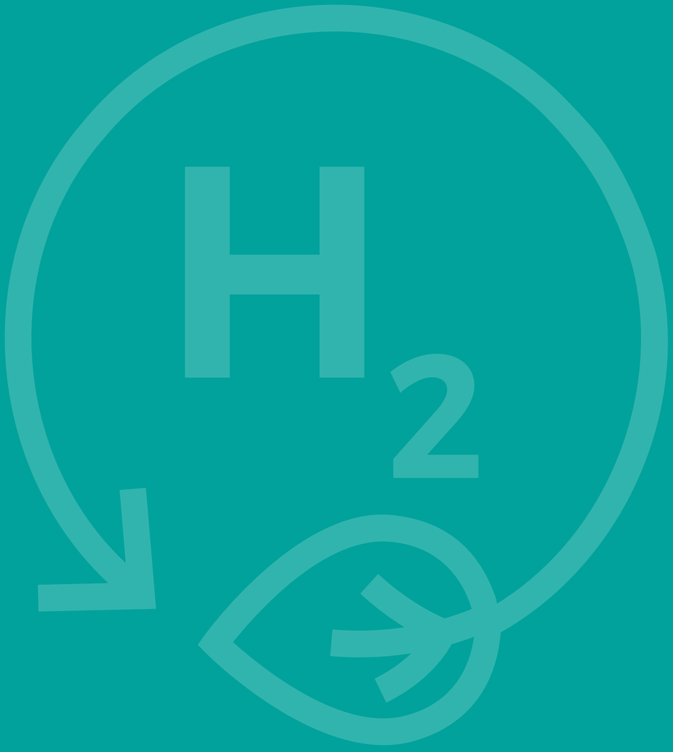
The absolute value for the environmental impacts is given in the report to accurately determine differences. To compare GNH_3, black NH_3 and grey NH_3 across all impact categories (Heatmap), the average percentage difference method was used since the scale is symmetrical and this more fairly represents the data for a comparative analysis.

Average %difference GNH_3 compared to black NH_3= $\frac{\text{Impact of Green NH3} - \text{Impact of Black NH3}}{(\text{Impact of Green NH3} + \text{Impact of Black NH3})/2} * 100$

Average %difference GNH_3 compared to grey NH_3 = $\frac{\text{Impact of Green NH3} - \text{Impact of Grey NH3}}{(\text{Impact of Green NH3} + \text{Impact of Grey NH3})/2} * 100$

Chapter 3:

Life Cycle Impact Assessment results



3. Life Cycle Impact Assessment results

The study reports on lifecycle impacts of: (A) full fuel lifecycle (cradle-to-grave) and (B) fuel production lifecycle (cradle-to-production gate). Although all impact categories were analysed, there is a focus on GHG and the GWP impact category to improve the understanding of production pathways that can provide low-carbon fuels to achieve global carbon emissions reduction targets in the transport sector. Depending on this boundary and lifecycle stage reported, the results of carbon emissions (carbon dioxide equivalents, CO_2-eq) are expressed in kg CO_2-eq per kg ammonia (product) and kg CO_2 per MJ energy as well as kg CO_2 per km in order to enable effective communication and comparison of results and proposed thresholds set by hydrogen certification bodies or national policy.

3.1 Part A: CRADLE-TO-PRODUCTION GATE

The cradle-to-production gate LCIA results using ReCiPe mid-point impact categories were used to compare GNH_3 to black ammonia and grey ammonia. The results expressed as the percentage difference of GNH_3 and compared to the reference of black and grey ammonia. The following sections provides details of these comparisons across all impact categories and scenarios.

3.1.1 GHG emissions and global warming potential

The GWP was 0.790 kg CO_2-eq/kg ammonia (scenario 1), 0.276 kg CO_2-eq/kg (scenario 2) and 0.106 kg CO_2-eq/kg ammonia or 0.598 CO_2eq/kg hydrogen, based on hydrogen content of ammonia (scenario 3). The production of GNH_3 achieves >70% decrease in GHG emissions compared to grey ammonia from natural gas (2.33 CO_2-eq/kg ammonia), or black ammonia from coal (5.831 kg CO_2-eq/kg ammonia), and therefore is below the threshold for the certification of GNH_3 as a low carbon fuel. The European EU-REDII and German TÜV SÜD schemes specify 70% reduction compared to reference fossil fuel of 94 gCO_2eq/MJ; which is 3.4 kg CO_2-eq/kg GH_2; or 0.61 kg CO_2-eq/kg GNH_3, based on the hydrogen content of ammonia (See Table 8 in Appendix for further details of certification schemes).

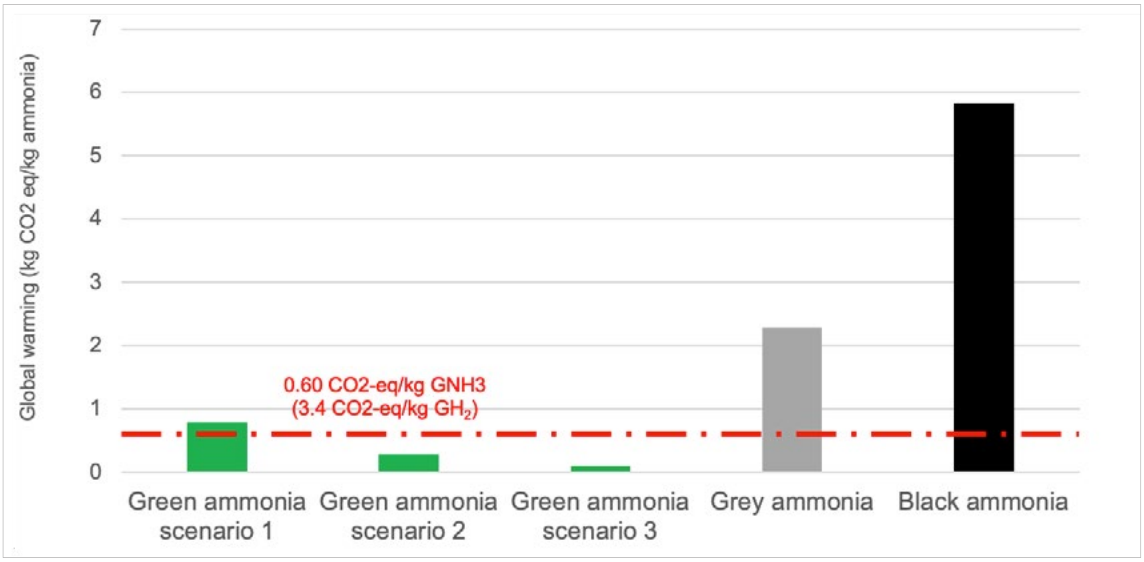


Figure 6: Carbon emissions from cradle-to-production gate of green ammonia. The carbon thresholds of 3.4 kg CO_2/kg GH_2 European EU-REDII and EU-RED II and TÜV SÜD schemes is shown (dashed line). (See Supplementary information)

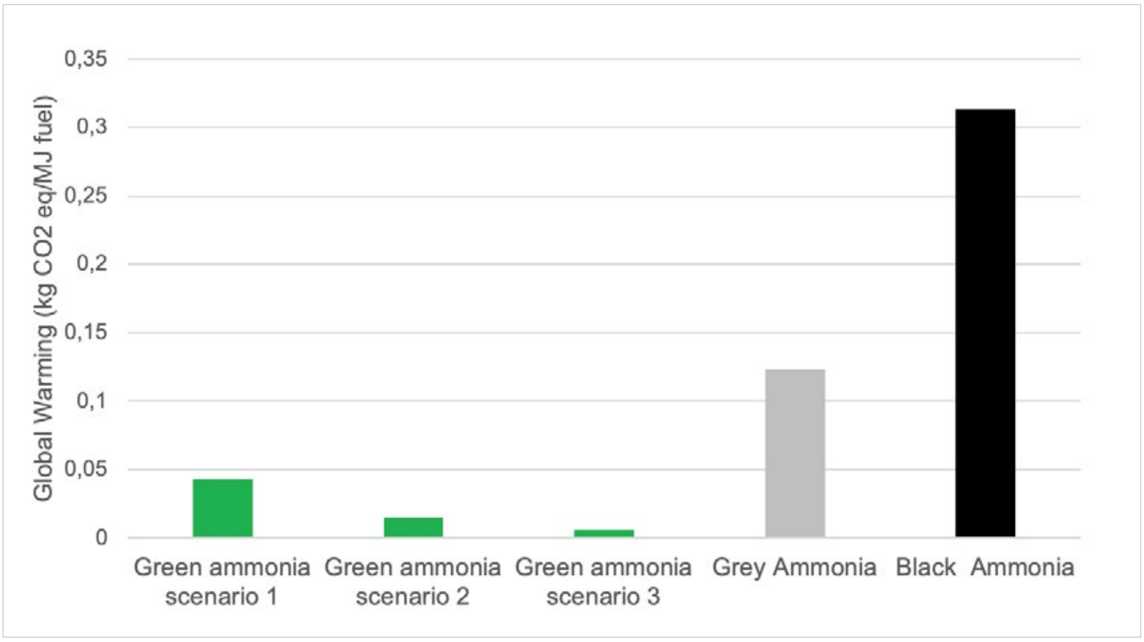


Figure 7: Carbon emissions from cradle-to-production gate in terms of energy intensity

3.1.2 Other environmental impacts

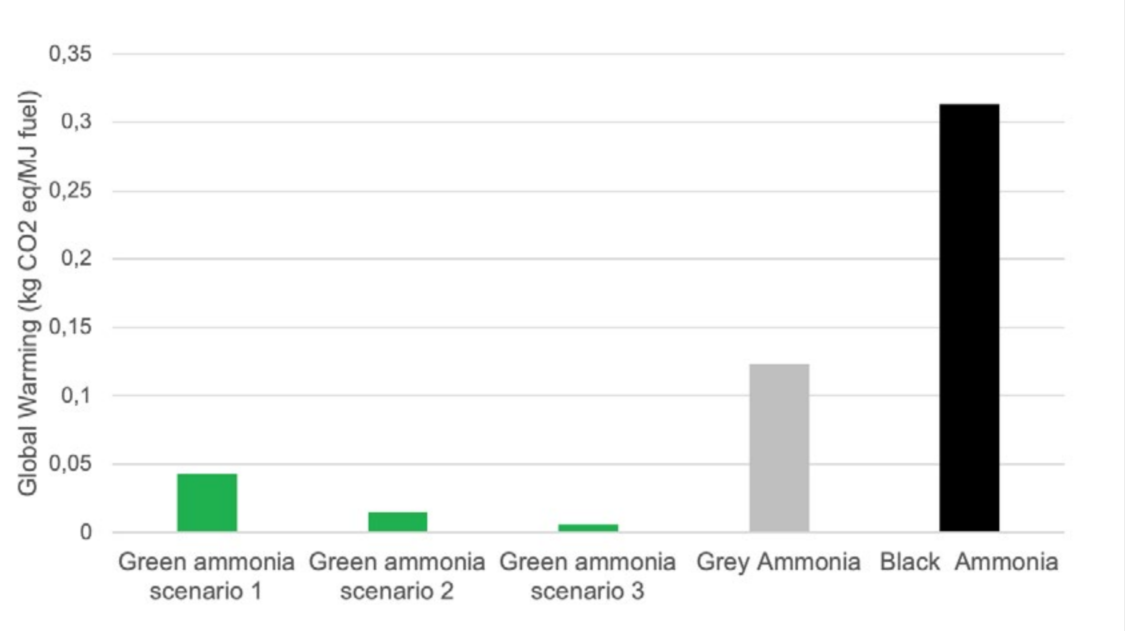


Figure 8: Ionising radiation

Ionising radiation potential impacts:

Compared to black ammonia ionising radiation potential (5.57x10^{-2} KBq Co 60-eq/kg ammonia), GNH$_3$ shows a decrease for scenario 1 (4.81x10^{-2} KBq Co 60-eq/kg ammonia), a decrease for scenario 2 (1.65x10^{-2} KBq Co 60-eq/kg ammonia) and decrease for scenario 3 (0.54x10^{-2} KBq Co 60-eq/kg ammonia). Compared to grey ammonia ionising radiation potential (1.20x10^{-2} KBq Co 60-eq/kg ammonia), GNH$_3$ shows an increase for scenario 1 (4.81x10^{-2} KBq Co 60-eq/kg ammonia), a decrease for scenario 2 (1.65x10^{-2} KBq Co 60-eq/kg ammonia) and decrease for scenario 3 (0.54x10^{-2} KBq Co 60-eq/kg ammonia).

Stratospheric ozone depletion potential impacts:

Compared to black ammonia stratospheric ozone depletion potential (2.99X10^{-6} Kg CFC11-eq/kg ammonia), GNH$_3$ shows a decrease for scenario 1 (0.34x10^{-6}Kg CFC11-eq/kg ammonia), a decrease for scenario 2 (0.12X10^{-6}Kg CFC11-eq/kg ammonia) and decrease for scenario 3 (0.06x10^{-6}Kg CFC11-eq/kg ammonia). Compared to grey ammonia stratospheric ozone depletion potential (0.28X10^{-6}Kg CFC11-eqkg ammonia), GNH$_3$ shows an increase for scenario 1 (0.34x10-6Kg CFC11-eq /kg ammonia), a decrease for scenario 2 (0.12X10^{-6}Kg CFC11-eq/kg ammonia) and decrease for scenario 3 (0.06x10^{-6}Kg CFC11-eq/kg ammonia).

Ozone formation human health potential impacts:

Compared to black ammonia ozone formation, human health potential (1.77x10^{-2}Kg NOx-eq/kg ammonia), GNH$_3$ shows a decrease for scenario 1 (0.23x10^{-2}Kg NOx-eq/kg ammonia), a decrease for scenario 2 (0.08x10^{-2}Kg NOx-eq/kg ammonia) and decrease for scenario 3 (0.04x10^{-2}kg NOx-eq /kg ammonia). Compared to grey ammonia ozone formation, human health potential (0.17x10^{-2}kg NOx-eq)/kg ammonia), GNH$_3$ shows an increase for scenario 1 (0.23x10^{-2}Kg NOx-eq/kg ammonia), a decrease for scenario 2 (0.08x10^{-2}Kg NOx-eq/kg ammonia) and decrease for scenario 3 (0.04x10^{-2}kg NOx-eq/kg ammonia).

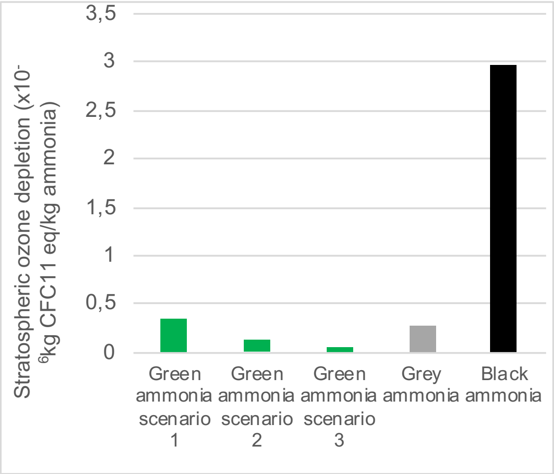


Figure 9: Stratospheric ozone depletion impacts

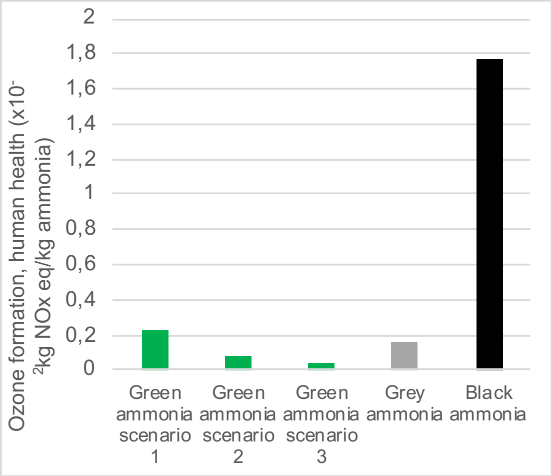


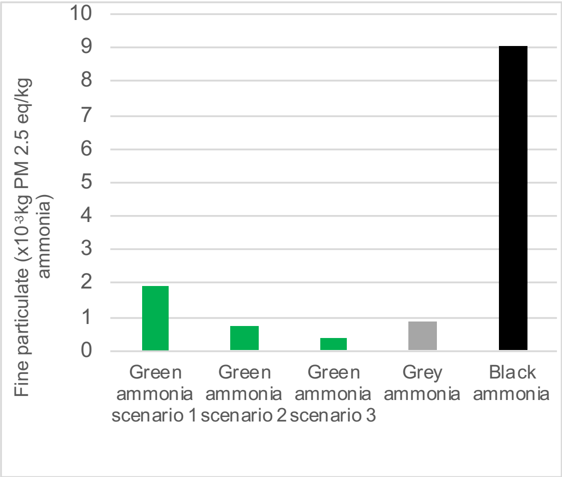
Figure 10: Ozone formation, human health impacts

Particulate formation potential impacts:

Compared to black ammonia particulate formation potential (9.08x10-^{3}Kg PM2.5-eq/kg ammonia), GNH$_3$ shows a decrease for scenario 1 (1.95x10^{-3}Kg PM2.5-eq/kg ammonia), a decrease for scenario 2 (0.70x10^{-3}Kg PM2.5-eq/kg ammonia) and decrease for scenario 3 (0.35x10^{-3}Kg PM2.5-eq)/kg ammonia). Compared to grey ammonia ozone formation, human health potential (0.000829 PM2.5-eq/kg ammonia), GNH$_3$ shows an increase for scenario 1 (1.95x10^{-3}Kg PM2.5-eq)/kg ammonia), a decrease for scenario 2 (0.70x10^{-3}Kg PM2.5-eq)/kg ammonia) and decrease for scenario 3 (0.35x10^{-3}Kg PM2.5-eq)/kg ammonia).

Ozone formation terrestrial ecosystems potential impacts:

Compared to black ammonia ozone formation terrestrial ecosystems potential (1.78x10^{-2}Kg NOx-eq)/Kg ammonia), GNH$_3$ shows a decrease for scenario 1 (0.23x10^{-2}Kg NOx-eq)/Kg ammonia), a decrease for scenario 2 (0.08x10^{-2}Kg NOx-eq)/Kg ammonia) and decrease for scenario 3 (0.04x10^{-2}Kg NOx-eq)/kg ammonia). Compared to grey ammonia ozone formation terrestrial ecosystems potential (0.18x10^{-2}Kg NOx-eq/Kg ammonia), GNH₃ shows an increase for scenario 1 (0.23x10^{-2}Kg NOx-eq)/Kg ammonia), a decrease for scenario 2 (0.08x10^{-2}Kg NOx-eq)/Kg ammonia) and decrease for scenario 3 (0.04x10^{-2}Kg NOx-eq)/Kg ammonia).



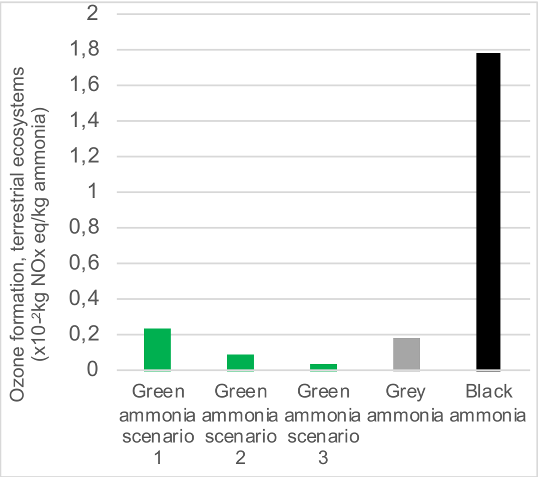


Figure 11: Fine particulate matter formation environmental impacts

Figure 12: Ozone formation, terrestrial ecosystems environmental impacts

Terrestrial acidification potential impacts:

Compared to black ammonia terrestrial acidification potential (2.97x10^{-2}Kg SO_2-eq/Kg ammonia), GNH₃ shows a decrease for scenario 1 (0.45x10^{-2}Kg SO_2-eq)/Kg ammonia), a decrease for scenario 2 (0.16x10^{-2}Kg SO_2-eq /Kg ammonia) and decrease for scenario 3 (0.10x10^{-2}Kg SO_2-eq/kg ammonia). Compared to grey ammonia terrestrial acidification potential (0.24x10^{-2}Kg SO_2-eq/Kg ammonia), GNH₃ shows an increase for scenario 1 (0.45x10^{-2}Kg SO_2-eq/Kg ammonia), a decrease for scenario 2 (0.16x10^{-2}Kg SO_2-eq)/Kg ammonia) and decrease for scenario 3 (0.10x10^{-2}Kg SO_2-eq/Kg ammonia).

Freshwater eutrophication potential impacts:

Compared to black ammonia freshwater eutrophication potential (4.68x10^{-3}Kg P-eq/Kg ammonia), GNH₃ shows a decrease for scenario 1 (0.49x10^{-3}Kg P-eq/Kg ammonia), a decrease for scenario 2 (0.18x10^{-3}Kg P-eq /Kg ammonia) and decrease for scenario 3 (0.10X10^{-3}Kg P-eq/kg ammonia). Compared to grey ammonia freshwater eutrophication potential (0.09x10^{-3}Kg P-eq/Kg ammonia), GNH₃ shows an increase for scenario 1 (0.49x10^{-3}Kg P-eq)/Kg ammonia), an increase for scenario 2 (0.18x10^{-3}Kg P-eq/Kg ammonia) and increase for scenario 3 (0.10X10^{-3}Kg P-eq/Kg ammonia).

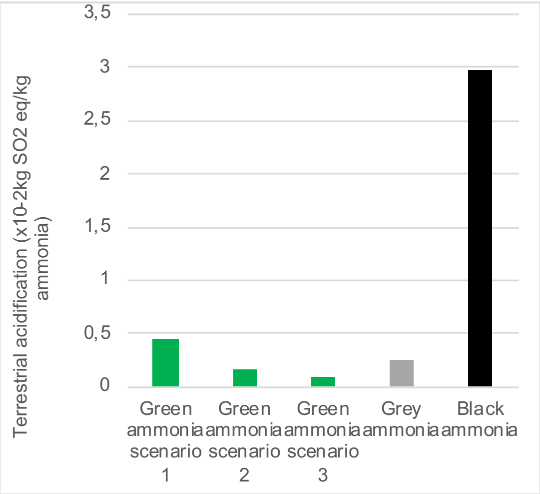


Figure 13: Terrestrial acidification environmental impacts

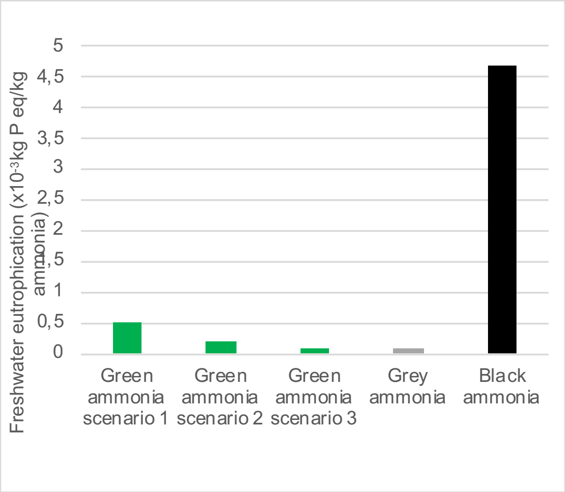


Figure 14: Freshwater eutrophication potential impacts

Marine eutrophication potential impacts:

Compared to black ammonia marine eutrophication potential (2.95x10^{-4}Kg N-eq/Kg ammonia), GNH$_3$ shows a decrease for scenario 1 (0.44x10^{-04}Kg N-eq/Kg ammonia), a decrease for scenario 2 (0.15x10^{-4}Kg N-eq/Kg ammonia) and decrease for scenario 3 (0.07x10^{-4}Kg N-eq/kg ammonia). Compared to grey ammonia marine eutrophication potential (0.08x10^{-4}Kg N-eq/Kg ammonia), GNH$_3$ shows an increase for scenario 1 (0.44x10^{-04}Kg N-eq/Kg ammonia), an increase for scenario 2 (0.15x10^{-4}Kg N-eq/Kg ammonia) and decrease for scenario 3 (0.07x10^{-4}Kg N-eq/Kg ammonia).

Terrestrial ecotoxicity potential impacts

Compared to black ammonia terrestrial ecotoxicity potential (2.01x10^{-1}Kg 1,4-DCB-eq/Kg ammonia), GNH$_3$ shows a decrease for scenario 1 (1.99x10^{-1}Kg 1,4-DCB-eq/Kg ammonia), a decrease for scenario 2 (0.70x10^{-1}Kg 1,4-DCB-eq/Kg ammonia) and decrease for scenario 3 (0.29x10^{-1}Kg 1,4-DCB-eq/kg ammonia). Compared to grey ammonia terrestrial ecotoxicity potential (0.32x10^{-1}Kg 1,4-DCB-eq /Kg ammonia), GNH$_3$ shows an increase for scenario 1 (1.99x10^{-1}Kg 1,4-DCB-eq/Kg ammonia), an increase for scenario 2 (0.70x10^{-1}Kg 1,4-DCB-eq/Kg ammonia) and decrease for scenario 3 (0.29x10^{-1}Kg 1,4-DCB-eq/Kg ammonia).

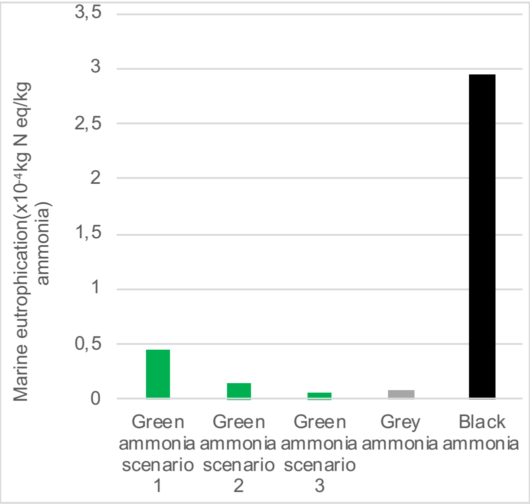


Figure 15: Marine eutrophication environmental impacts

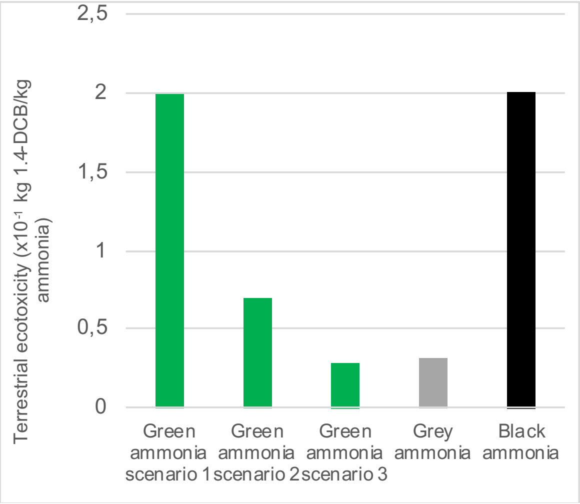


Figure 16: Terrestrial ecotoxicity environmental impacts

Freshwater ecotoxicity potential impacts:

Compared to black ammonia freshwater ecotoxicity potential ($2.76x10^{-2}$Kg 1,4-DCB-eq/Kg ammonia), GNH_3 shows a decrease for scenario 1 ($0.67x10^{-2}$Kg 1,4-DCB-eq/Kg ammonia), a decrease for scenario 2 ($0.23x10^{-2}$Kg 1,4-DCB-eq/Kg ammonia) and decrease for scenario 3 ($0.09x10^{-2}$Kg 1,4-DCB-eq/kg ammonia). Compared to grey ammonia freshwater ecotoxicity potential ($0.08x10^{-2}$Kg 1,4-DCB-eq /Kg ammonia), GNH_3 shows an increase for scenario 1 ($0.67x10^{-2}$Kg Kg 1,4-DCB-eq/Kg ammonia), an increase for scenario 2 ($0.23x10^{-2}$Kg 1,4-DCB-eq/Kg ammonia) and increase for scenario 3 ($0.09x10^{-2}$Kg 1,4-DCB-eq/Kg ammonia).

Marine ecotoxicity potential impacts:

Compared to black ammonia marine ecotoxicity potential ($3.88x10^{-2}$Kg 1,4-DCB-eq/Kg ammonia), GNH_3 shows a decrease for scenario 1 ($0.95x10^{-2}$Kg 1,4-DCB-eq/Kg ammonia), a decrease for scenario 2 ($0.33x10^{-2}$Kg 1,4-DCB-eq/Kg ammonia) and decrease for scenario 3 ($0.12x10^{-2}$Kg 1,4-DCB-eq/kg ammonia). Compared to grey ammonia marine ecotoxicity potential ($0.11x10^{-2}$Kg 1,4-DCB-eq /Kg ammonia), GNH_3 shows an increase for scenario 1 ($0.95x10^{-2}$Kg 1,4-DCB-eq/Kg ammonia), an increase for scenario 2 ($0.33x10^{-2}$Kg 1,4-DCB-eq/Kg ammonia) and increase for scenario 3 ($0.12x10^{-2}$ Kg 1,4-DCB-eq/Kg ammonia).

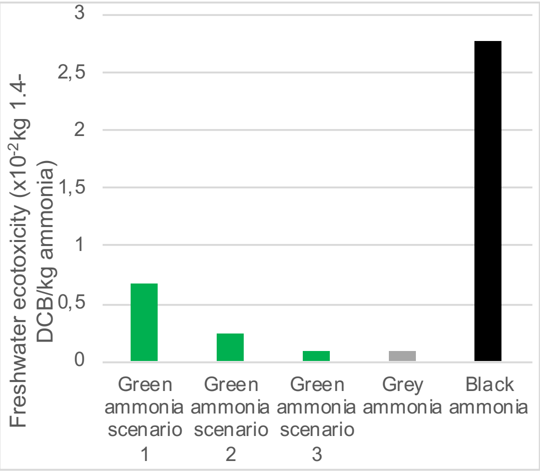


Figure 17: Freshwater ecotoxicity environmental impacts

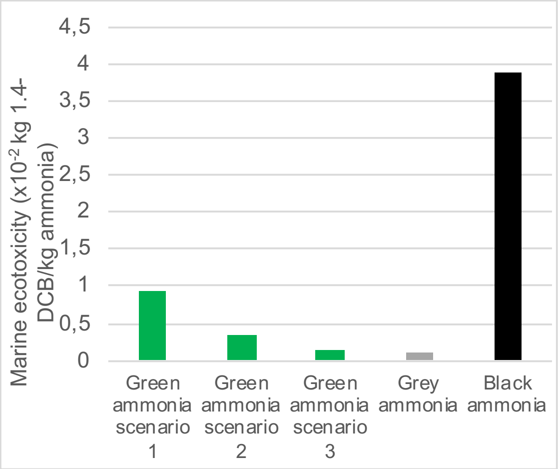


Figure 18: Marine ecotoxicity environmental impacts

Human carcinogenic toxicity potential impacts:

Compared to black ammonia human carcinogenic toxicity potential ($2.50x10^{-4}$Kg 1,4-DCB-eq/Kg ammonia), GNH$_3$ shows an increase for scenario 1 ($3.18x10-^{4}$Kg 1,4-DCB-eq/Kg ammonia), a decrease for scenario 2 ($1.14x10^{-4}$Kg 1,4-DCB-eq/Kg ammonia) and decrease for scenario 3 ($0.60X10^{-04}$Kg 1,4-DCB-eq/kg ammonia). Compared to grey ammonia human carcinogenic toxicity potential ($1.84x10^{-4}$Kg 1,4-DCB-eq /Kg ammonia), GNH$_3$ shows an increase for scenario 1 ($3.18x10^{-4}$Kg 1,4-DCB-eq/Kg ammonia), a decrease for scenario 2 ($1.14x10^{-4}$Kg 1,4-DCB-eq/Kg ammonia) and decrease for scenario 3 ($0.60X10^{-04}$Kg 1,4-DCB-eq/Kg ammonia).

Human non-carcinogenic toxicity potential impacts:

Compared to black ammonia human non-carcinogenic toxicity potential ($1.03x10^{-1}$Kg 1,4-DCB-eq/Kg ammonia), GNH$_3$ shows a decrease for scenario 1 ($0.46x10^{-1}$Kg 1,4-DCB-eq/Kg ammonia), a decrease for scenario 2 ($0.16x10^{-1}$Kg 1,4-DCB-eq/Kg ammonia) and decrease for scenario 3 ($0.09x10^{-1}$Kg 1,4-DCB-eq/kg ammonia). Compared to grey ammonia human non-carcinogenic toxicity potential ($0.08x10^{-1}$Kg 1,4-DCB-eq /Kg ammonia), GNH$_3$ shows an increase for scenario 1 ($0.46x10^{-1}$Kg 1,4-DCB-eq/Kg ammonia), an increase for scenario 2 ($0.16x10^{-1}$Kg 1,4-DCB-eq/Kg ammonia) and increase for scenario 3 ($0.09x10^{-1}$Kg 1,4-DCB-eq/Kg ammonia).

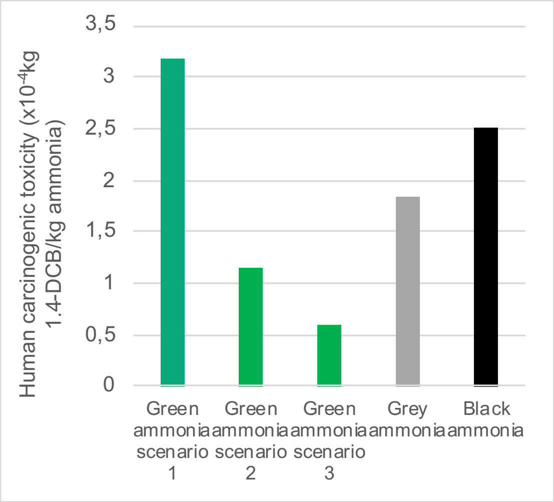


Figure 19: Human carcinogenic toxicity potential impacts

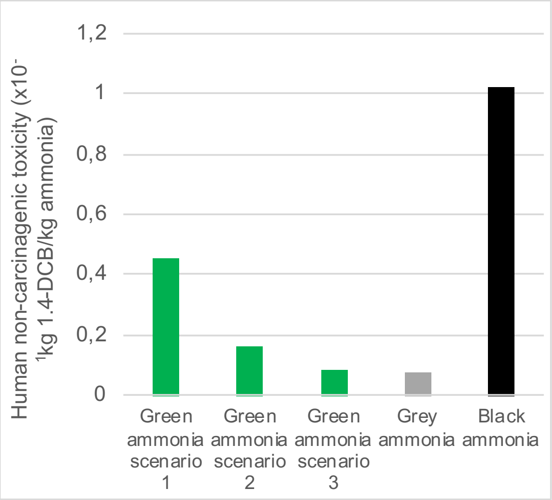


Figure 20: Human non-carcinogenic toxicity environmental impacts

Land use potential impacts:

Compared to black ammonia land use potential ($0.93x10^{-1}m^2/a$ crop-eq/Kg ammonia), GNH_3 shows an increase for scenario 1 ($2.60x10^{-1}m^2/a$ crop-eq/Kg ammonia), a decrease for scenario 2 ($0.86x10^{-1}m^2/a$ crop-eq/Kg ammonia) and decrease for scenario 3 ($0.08x10^{-1}m^2/a$ crop-eq/kg ammonia). Compared to grey ammonia land use potential ($0.15x10^{-1}m^2/a$ crop-eq/Kg ammonia), GNH_3 shows an increase for scenario 1 ($2.60x10^{-1}m^2/a$ crop-eq /Kg ammonia), an increase for scenario 2 ($0.86x10^{-1}m^2/a$ crop-eq//Kg ammonia) and decrease for scenario 3 ($0.08x10^{-1}m^2/a$ crop-eq /Kg ammonia).

Mineral resource scarcity potential impacts:

Compared to black ammonia mineral resource scarcity potential ($2.36x10^{-2}$Kg Cu-eq/ Kg ammonia), GNH_3 shows a decrease for scenario 1 ($1.49x10^{-2}$Kg Cu-eq/Kg ammonia), a decrease for scenario 2 ($0.55x10^{-2}$Kg Cu-eq/Kg ammonia) and decrease for scenario 3 ($0.33x10^{-2}$Kg Cu-eq/kg ammonia). Compared to grey ammonia mineral resource scarcity potential ($0.49x10^{-2}$Kg Cu-eq/Kg ammonia), GNH_3 shows an increase for scenario 1 (($1.49x10^{-2}$Kg Cu-eq /Kg ammonia), an increase for scenario 2 ($0.55x10^{-2}$Kg Cu-eq /Kg ammonia) and decrease for scenario 3 ($0.33x10^{-2}$Kg Cu-eq /Kg ammonia).

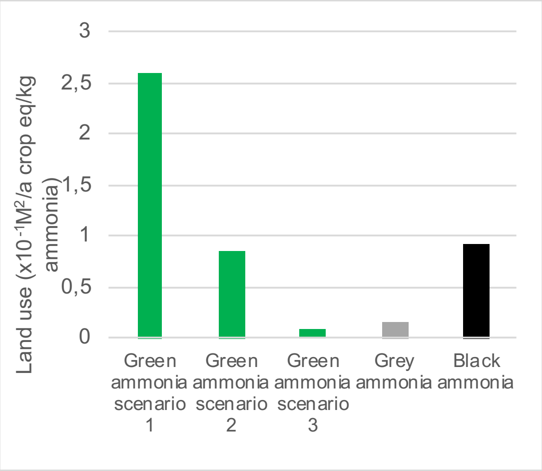


Figure 21: Land use environmental impacts

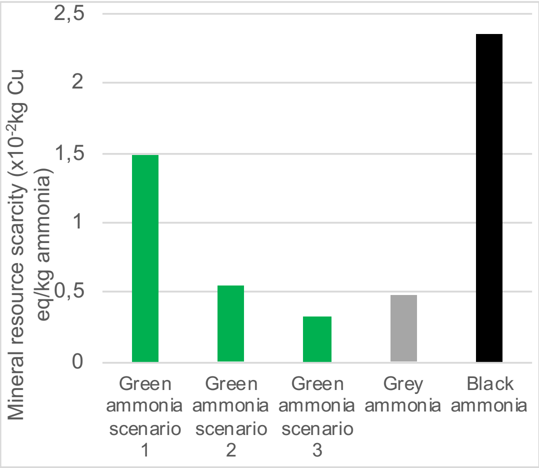


Figure 22: Mineral resource scarcity environmental impacts

Fossil resource scarcity potential impacts:

Compared to black ammonia fossil resource scarcity potential (20.16x10^{-1}Kg oil-eq/Kg ammonia), GNH$_3$ shows a decrease for scenario 1 (2.01x10^{-1}Kg oil-eq/Kg ammonia), a decrease for scenario 2 (0.70x10^{-1}Kg oil-eq/Kg ammonia) and decrease for scenario 3 (0.27x10^{-1}Kg oil-eq/kg ammonia). Compared to grey ammonia fossil resource scarcity potential (8.04x10^{-1}Kg oil-eq/Kg ammonia), GNH$_3$ shows a decrease for scenario 1 (2.01x10^{-1}Kg oil-eq /Kg ammonia), a decrease for scenario 2 (0.70x10^{-1}Kg oil-eq/Kg ammonia) and decrease for scenario 3 (0.27x10^{-1}Kg oil-eq /Kg ammonia).

Water consumption potential impacts:

Compared to black ammonia water consumption potential (2.27x10^{-2}m^3/Kg ammonia), GNH$_3$ shows an increase for scenario 1 (4.75x10^{-2}m^3/Kg ammonia), a decrease for scenario 2 (1.54x10^{-2}m^3/Kg ammonia) and increase for scenario 3 (3.17x10^{-2}m^3/kg ammonia). Compared to grey ammonia water consumption potential (5.59x10^{-2}m^3/Kg ammonia), GNH$_3$ shows a decrease for scenario 1 (4.75x10^{-2}m^3/Kg ammonia), a decrease for scenario 2 (1.54x10^{-2}m^3/Kg ammonia) and decrease for scenario 3 (3.17x10^{-2}m^3/Kg ammonia).

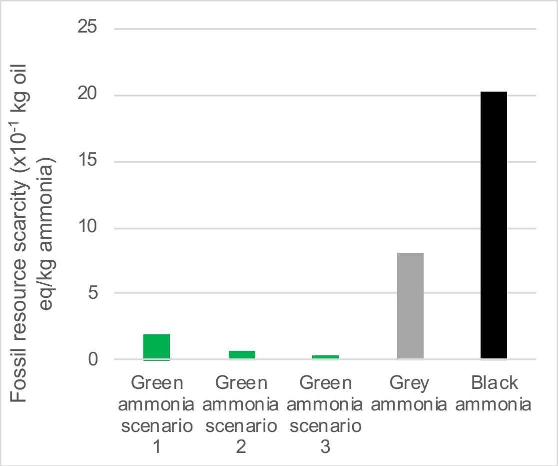


Figure 23: Fossil resource scarcity environmental impacts

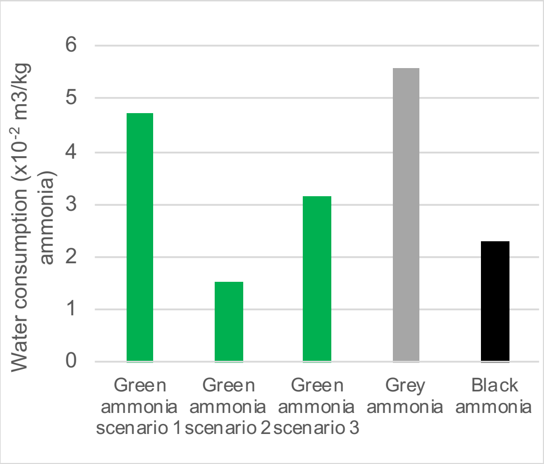
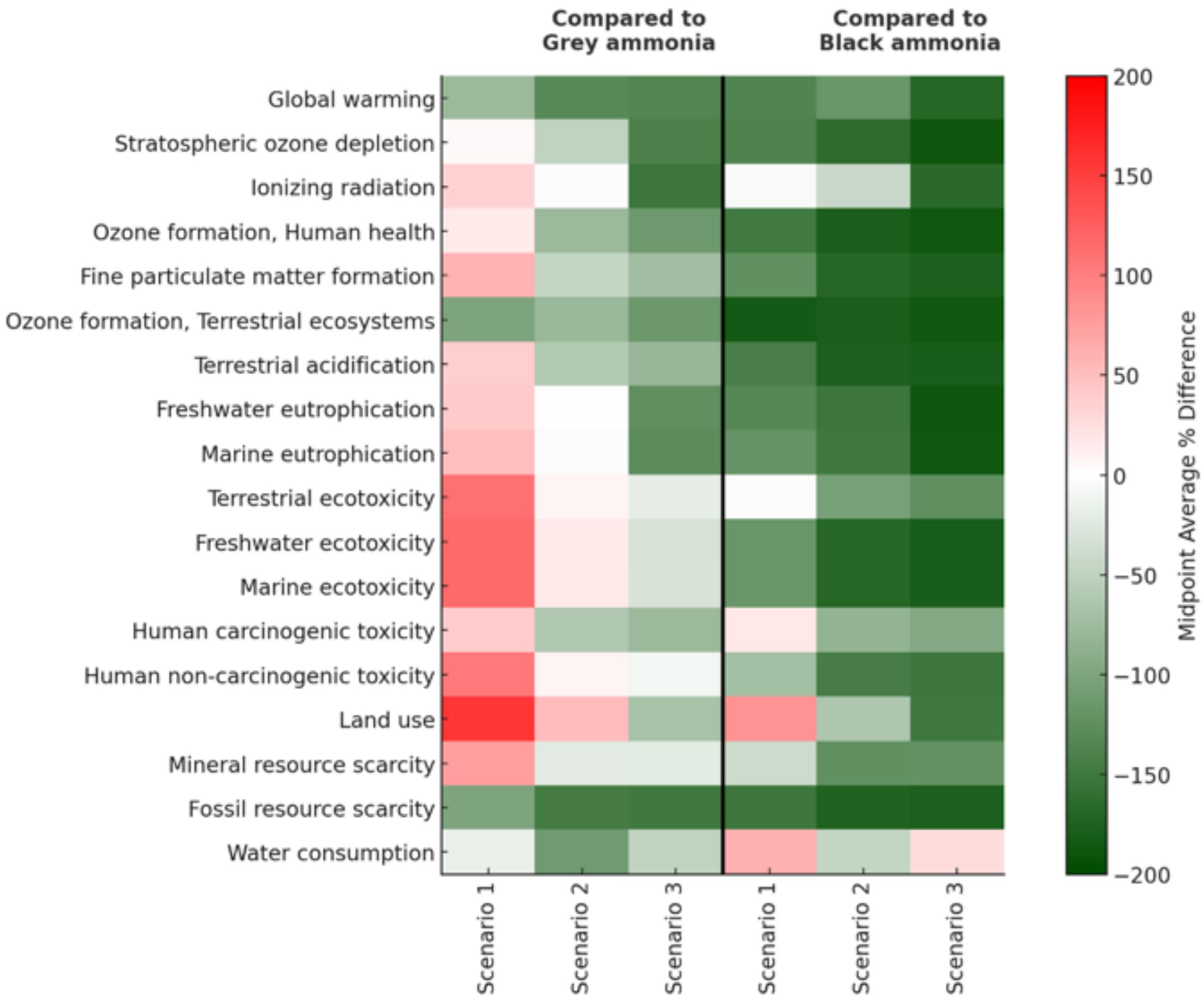


Figure 24: Water consumption environmental impacts

The comparison of GNH_3 with black ammonia and grey ammonia across all 18 impact categories is shown in the heatmap of Table 3. Note that the comparison uses the average percentage difference method (in order to present the data at symmetrical scale to enable comparisons without bias) and these percentages will therefore differ from the description of individual impacts.

Table 3: Cradle-to-production gate comparison of GNH₃ with grey and black ammonia across 18 mid-point impact categories



Compared to black ammonia, GNH₃ had decreased impacts in 15/18 mid-point impact categories for scenario 1, 18/18 mid-point impact categories for scenario 2, and 17/18 mid-point impact categories for scenario 3. The mid-point impact categories where GNH₃ had a greater impact than black ammonia was water use (scenario 1 and 3), human carcinogenic toxicity and land use (scenario 1 only).

Compared to grey ammonia production, GNH₃ had decreased impacts in 4/18 mid-point impact categories for scenario 1, 13/18 for scenario 2 and 18/18 mid-point impact categories for scenario 3. The mid-point impact categories where GNH₃ had a greater impact than grey ammonia is mainly related to ecotoxicity (terrestrial, freshwater and marine), human non-carcinogenic toxicity, land use, and eutrophication (freshwater and marine).

In summary, GNH_3 shows a decrease in many mid-point impact categories, there are several impacts categories where this is not the case (depending on the scenario and whether the comparison is to black or grey ammonia) and this may be a cause for concern. Although the differences of these mid-point absolute values for these impacts are significant, they do not necessarily translate into significant environmental impacts since these impact indicators should be normalised and characterised to determine damage to areas of protection (human health, ecosystems and resources). This is carried out with endpoint and single environmental impact score in the following section.

3.1.3 End-point results for the production lifecycle (A)

In the following, we present the LCIA results for the ReCiPe end-point damage categories (human health, ecosystems and resource depletion) comparing GNH_3 production to grey and black ammonia production.

Impacts on human health:

Compared to black ammonia human health damage potential ($1.12X10^{-5}$DALY / Kg ammonia), GNH_3 shows a decrease for scenario 1 ($0.21X10^{-5}$DALY/Kg ammonia), a decrease for scenario 2 ($0.041X10^{-5}$DALY /Kg ammonia) and decrease for scenario 3 ($0.039X10^{-5}$DALY /kg ammonia). Compared to grey ammonia human health damage potential ($0.28X10^{-5}$DALY /Kg ammonia), GNH_3 shows a decrease for scenario 1 ($0.21X10^{-5}$DALY/Kg ammonia), a decrease for scenario 2 ($0.04X10^{-5}$DALY /Kg ammonia) and decrease for scenario 3 ($0.04X10^{-5}$DALY /Kg ammonia). Overall, producing GNH_3 (scenario 1, 2, 3) results in decreased impacts to human health (in terms of Years of Life Lost and Years Lived with Disability) compared to black and grey ammonia

Impacts to ecosystems:

Compared to black ammonia ecosystems damage potential ($2.92x10^{-8}$ species. yr /Kg ammonia), GNH_3 shows a decrease for scenario 1 ($0.67x10^{-8}$ species. yr /Kg ammonia), a decrease for scenario 2 ($0.12x10^{-8}$ species. yr /Kg ammonia) and decrease for scenario 3 ($0.11x10^{-8}$ species. yr /Kg ammonia). Compared to grey ammonia ecosystems damage potential ($0.81x10^{-8}$ species. yr /Kg ammonia), GNH_3 shows a decrease for scenario 1 ($0.67x10^{-8}$ /Kg ammonia), a decrease for scenario 2 ($0.12x10^{-8}$ species. yr /Kg ammonia) and decrease for scenario 3 ($0.11x10^{-8}$ species. yr /Kg ammonia).

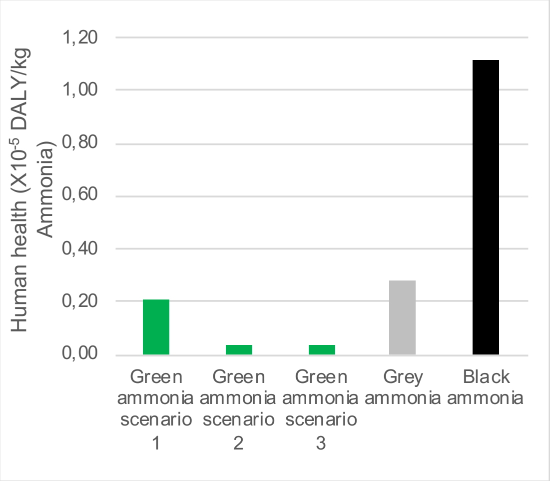


Figure 25: Damage on human health at production gate

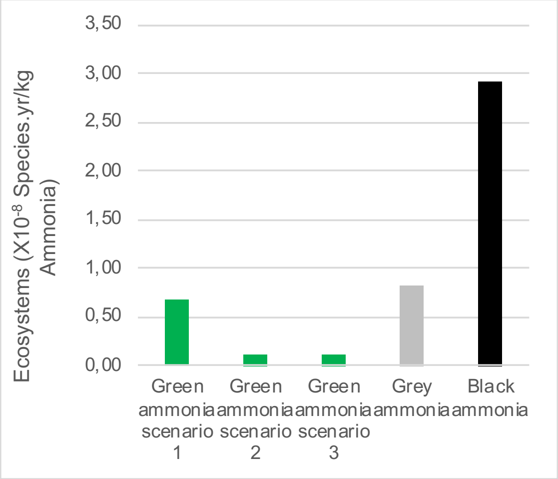


Figure 26: Damage on ecosystems at production gate

Impacts to resource depletion:

Compared to black ammonia resource depletion damage potential ($2.35x10^{-1}$USD2013 / Kg ammonia), GNH$_3$ shows a decrease for scenario 1 ($0.49x10^{-1}$ USD2013 /Kg ammonia), a decrease for scenario 2 ($0.09x10^{-1}$ USD2013 /Kg ammonia) and decrease for scenario 3 ($0.06x10^{-1}$ USD2013 /kg ammonia). Compared to grey ammonia resource depletion damage potential ($2.86x10^{-1}$ USD2013 /Kg ammonia), GNH$_3$ shows a decrease for scenario 1 (/Kg ammonia), a decrease for scenario 2 ($0.09x10^{-1}$ USD2013 /Kg ammonia) and decrease for scenario 3 ($0.06x10^{-1}$ USD2013 /Kg ammonia).

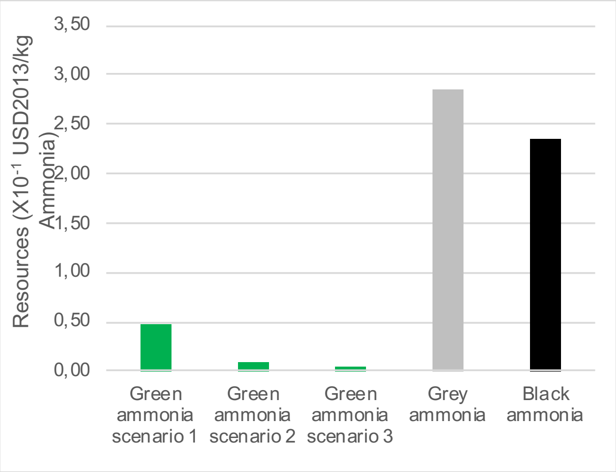


Figure 27: Damage on resources at production gate

3.1.4 Contribution analysis for the production lifecycle (A)

The ReCiPe single score (measured in points, Pt) for GNH_3 production was 0.0047, 0.0015, 0.006 Pt (scenario 1, 2, 3 respectively), compared to 0.054 Pt for grey ammonia and 0.196 Pt for black ammonia. The contribution analysis results (Figure 28 and 29) show the contribution of impact categories and lifecycle stages/processes to the overall single score. The most significant impact categories that contribute to the overall environmental performance in the life cycle of GNH_3 production are Fine Particulate Matter (PM) and GWP, accounting for 55% and 33%, respectively.

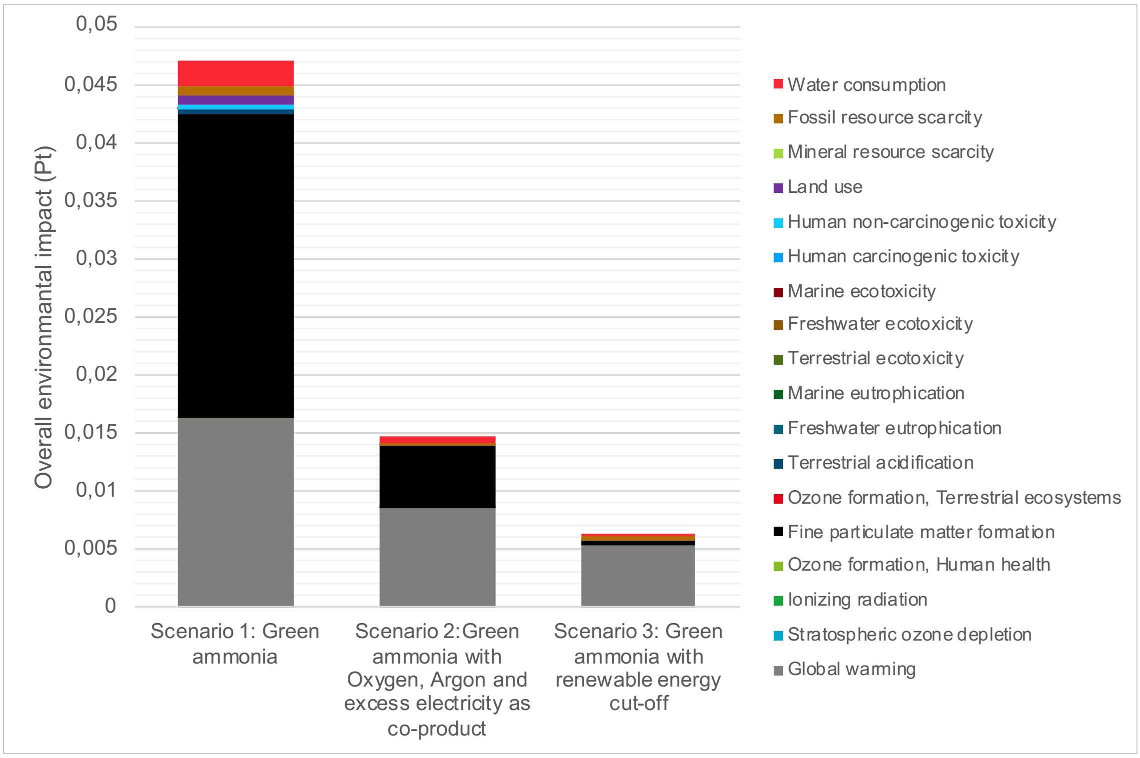


Figure 28: Lifecycle impact contribution per kilogram of green ammonia (cradle-to-production gate)

In terms of processes having the greatest contribution to the lifecycle impacts, the electrolysis of water accounts for 68 % of the life cycle emissions and air separation unit, ammonia synthesis and hydrogen storage accounting for 15%, 13% and 2% respectively (Figure 29).

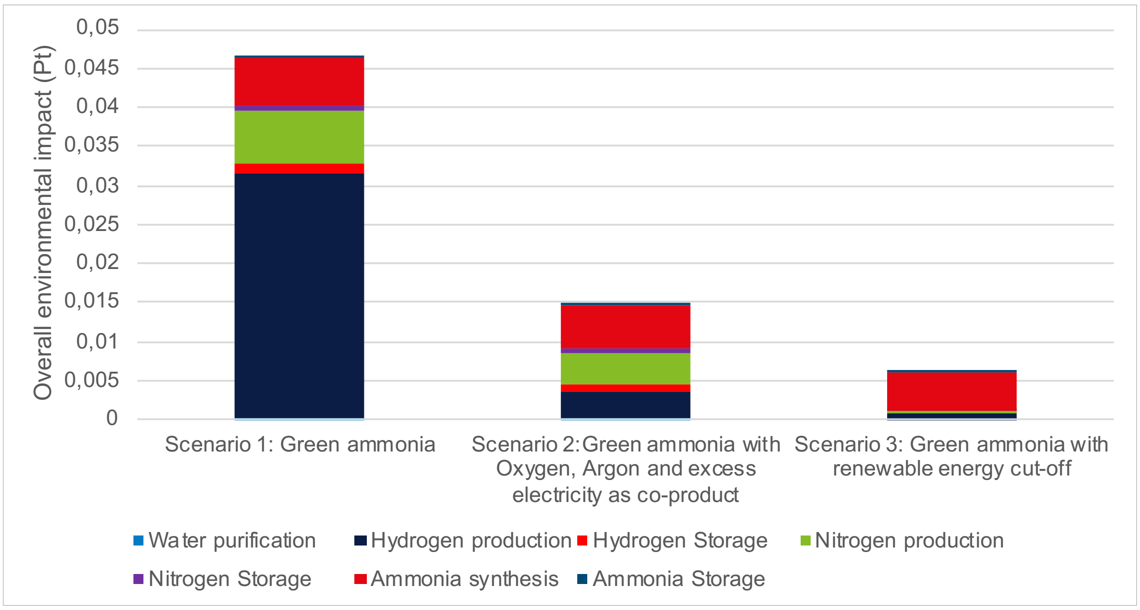


Figure 29: Lifecycle stage/process contribution per kilogram of green ammonia (cradle-to-production gate)

3.2 Part B: CRADLE-TO-GRAVE

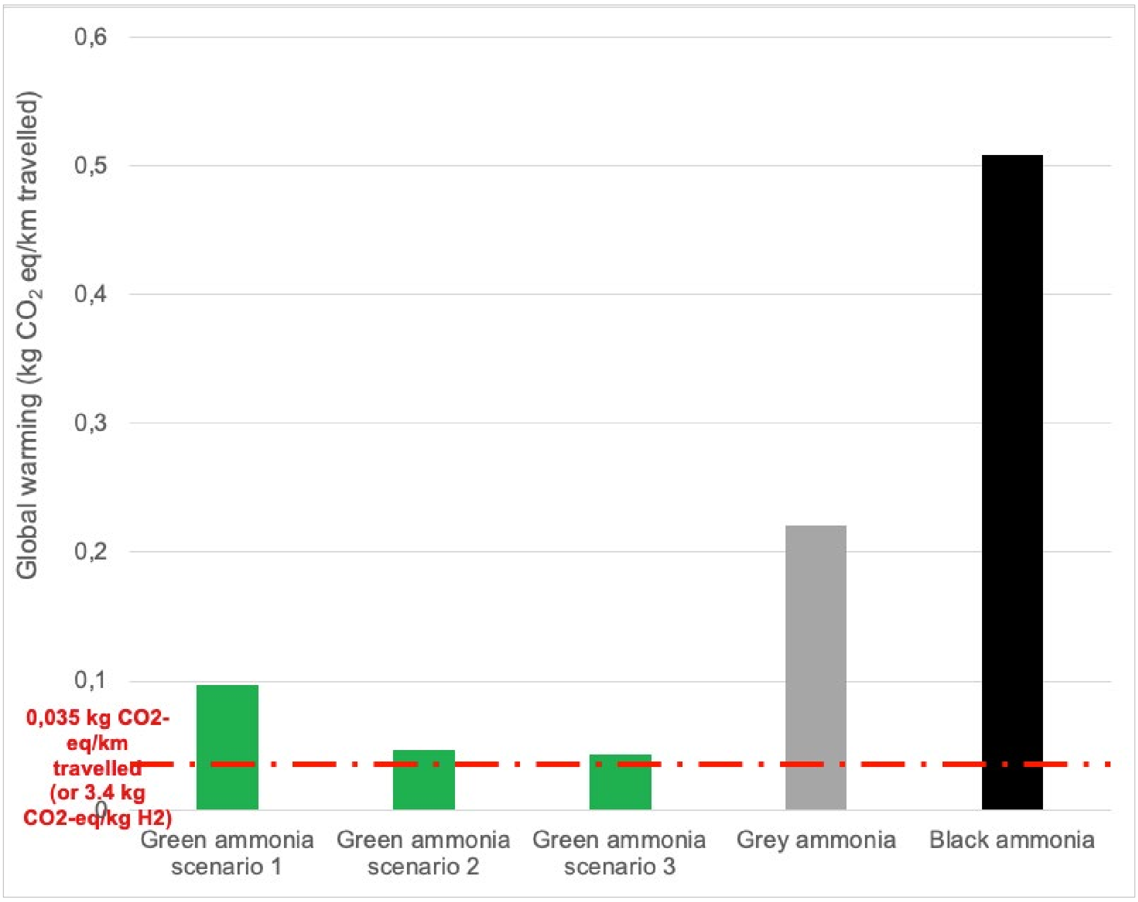
The cradle-to-grave LCIA results for the ReCiPe mid-point impact categories were used to compare green, grey and black ammonia. The results expressed as the percentage difference of green ammonia and compared to the reference of black and grey ammonia. The following sections provides details of these comparisons across all impact categories and scenarios.

3.2.1 GHG emissions and global warming potential

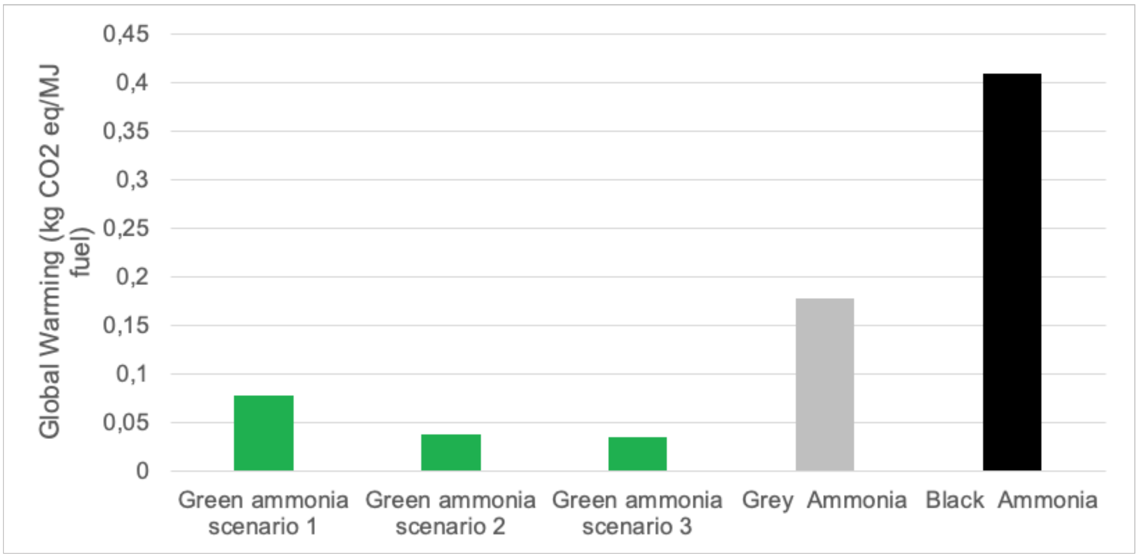
Compared to black ammonia global warming potential (5.08x10^{-1}/km travelled), GNH$_3$ shows a decrease for scenario 1 (0.97x10^{-1} kgCO$_2$-eq /km travelled), a decrease for scenario 2 (0.47x10^{-1} kg CO$_2$-eq /km travelled) and decrease for scenario 3 (0.43x10^{-1} kg CO$_2$-eq /km travelled). Compared to grey ammonia global warming potential (2.21x10^{-1}/km travelled), GNH$_3$ shows an increase for scenario 1 (0.97x10^{-1} kgCO$_2$-eq /km travelled), a decrease for scenario 2 (0.47x10^{-1} kg CO$_2$-eq /km travelled) and decrease for scenario 3 (0.43x10^{-1}kg CO$_2$-eq /km travelled). The production and use of GNH$_3$ (scenario 3) achieve >70% reduction in GHG compared to grey or black GNH$_3$ or diesel fuel (0.789 kgCO$_2$-eq /kg, ICCT, 2021) and will likely achieve certification as a low-carbon fuel.

However, there are considerable GHG emissions from the cracking and distribution of GNH_3. While the GWP for cradle-to-production gate is 0.598 kg CO_2-eq/kg hydrogen, the transportation, cracking, distribution and use in heavy duty vehicles incurs additional carbon emissions of 3.522 kg CO_2-eq/kg hydrogen, such that the carbon intensity at re-fuelling station amounts to 4.11 kg CO_2-eq/kg of H_2 equivalent. The emissions and energy intensity of GNH_3 cracking, transport and distribution to refuelling stations for heavy duty transport may negate the carbon savings of GNH_3 production and pose a risk for the certification as a low-carbon fuel. There is uncertainty to the risk of certification, since EU-REDII and TÜV SÜD specifies a 70% reduction from reference fuel of natural gas (94 gCO_2-eq/MJ), which amounts to 28 gCO_2-eq/MJ or 3.4 $kgCO_2$-eq /kg hydrogen. If the absolute threshold, rather than a percentage reduction from the appropriate reference fossil fuel is used and applied at the point of consumption (re-fuelling station, cradle-to-tank or well-to-tank) or end-use (cradle-to-grave or well-to-tank), then GNH_3 may not achieve certification as a low carbon fuel under EU-RED II and TÜV SÜD schemes since it exceeds these thresholds. However, GNH_3 is below the threshold for the EU CertifHy scheme which is 4.4 $kgCO_2$-eq /kg hydrogen at the point of consumption (See Appendix S8). This highlights the current lack of a clarity and uncertainty in the certification schemes needed to meet green market requirements, as well as the and the lack of interoperability between schemes; and this represents a substantial risk to investment and global trade.

A.



B.



C.

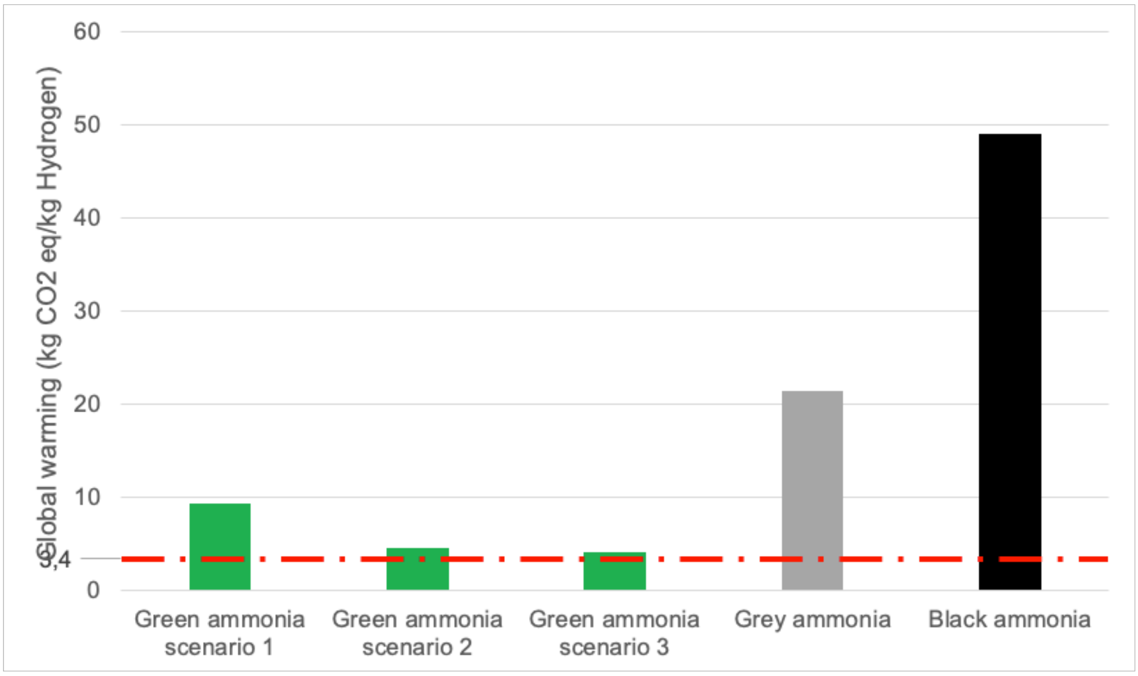


Figure 30: Carbon emissions from cradle-to-grave in terms of A: GWP per kilometre travelled, B: GWP of based on energy content of fuel and C: GWP of hydrogen equivalents. The carbon thresholds of 3.4 kg CO_2/kg GH_2 for European EU-RED II and TÜV SÜD schemes is shown with a dashed line.

3.2.2 Other environmental impacts

Stratospheric ozone depletion potential impacts:

Compared to black ammonia stratospheric ozone depletion potential (2.64x10^{-7}Kg CFC11-eq/km travelled), GNH$_3$ shows a decrease for scenario 1 (0.48x10^{-7}Kg CFC11-eq /km travelled), a decrease for scenario 2 (0.27x10^{-7}Kg CFC11-eq /km travelled) and decrease for scenario 3 (0.08x10^{-7}Kg CFC11-eq /km travelled). Compared to grey ammonia stratospheric ozone depletion potential (0.46x10^{-7}Kg CFC11-eq /km travelled), GNH$_3$ shows an increase for scenario 1 (0.48x10^{-7}Kg CFC11-eq /km travelled), a decrease for scenario 2 (0.27x10^{-7}Kg CFC11-eq /km travelled) and decrease for scenario 3 (0.08x10^{-7}Kg CFC11-eq /km travelled).

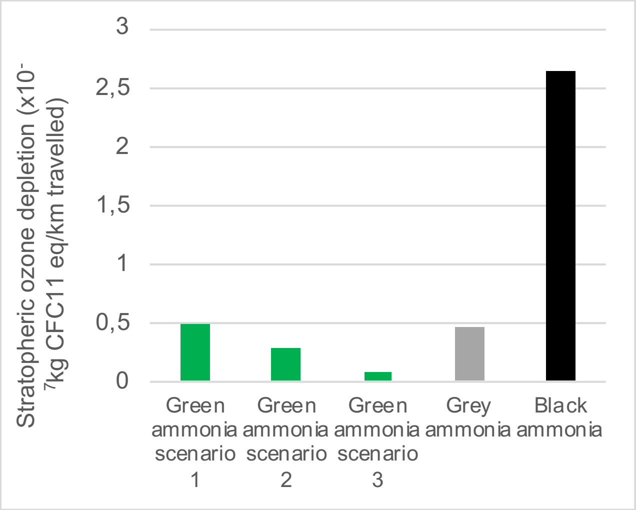


Figure 31: Stratospheric ozone depletion environmental impacts

Ionising radiation potential impacts:

Compared to black ammonia ionising radiation potential (1.06x10^{-2} KBq Co-60-eq/km travelled), GNH$_3$ shows a decrease for scenario 1 (1.01x10^{-2} KBq Co-60-eq/km travelled), a decrease for scenario 2 (0.69x10^{-2} KBq Co-60-eq/km travelled) and decrease for scenario 3 (0.10x10^{-2} KBq Co-60-eq/km travelled). Compared to grey ammonia ionising radiation potential (0.71x10^{-2}KBq Co-60-eq/km travelled), GNH$_3$ shows an increase for scenario 1 (1.01x10^{-2} KBq Co-60-eq /km travelled), a decrease for scenario 2 (0.69x10^{-2} KBq Co-60-eq /km travelled) and decrease for scenario 3 (0.10x10^{-2} KBq Co-60-eq /km travelled).

Ozone formation, human health potential impacts:

Compared to black ammonia, the ozone formation, human health potential (1.48x10^{-3} Kg NOx-eq/km travelled), GNH$_3$ shows a decrease for scenario 1 (0.22x10^{-3} Kg NOx-eq/km travelled), a decrease for scenario 2 (0.08x10^{-3} Kg NOx-eq/km travelled) and decrease for scenario 3 (0.05x10^{-3} Kg NOx-eq/km travelled). Compared to grey ammonia ozone formation, human health potential (0.19x10^{-3}Kg NOx-eq/km travelled), GNH$_3$ shows an increase for scenario 1 (0.22x10^{-3} Kg NOx-eq /km travelled), a decrease for scenario 2 (0.08x10^{-3} Kg NOx-eq /km travelled) and decrease for scenario 3 (0.05x10^{-3} Kg NOx-eq / km travelled).

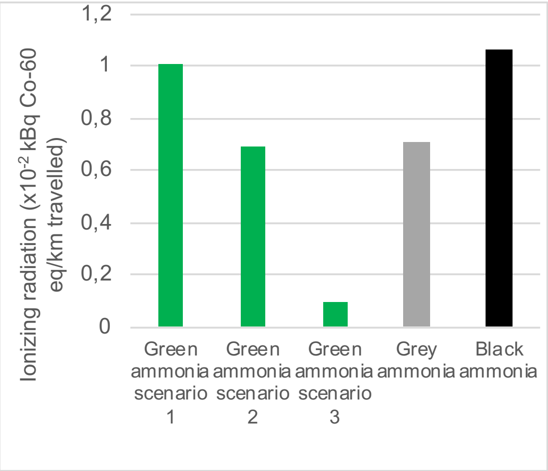


Figure 32: Ionizing radiation environmental impacts

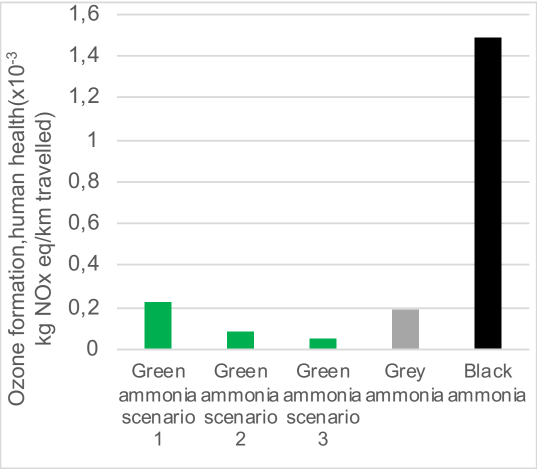


Figure 33: Ozone formation, human health environmental impacts

Particulate formation potential impacts:

Compared to black ammonia particulate formation potential (7.70x10^{-4} Kg PM2.5-eq/km travelled), GNH$_3$ shows a decrease for scenario 1 (1.84x10^{-4} Kg PM2.5-eq/km travelled), a decrease for scenario 2 (0.64x10^{-4} Kg PM2.5-eq/km travelled) and decrease for scenario 3 (0.48x10^{-4}Kg PM2.5-eq/km travelled). Compared to grey ammonia particulate formation potential (1.02x10^{-4} Kg PM2.5-eq/km travelled), GNH$_3$ shows an increase for scenario 1 (1.84x10^{-4} Kg PM2.5-eq /km travelled), a decrease for scenario 2 (0.64x10^{-4} Kg PM2.5-eq / km travelled) and decrease for scenario 3 (0.48x10^{-4}Kg PM2.5-eq /km travelled).

Ozone formation, terrestrial ecosystems potential impacts:

Compared to black ammonia ozone formation, terrestrial ecosystem potential (1.49x10^{-3} Kg NOx-eq /km travelled), GNH$_3$ shows a decrease for scenario 1 (0.06x10^{-3} Kg NOx-eq /km travelled), a decrease for scenario 2 (0.08x10^{-3} Kg NOx-eq /km travelled) and decrease for scenario 3 (0.05x10^{-3} Kg NOx-eq /km travelled). Compared to grey ammonia ozone formation, terrestrial ecosystem potential (0.19x10^{-3}Kg NOx-eq /km travelled), GNH$_3$ shows a decrease for scenario 1 (0.06x10^{-3} Kg NOx-eq /km travelled), a decrease for scenario 2 (0.08x10^{-3} Kg NOx-eq /km travelled) and decrease for scenario 3 (0.05x10^{-3} Kg NOx-eq /km travelled).

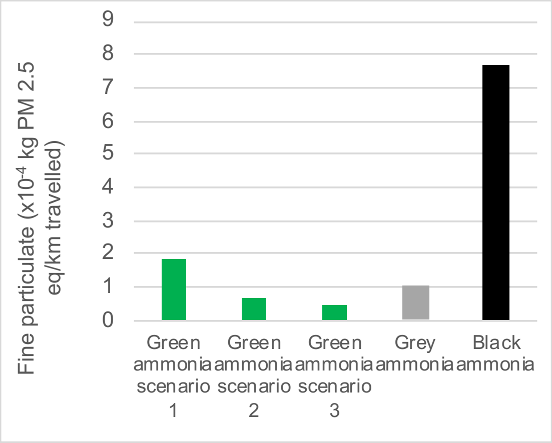


Figure 34: Fine particulate matter formation environmental impacts

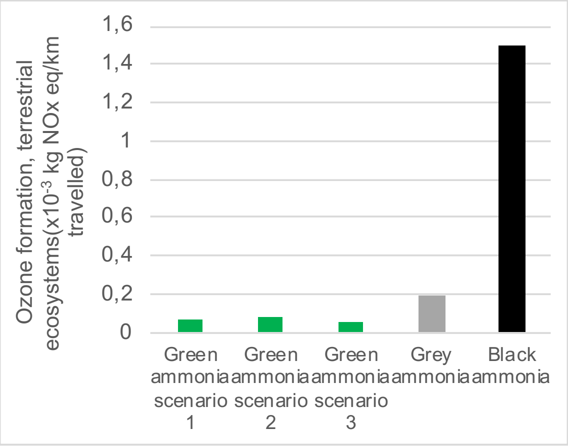


Figure 35: Ozone formation, terrestrial ecosystems environmental impacts

Terrestrial acidification potential impacts:

Compared to black ammonia terrestrial acidification potential (2.50x10^{-3} Kg SO_2-eq/km travelled), GNH_3 shows a decrease for scenario 1 (0.42x10^{-3} Kg SO_2-eq /km travelled), a decrease for scenario 2 (0.15x10^{-3} Kg SO_2-eq /km travelled) and decrease for scenario 3 (0.12x10^{-3} Kg SO_2-eq /km travelled). Compared to grey ammonia terrestrial acidification potential (0.28x10^{-3} Kg SO_2-eq /km travelled), GNH_3 shows an increase for scenario 1 (0.42x10^{-3} Kg SO_2-eq /km travelled), a decrease for scenario 2 (0.15x10^{-3} Kg SO_2-eq /km travelled) and decrease for scenario 3 (0.12x10^{-3} Kg SO_2-eq /km travelled).

Freshwater eutrophication potential impacts:

Compared to black ammonia freshwater eutrophication potential (4.30x10^{-4} Kg P-eq/km travelled), GNH_3 shows a decrease for scenario 1 (0.89x10^{-4} Kg P-eq/km travelled), a decrease for scenario 2 (0.58x10^{-4} Kg P-eq/km travelled) and decrease for scenario 3 (0.14x10^{-4} Kg P-eq /km travelled). Compared to grey ammonia freshwater eutrophication potential (0.58x10^{-4} Kg P-eq/km travelled), GNH_3 shows an increase for scenario 1 (0.89x10^{-4} Kg P-eq /km travelled), a no change for scenario 2 (0.58x10^{-4} Kg P-eq/km travelled) and decrease for scenario 3 (0.14x10^{-4} Kg P-eq /km travelled).

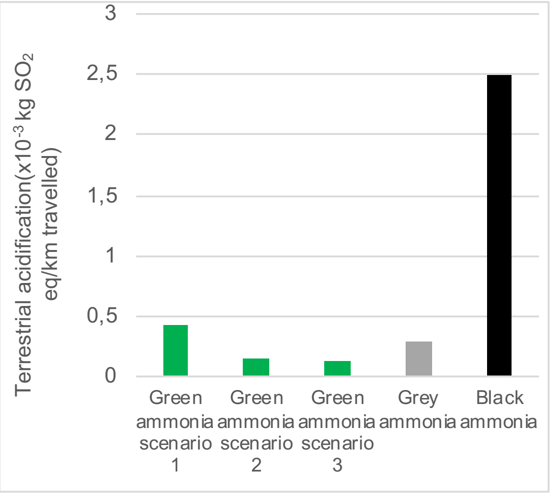


Figure 36: Terrestrial acidification environmental impacts

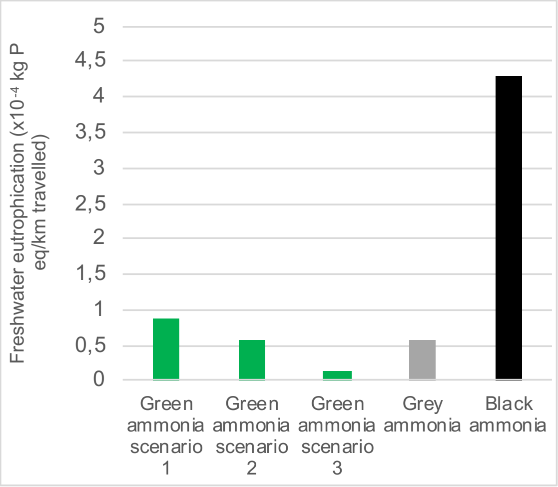


Figure 37: Freshwater eutrophication environmental impacts

Marine eutrophication potential impacts:

Compared to black ammonia marine eutrophication potential (2.73×10^{-5} Kg N-eq/km travelled), GNH$_3$ shows a decrease for scenario 1 (0.69×10^{-5} Kg N-eq/km travelled), a decrease for scenario 2 (0.40×10^{-5} Kg N-eq/km travelled) and decrease for scenario 3 (0.09×10^{-5} Kg N-eq /km travelled). Compared to grey ammonia marine eutrophication potential (0.41×10^{-5} Kg N-eq/km travelled), GNH$_3$ shows an increase for scenario 1 (0.69×10^{-5} Kg N-eq /km travelled), a decrease for scenario 2 (0.40×10^{-5} Kg N-eq /km travelled) and decrease for scenario 3 (0.09×10^{-5} Kg N-eq /km travelled).

Terrestrial ecotoxicity potential impacts:

Compared to black ammonia terrestrial ecotoxicity potential (1.91×10^{-2} Kg 1,4-DCB-eq/km travelled), GNH$_3$ shows a decrease for scenario 1 (1.86×10^{-2} Kg 1,4-DCB-eq /km travelled), a decrease for scenario 2 (0.59×10^{-2} Kg 1,4-DCB-eq /km travelled) and decrease for scenario 3 (0.45×10^{-2} Kg 1,4-DCB-eq /km travelled). Compared to grey ammonia terrestrial ecotoxicity potential (0.55x10-2 Kg 1,4-DCB-eq /km travelled), GNH$_3$ shows an increase for scenario 1 (1.86×10^{-2} Kg 1,4-DCB-eq /km travelled), an increase for scenario 2 (0.59×10^{-2} Kg 1,4-DCB-eq /km travelled) and decrease for scenario 3 (0.45×10^{-2} Kg 1,4-DCB-eq /km travelled).

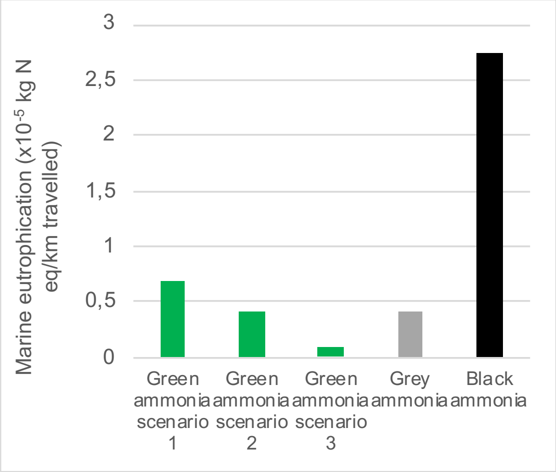


Figure 38: Marine eutrophication environmental impacts

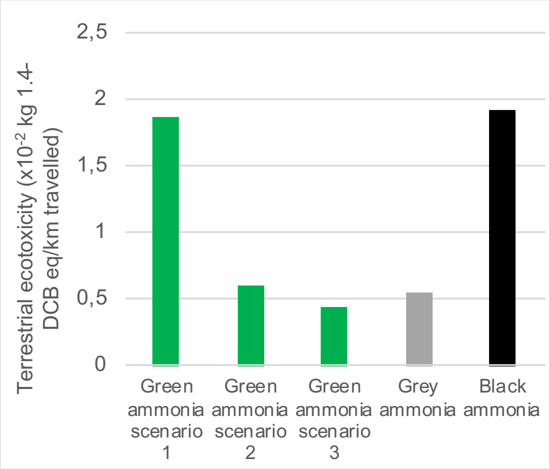


Figure 39: Terrestrial ecotoxicity environmental impacts

Freshwater ecotoxicity potential impacts:

Compared to black ammonia freshwater ecotoxicity potential (2.33x10^{-3} Kg 1,4-DCB-eq/km travelled), GNH_3 shows a decrease for scenario 1 (0.62x10^{-3} Kg 1,4-DCB-eq /km travelled), a decrease for scenario 2 (0.20x10^{-3} Kg 1,4-DCB-eq /km travelled) and decrease for scenario 3 (0.12x10^{-3} Kg 1,4-DCB-eq /km travelled),The compared to grey ammonia freshwater ecotoxicity potential (0.16x10^{-3} Kg 1,4-DCB-eq /km travelled), GNH_3 shows an increase for scenario 1 (0.62x10^{-3} Kg 1,4-DCB-eq /km travelled), an increase for scenario 2 (0.20x10^{-3} Kg 1,4-DCB-eq /km travelled) and decrease for scenario 3 (0.12x10^{-3} Kg 1,4-DCB-eq /km travelled).

Marine ecotoxicity potential impacts:

Compared to black ammonia marine ecotoxicity potential (3.28x10^{-3} Kg 1,4-DCB-eq/km travelled), GNH_3 shows a decrease for scenario 1 (0.88x10^{-3} Kg 1,4-DCB-eq /km travelled), a decrease for scenario 2 (0.28x10^{-3} Kg 1,4-DCB-eq /km travelled) and decrease for scenario 3 (0.17x10^{-3} Kg 1,4-DCB-eq /km travelled). Compared to grey ammonia marine ecotoxicity potential (0.23x10^{-3} Kg 1,4-DCB-eq /km travelled), GNH_3 shows an increase for scenario 1 (0.88x10^{-3} Kg 1,4-DCB-eq /km travelled), an increase for scenario 2 (0.28x10^{-3} Kg 1,4-DCB-eq /km travelled) and decrease for scenario 3 (0.17x10^{-3} Kg 1,4-DCB-eq /km travelled).

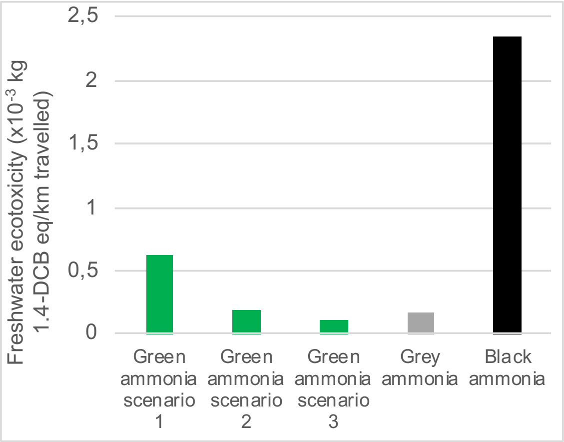


Figure 40: Freshwater ecotoxicity environmental impacts

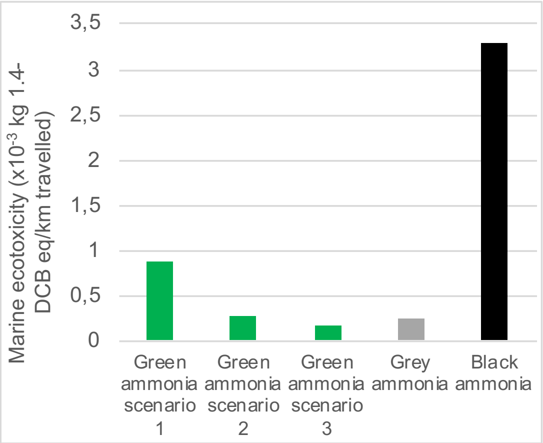


Figure 41: Marine ecotoxicity environmental impacts

Human carcinogenic toxicity potential impacts:

Compared to black ammonia human carcinogenic toxicity potential ($2.57x10^{-5}$ Kg 1,4-DCB-eq/km travelled), GNH_3 shows an increase for scenario 1 ($3.07x10^{-5}$ Kg 1,4-DCB-eq /km travelled), a decrease for scenario 2 ($1.07x10^{-5}$ Kg 1,4-DCB-eq /km travelled) and decrease for scenario 3 ($0.91x10^{-5}$ Kg 1,4-DCB-eq /km travelled), Compared to grey ammonia human carcinogenic toxicity potential ($2.04X10^{-5}$ Kg 1,4-DCB-eq /km travelled), GNH_3 shows an increase for scenario 1 ($3.07x10^{-5}$ Kg 1,4-DCB-eq /km travelled), a decrease for scenario 2 ($1.07x10^{-5}$ Kg 1,4-DCB-eq /km travelled) and decrease for scenario 3 ($0.91x10^{-5}$ Kg 1,4-DCB-eq /km travelled).

Human non-carcinogenic toxicity potential impacts:

Compared to black ammonia human non-carcinogenic toxicity potential ($9.05x10^{-3}$ Kg 1,4-DCB-eq/km travelled), GNH_3 shows a decrease for scenario 1 ($4.32x10^{-3}$ Kg 1,4-DCB-eq /km travelled), a decrease for scenario 2 ($1.48x10^{-3}$Kg 1,4-DCB-eq /km travelled) and decrease for scenario 3 ($1.25x10^{-3}$Kg 1,4-DCB-eq /km travelled). Compared to grey ammonia human non-carcinogenic toxicity potential (1.36x10-3Kg 1,4-DCB-eq /km travelled), GNH_3 shows an increase for scenario 1 ($4.32x10^{-3}$ Kg 1,4-DCB-eq /km travelled), an increase for scenario 2 ($1.48x10^{-3}$ Kg 1,4-DCB-eq /km travelled) and decrease for scenario 3 ($1.25x10^{-3}$ Kg 1,4-DCB-eq /km travelled).

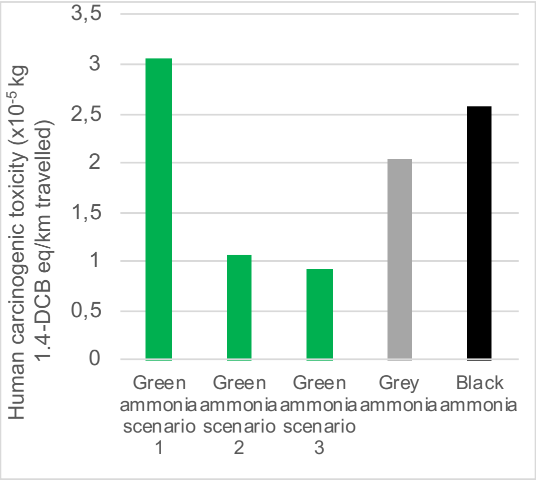


Figure 42: Human carcinogenic toxicity environmental impacts

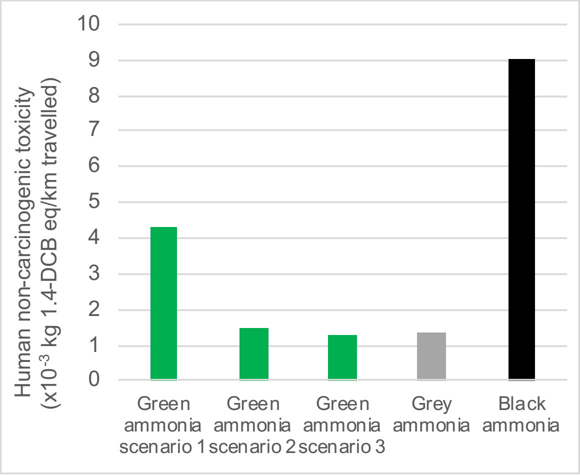


Figure 43: Human non-carcinogenic toxicity environmental impacts

Land use:

Compared to black ammonia land use potential ($0.90x10^{-2}$ m^2/a crop-eq/km travelled), GNH_3 shows an increase for scenario 1 ($2.20x10^{-2}$ m^2/a crop-eq /km travelled), a decrease for scenario 2 ($0.46x10^{-2}$ m^2/a crop-eq /km travelled) and decrease for scenario 3 ($0.13x10^{-2}$ m^2/a crop-eq /km travelled). Compared to grey ammonia land use potential ($0.27x10^{-2}$ m^2/a crop-eq /km travelled), GNH_3 shows an increase for scenario 1 ($2.20x10^{-2}$ m^2/a crop-eq /km travelled), an increase for scenario 2 ($0.46x10^{-2}$ m^2/a crop-eq /km travelled) and decrease for scenario 3 ($0.13x10^{-2}$ m^2/a crop-eq /km travelled).

Mineral resource scarcity potential impacts:

Compared to black ammonia mineral resources scarcity potential ($2.18x10^{-3}$ Kg Cu-eq/km travelled), GNH_3 shows a decrease for scenario 1 ($1.46x10^{-3}$ Kg Cu-eq/km travelled), a decrease for scenario 2 ($0.53x10^{-3}$ Kg Cu-eq/km travelled) and decrease for scenario 3 ($0.54x10^{-3}$ Kg Cu-eq /km travelled). Compared to grey ammonia mineral resources scarcity potential ($0.67x10^{-3}$ Kg Cu-eq/km travelled), GNH_3 shows an increase for scenario 1 ($1.46x10^{-3}$ Kg Cu-eq /km travelled), a decrease for scenario 2 ($0.53x10^{-3}$ Kg Cu-eq /km travelled) and decrease for scenario 3 ($0.54x10^{-3}$ Kg Cu-eq /km travelled).

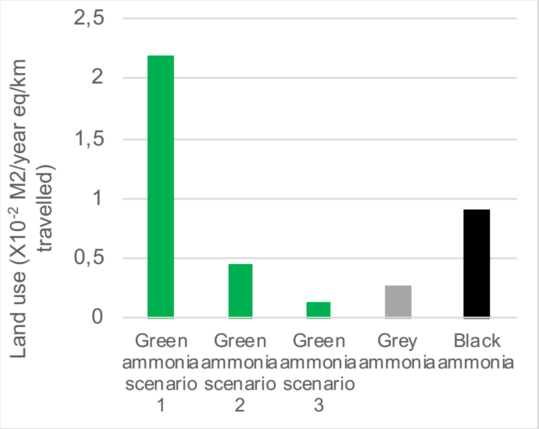


Figure 44: Land use environmental impacts

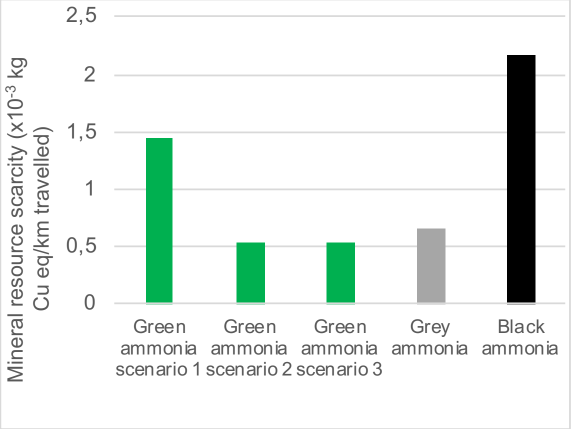


Figure 45: Mineral resource scarcity environmental impacts

Fossil resource scarcity potential impacts:

Compared to black ammonia water consumption potential (1.72x10^{-1} Kg oil-eq /km travelled), GNH$_3$ shows a decrease for scenario 1 (0.24x10^{-1} Kg oil-eq /km travelled), a decrease for scenario 2 (0.12x10^{-1} Kg oil-eq /km travelled) and a decrease for scenario 3 (0.11x10^{-1} Kg oil-eq /km travelled). Compared to grey ammonia water consumption potential (0.74x10^{-1} Kg oil-eq /km travelled), GNH$_3$ shows a decrease for scenario 1 (0.24x10^{-1} Kg oil-eq /km travelled), a decrease for scenario 2 (0.12x10^{-1} Kg oil-eq /km travelled) and decrease for scenario 3 (0.11x10^{-1} Kg oil-eq /km travelled.

Water consumption:

Compared to black ammonia water consumption potential (2.23x10^{-3} m^3/km travelled), GNH$_3$ shows an increase for scenario 1 (4.21x10^{-3} m^3 /km travelled), a decrease for scenario 2 (1.40x10^{-3} m^3/km travelled) and an increase for scenario 3 (2.96x10^{-3} m^3/km travelled), Compared to grey ammonia water consumption potential (4.92x10^{-3} m^3/km travelled), GNH$_3$ shows a decrease for scenario 1 (4.21x10^{-3} m^3 /km travelled), a decrease for scenario 2 (1.40x10-3 m^3/km travelled) and decrease for scenario 3 (2.96x10^{-3} m^3/km travelled.

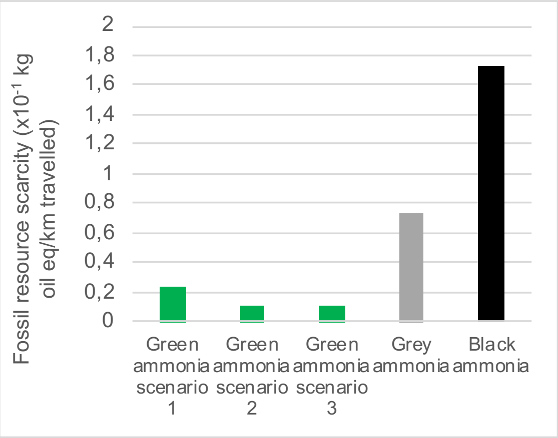


Figure 46: Fossil resource scarcity environmental impacts

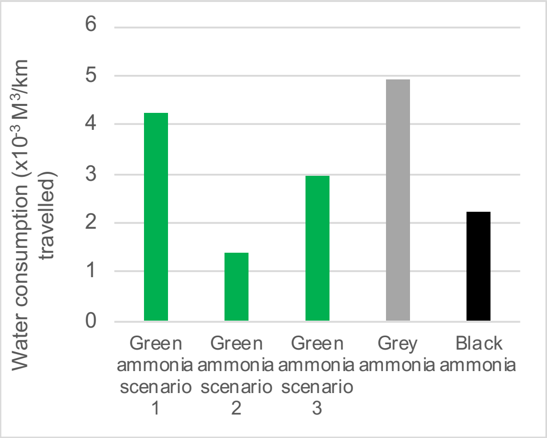
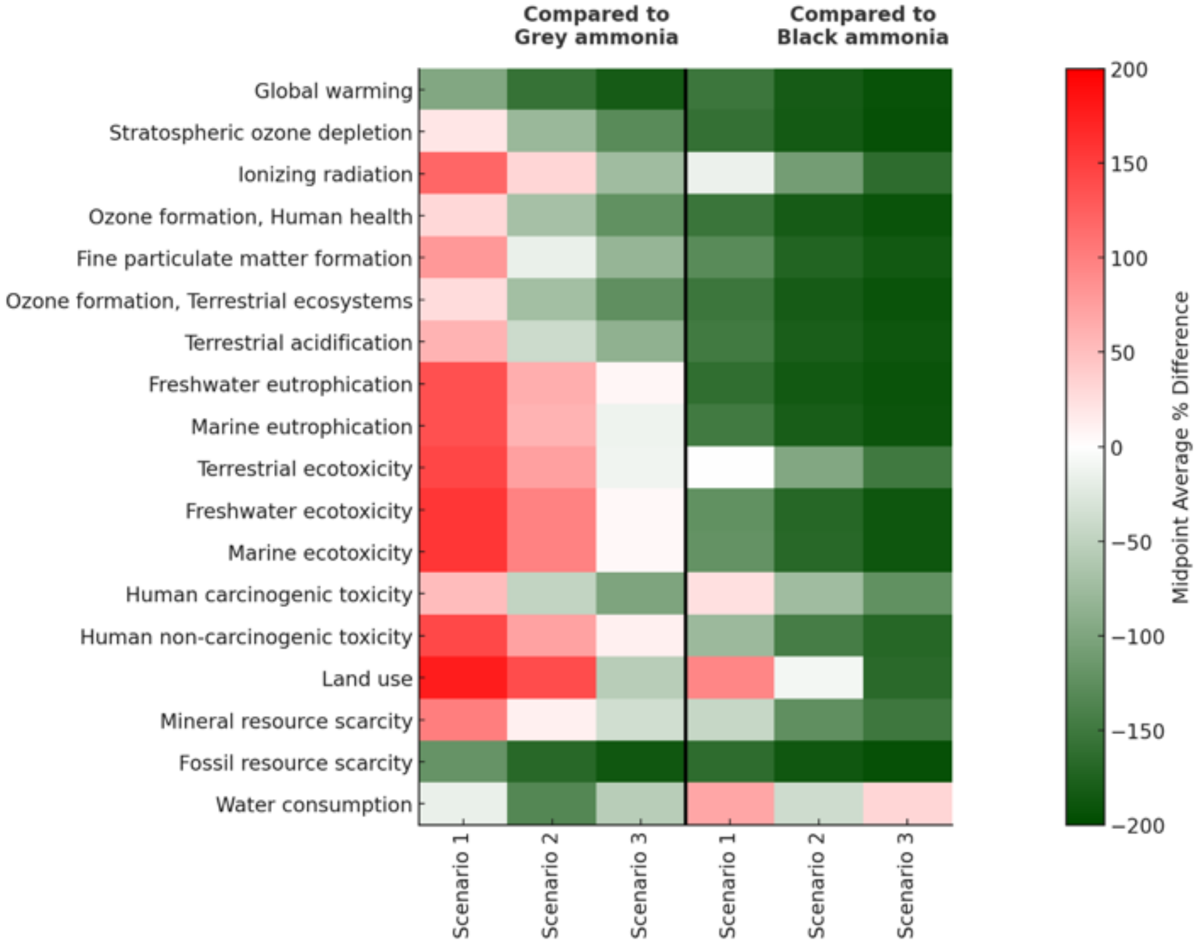


Figure 47: Water consumption environmental impacts

The cradle-to-grave comparison of GNH_3 with black ammonia and grey ammonia across all 18 impact categories is shown in the heatmap of Table 4. Note that the comparison uses the average percentage difference method (in order to present the data a symmetrical scale to enable comparisons without bias) and these percentages will therefore differ from the description of individual impacts.

Table 4: Cradle-to-grave comparison of GNH_3 with grey and black ammonia across 18 mid-point impact categories



Compared to black ammonia, GNH_3 had decreased impacts in 15/18 mid-point impact categories for scenario 1, 18/18 mid-point impact categories for scenario 2, and 17/18 mid-point impact categories for scenario 3. The mid-point impact categories where GNH_3 had a greater impact than black ammonia was water use (scenario 1 and 3), human carcinogenic toxicity and land use (scenario 1 only).

Compared to grey ammonia production, GNH_3 had decreased impacts in 4/18 mid-point impact categories for scenario 1, 13/18 for scenario 2 and 18/18 mid-point impact categories for scenario 3. The mid-point impact categories where GNH_3 had a greater impact than grey ammonia is mainly related to ecotoxicity (terrestrial, freshwater and marine), human carcinogenic toxicity, land use, and eutrophication (freshwater and marine).

In summary, although GNH_3 shows a decrease in many mid-point impact categories, there are several impacts categories where this is not the case (depending on the scenario and whether the comparison is to Black or Grey ammonia) and this may be a cause for concern.

3.2.3 End-point results for the extended lifecycle (B)

In the following, we present the LCIA results for the ReCiPe end-point damage categories comparing GNH_3 produced in South Africa and used for transport in Germany, versus grey and black ammonia production with the same end use.

Impacts on human health:

Compared to black ammonia human health damage potential (9.62×10^{-7} DALY /Km travelled), GNH_3 shows a decrease for scenario 1 (2.23×10^{-7} DALY /Km travelled), a decrease for scenario 2 (0.88×10^{-7} DALY /Km travelled) and decrease for scenario 3 (0.88×10^{-7} DALY /Km travelled). Compared to grey ammonia human health damage potential (2.80×10^{-7} DALY /Km travelled), GNH_3 shows a decrease for scenario 1 (2.23×10^{-7} DALY / Km travelled), a decrease for scenario 2 (0.88×10^{-7} DALY /Km travelled) and decrease for scenario 3 (0.88×10^{-7} DALY /Km travelled). Overall, producing GNH_3 (scenario 1, 2, 3) results in decreased impacts to human health (in terms of Years of Life Lost and Years Lived with Disability) compared to black and grey ammonia

Impacts to ecosystems:

Compared to black ammonia ecosystems damage potential (2.54×10^{-9} species. yr /Km travelled), GNH_3 shows a decrease for scenario 1 (0.72×10^{-9} species. yr /Km travelled), a decrease for scenario 2 (0.28×10^{-9} species. yr /Km travelled) and decrease for scenario 3 (0.27×10^{-9} species. yr /Km travelled). Compared to grey ammonia ecosystems damage potential (0.83×10^{-9} species. yr /Km travelled), GNH_3 shows a decrease for scenario 1 (0.72×10^{-9} species. yr /Km travelled), a decrease for scenario 2 (0.28×10^{-9} species. yr /Km travelled) and decrease for scenario 3 (0.27×10^{-9} species. yr /Km travelled).

Resource depletion:

Compared to black ammonia resource depletion damage potential (2.02x10^{-2} USD2013 /Km travelled), GNH$_3$ shows a decrease for scenario 1 (0.52x10^{-2} USD2013 /Km travelled), a decrease for scenario 2 (0.19x10^{-2} USD2013 /Km travelled) and decrease for scenario 3 (0.17x10^{-2} USD2013 /Km travelled). Compared to grey ammonia resource depletion damage potential (2.44x10^{-2} USD2013 /Km travelled), GNH$_3$ shows a decrease for scenario 1 (0.52x10^{-2} USD2013 /Km travelled), a decrease for scenario 2 (0.19x10^{-2} USD2013 /Km travelled) and decrease for scenario 3 (0.17x10^{-2} USD2013 /Km travelled).

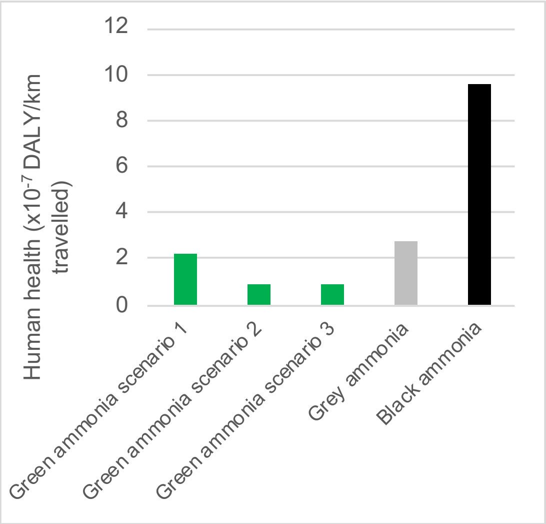


Figure 48: Impacts on human health

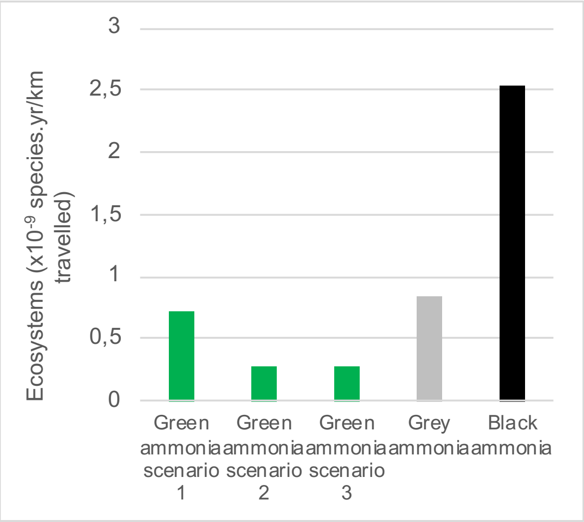


Figure 49: Impacts on ecosystems

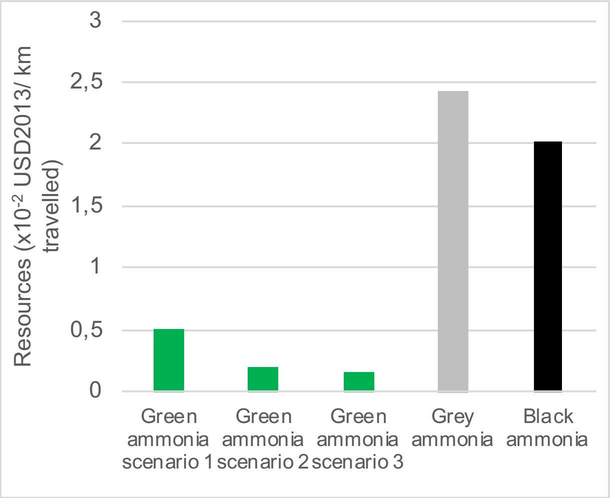


Figure 50 Impacts on resources

3.2.4 Contribution analysis of the extended lifecycle (B)

The ReCiPe single score (measured in points, Pt) for GNH_3 production, distribution and use was 0.087, 0.054, 0.046 Pt (scenario 1, 2, 3 respectively), compared to 0.414 Pt for grey ammonia and 1.518 Pt for black ammonia. The contribution analysis (Figure 51 and 52) shows the contribution of impact categories and lifecycle stages/processes to the overall single score. The most significant impact categories that contribute to the overall environmental performance in the life cycle of GNH_3 production are FPM and GWP, accounting for 51% and 39 % of total contribution.

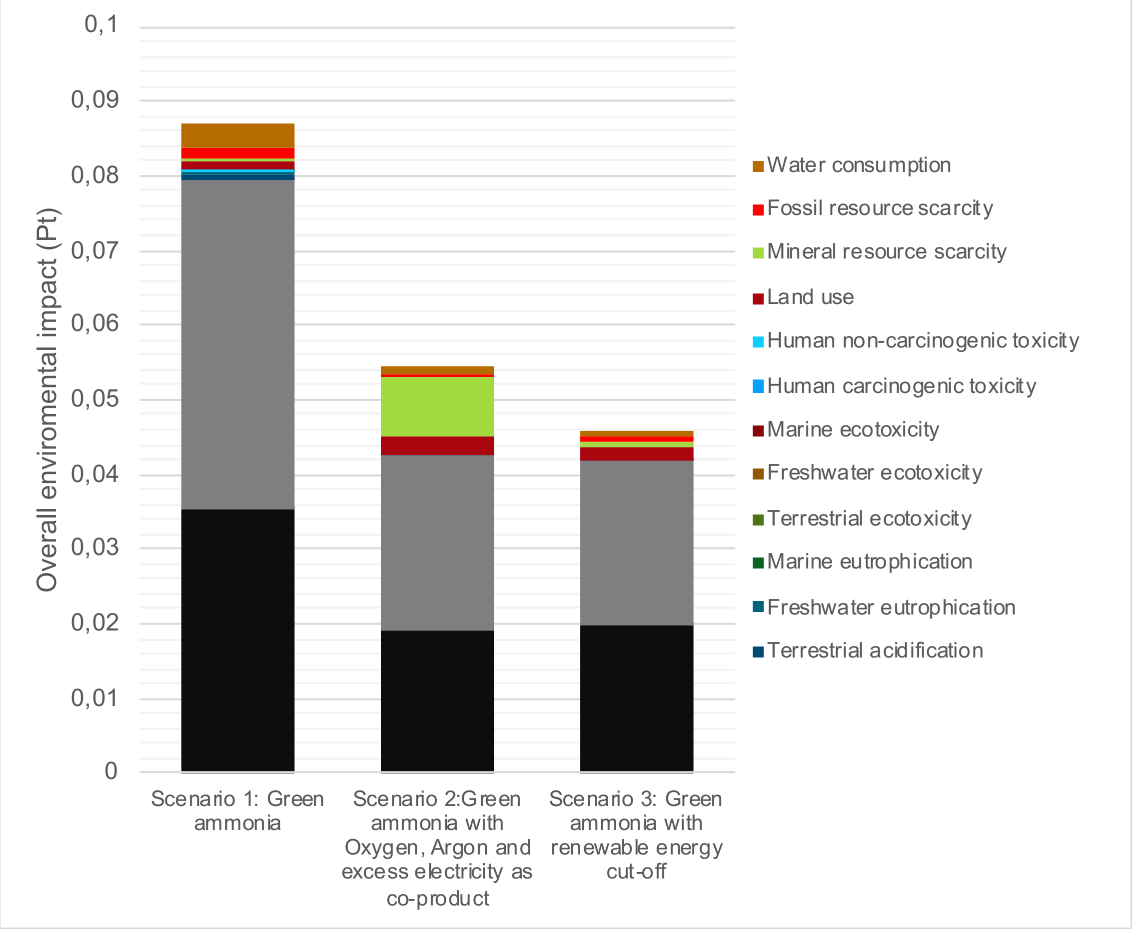


Figure 51: Impact category contribution analysis for cradle-to-grave

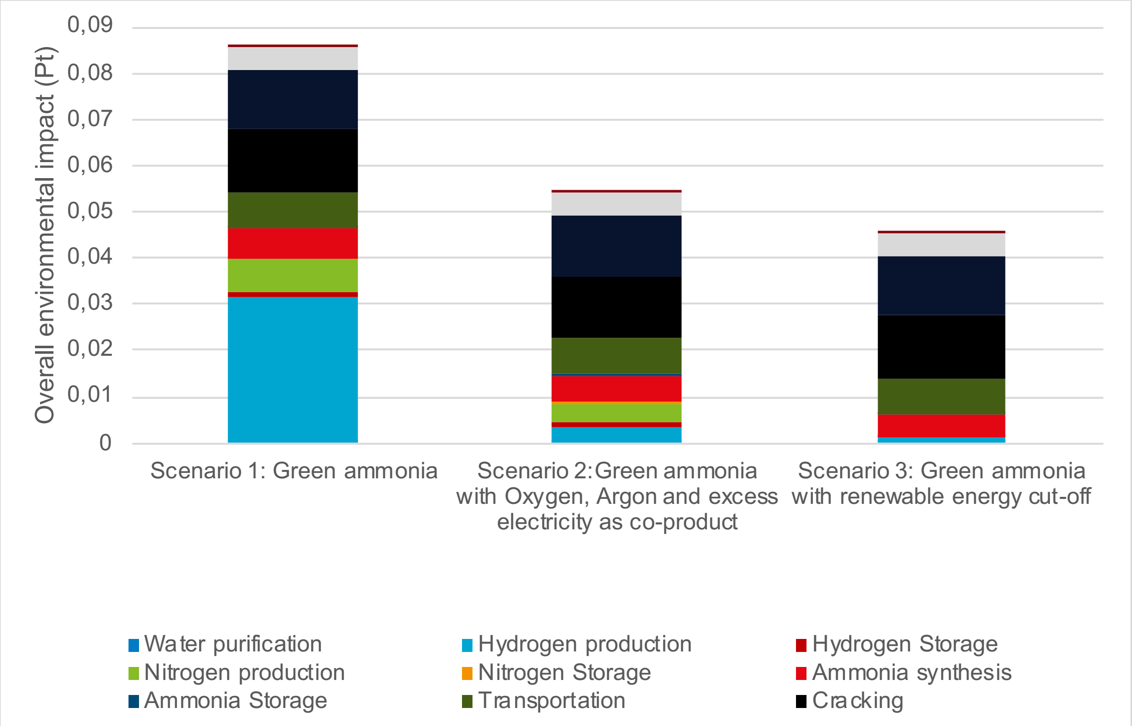


Figure 52: Process contribution analysis for cradle-to-grave

Alkaline electrolysis of water is responsible for the most (37%) of the cradle-to-grave impacts, followed by cracking (16%), compression and storage (15%) and transport (9%).

Discussion

Green ammonia can reduce the grid dependency and the curtailment of renewables by acting as an energy carrier to facilitate the distribution of renewable energy from areas of production (high wind and solar resources) to areas of fuel consumption (energy demand) (Zhao *et al* 2023). Although GNH_3 produced from renewable energy is a fuel with zero carbon, there are embodied carbon emissions associated with manufacturing infrastructure and fossil-based electricity used in the supply chain to transport and distribute to end users.

This LCA study reveals a significant amount of embodied emissions from the manufacture of capital infrastructure in the production of GNH_3. The majority (68%) of the carbon emissions of green ammonia production are related to the energy requirement of alkaline electrolysis, which reflects the carbon intensity of the electricity supply (0.052 kg CO_2/KWh for combined wind and solar PV) and energy intensity of electrolysis (49.11 KWh per kg hydrogen). As energy supply is becoming less reliant on fossil-fuels and increasingly decarbonised, the carbon intensity of energy and embodied emissions are set to decrease in the future for most countries (IEA 2022). The Conference of the Parties (COP) under the United Nations Framework Convention on Climate Change (UNFCCC) distinguishes between Annex I and non-Annex I countries, setting differentiated responsibilities for carbon emission reductions. Annex I countries are primarily developed nations and economies in transition, mandated to lead by setting quantifiable emissions reduction targets. Non-Annex I countries, mainly developing nations, are encouraged to undertake mitigation actions but are not bound by quantifiable targets, reflecting the principle of common but differentiated responsibilities and respective capabilities (UNFCCC 1992). The EU has set ambitious targets to reduce GHG emissions by at least 55% by 2030 (relative to 1990 levels) and aims for carbon neutrality by 2050 (EC 2021). This is operationalised through annual emission reduction targets, sector-specific legislation, and the Emissions Trading System (ETS). As an EU member state, Germany, follows the EU overarching targets, but also sets national objectives and aims for a reduction of GHG emissions by at least 65% by 2030, 88% by 2040, and to achieve near-zero emissions by 2045, relative to 1990 levels (FME 2021). In contrast, South Africa is a non-Annex I country but has committed to Nationally Determined Contributions (NDC) and a peak of GHG emissions between 2020-2025, a plateau for a decade, and a decline in absolute terms from 2035 (DEA, 2021) with an aspiration to reach net zero by 2050 (DFFE, 2020).

Recycling of materials from the technology and infrastructure at end of life was included, although the recycling of wind and solar PV components was not included since the recycling practices are currently limited. Therefore, ensuring the recycling of solar PV and wind power infrastructure at end of life, which is a requirement of South Africa's recent Extended Producer Responsibility legislation (EPR 2020), could also significantly reduce the embodied emissions and reduce resource depletion with the recovery of critical raw materials used in the renewable energy infrastructure (solar PV, wind power and battery). For instance, that of aluminium, copper, iron, lead, nickel, zinc, silver, cadmium, molybdenum, selenium, tin, tellurium dysprosium and neodymium (Carrara *et al*. 2020).

The lifecycle stages/process that make the greatest contribution to the overall environmental impacts for cradle-to-grave score are electrolysis (37%), cracking (16%), compression and storage (15%) and the air separation process (8%). It is noteworthy that considerable impacts of the cradle-to-grave of GNH_3 are related to the transport, cracking and distribution to end users in Germany, due to the loss of hydrogen in cracking (15%), the energy requirement of hydrogen compression (2.7 kWh/kg) and the loss of hydrogen in storage (1.4% from 2 weeks storage) (Andersen and Grönkvist 2019; Giddey *et al*., 2017). While the GWP for cradle-to-production gate is 0.599 kg CO_2-eq/kg hydrogen, the transportation, cracking, distribution and use in heavy duty vehicles incurs additional GWP of 3.522 kg CO_2-eq/kg hydrogen. This indicates that considerable GHG emissions are incurred to transportation, cracking, distribution and use, which may result in the GWP exceeding the threshold for certification which is typically <4 kg CO_2-eq/kg hydrogen.

In summary, GNH_3 from coastal production in South Africa and used for heavy duty transport in Germany, has a carbon emission reduction of >70% when compared to heavy-duty vehicles using grey ammonia, black ammonia or diesel fuel, and will likely receive certification as a low carbon fuel. However, the carbon intensity is 0.598 kg CO_2-eq/kg hydrogen equivalent at the production gate (scenario 3), 3.96 kg CO_2 eq/kg hydrogen at the refilling station and 4.12 kg CO_2 eq/kg hydrogen equivalent at the end of life after conversion into electrical energy to power the fuel cell electric vehicle (FCEV) drivetrain. The EU Renewable Energy Directive (EU RED-II) which sets out GHG emission criteria for countries in the EU, indicates a 70% reduction from natural gas with 0.094 kg CO_2-eq /MJ, which represents a threshold of 0.028 kg CO_2-eq /MJ or 3.4 kg CO_2-eq/kg hydrogen (EUR-Lex 2023). If this absolute threshold is then applied to GNH_3 production as well as end-use, then GNH_3 will be unlikely to meet the specification to be considered a low-carbon fuel in EU markets. This highlights the current lack of a clarity and uncertainty in the certification systems and harmonious standards for hydrogen fuels, which represents a substantial risk in meeting market requirements and, therefore may present a market risk to the supply of GNH_3 as a low-carbon fuels; such as the supply to Germany (the EU) to fulfil their decarbonisation mandates.

The decarbonisation of energy supply systems through an increase of renewable energy in the energy supply mix will reduce embodied emissions, but reducing hydrogen losses in cracking of ammonia and reducing the carbon intensity of hydrogen distribution to end users is also needed. Moving the distribution of hydrogen to pipelines through the re-purposing of the existing natural gas grid (FuelCellWorks, 2023) or with new dedicated hydrogen pipelines, together with underground storage in salt-caverns (Clean Energy Wire 2024a) could reduce distribution related carbon emissions. Alternatively, the distribution related carbon emissions could be addressed through solutions such as on-board cracking of ammonia in vehicles, which is at prototype or early commercial stage of technology development (Transinfo, 2023).

Previous LCA studies have estimated that the carbon emissions of GNH_3 using wind power are 0.24-0.54 kg CO_2-eq/kg ammonia, while the carbon emissions of GNH_3 using solar PV power are 0.59 -0.70 kg CO_2-eq/kg of ammonia (Sadeek *et al* 2020; Samsatli and Samsatli, 2020, Boero *et al* 2021, Marinussen, *et al* 2012 Bicer *et al*. 2016 and 2017, Sadeek *et al* 2019; de Kleijne *et al*. 2022). This would favour wind as the preferred renewable energy resource. However, the combined use of wind and solar PV resources increases the energy available for self-consumption and hence improves the performance of the ammonia production in islanded mode (with no supply of electricity from the national electrical grid).

In the Saldanha bay case study, the energy availability of ammonia synthesis was further increased by including battery energy storage and the addition of a steam turbine to utilise process heat from the ammonia synthesis plant. However, the addition of the steam turbine incurred a 23% additional water demand beyond that required for hydrogen production by electrolysis and the cleaning of solar PV panels. This water requirement amounts to 162 000 m^3/year based on predominantly evaporative wet cooling employed at power stations in South Africa (WRC, 2021). Although this water requirement is met by increased seawater desalination, it is perhaps inappropriate for regions of water scarcity. In addition, the seawater desalination has a considerable electricity demand of approximately 2.93 KWh/m^3 water purified (Zhao *et al*. 2020). Future techno-economic modelling should explore other electrolysis types that could reduce this energy and water requirement and thereby improve efficiency. For example, solid state electrolysis can utilise process heat and has an efficiency of up 80%, compared to 60% to 70% for alkaline and membrane electrolysis (Bhowmik *et al*. 2019; Schmidt *et al*. 2017). Similarly, the electricity requirement for water purification using reverse osmosis could be fully or partially replaced with the thermal distillation of seawater using process heat and mechanical vapour compression desalination (Shamet and Antar 2023).

The certification of low-carbon fuels is underpinned by a joint understanding of the applied methodology used, and confidence in certification is an important enabler of green hydrogen investment and market development. There are several methodological choices in the lifecycle carbon assessment, such as the boundary, scope definition, allocation of co-products and additionality that need to be adequately clarified for certification or to inform policy (de Kleijne *et al*. 2022). While a common methodology for estimating the carbon intensity of GH_2 and derivatives has recently been developed (IPHE 2023 and ISO/TS 19870, 2023), the carbon certification systems are only emerging and have discrepancies for carbon thresholds, the scope definition and where the boundaries are drawn within the supply chain for emissions accounting. These discrepancies and a lack of harmony between certification schemes could mean that they are not recognised between exporting and importing jurisdictions, which would impact the investment and trade and hinder market confidence in low carbon hydrogen. On project development level, this may present an obstacle for a viable business case, since market off-take is a cornerstone of a bankable feasibility project. Several thresholds are based on governments aspirational climate mitigation targets for 2050 such as the Announced Pledges Scenario where the 2050 global average emissions intensity falls below 3 kg CO_2-eq/kg hydrogen, and the Net Zero Scenario where the intensity reaches levels under 1 kg CO_2-eq/kg hydrogen which is required to mitigate climate change by 1.5 ^{0}C. In addition, several countries are developing certification systems for green hydrogen and its derivatives. For example, the Green Hydrogen Organisation has a threshold of 1.0 kg CO_2-eq/kg hydrogen while the Japan Hydrogen Association, EU RED-II specify a 70% reduction compared to grey hydrogen from natural gas, which represents a threshold of 3.4 kg CO_2-eq/kg hydrogen (IEA 2023, Sieler and Dorr 2023).

The current certification of GH_2 and GNH_3 is centred on carbon emissions, which holds significance for its adoption as a suitable fuel for countries to help meet their carbon emission reduction targets. However, for the widespread adoption of GH_2 and/or GNH_3, a comprehensive assessment covering various impact categories, as carried out in this study, will be needed to inform hydrogen policy for a sustainable energy supply (Piria *et al*. 2021). This may also include other local environmental aspects such as direct and indirect land-use change (LUC and iLUC), impacts to endemic biodiversity, and the local availability of water. Some of these aspects can be addressed through strategic environmental impact assessments and the incorporating multi-functionality into land-use such as the integration of agriculture with PV plants (agrivoltaics). In addition, socio-economic and governance aspects will be important such as employment opportunities and balancing the economic opportunities of GNH_3 export with macro-economic and global benefits, compared to local use and local economic development benefits.

The concept of the resource nexus, which emphasizes the interdependencies between different natural resources and systems of provision, provides a useful framework for understanding and managing the complexities of the energy transition (Bleischwitz *et al*. 2018) to help achieve the Sustainable Development Goals. In the context of GNH_3, the resource nexus approach reveals interconnections between the water, energy, and food systems. For instance, the production of green ammonia requires significant amounts of water and energy, and the choice of production location can have implications for land use and the transport of materials. Furthermore, ammonia has an existing use as a fertiliser in agriculture and additional demand for energy may place pressure on already constrained nitrogen cycle. In this regard, GNH_3 as a sustainable energy carrier has the potential to stress the already limited nitrogen resources, since ammonia is used in chemical fertilizers (Galloway *et al*., 2008). Increased production of ammonia for energy may lead to nitrogen shortages, which will affecting crop yields and food security (De Bellis *et al*. 2020). Additionally, the pure water requirement for hydrogen production and ammonia synthesis may increase water scarcity by reducing availability for agriculture and other uses. The water, food and energy nexus of ammonia production necessitates the adoption of sustainable production practices and judicious resource management to ensure that GNH_3 developments contribute to societal needs while protecting natural resources and ecosystems (Guillén-Gosálbez *et al* 2019; Bhowmik *et al*., 2019).

For GNH_3 to meet low-carbon certification criteria and achieve market confidence as a sustainable fuel, a more comprehensive assessment may be needed to incorporate the environmental, social and economic aspects of sustainability. This presents considerable complexity, which can best be addressed through complementary social LCA and Life Cycle Costing of proposed developments. Alternatively, one could consider a multi-objective optimisation and integrated Life Cycle Sustainability Assessment studies (Mathias *et al*., 2010; Valdivia *et al*., 2012; Tock, *et al*. 2015; Azapagic 1999).

Conclusions

This LCA study was based on project designs of a coastal production facility that uses renewable energy from wind and solar PV to desalinate seawater, produce GH_2 and synthesise GNH_3 fuel. The GNH_3 produced could be used in several markets for different end uses, but this study assumed export with the transport of GNH_3 to Europe, cracking to GH_2 and distribution for powering fuel-cell driven heavy duty transport.

The environmental impacts of GNH_3 were compared to grey ammonia produced from natural gas and black ammonia produced from coal. The assessment considered 18 impact categories, but focused on the carbon intensity of GNH_3. Two LCAs were carried out with different system boundaries, namely cradle-to-production gate and cradle-to-grave. The study also assessed various scenarios of ammonia production with different scope regarding the production of co-products and whether the embodied emissions of the renewable energy supply are included in accordance with methodology for the certification of GH_2 as a low-carbon fuel.

The global ambition to mitigate climate change by 1.5 °C requires that near zero carbon fuels (< 1 kg CO_2-eq/kg) are achieved by 2050. The thresholds for certification as a low-carbon fuel range from 0.45 to 5.04 kg CO_2-eq/kg hydrogen, **with several certification systems having a threshold <4 kg CO_2/kg hydrogen. For example, the Japan Hydrogen Association, European Union RED-II specify a 70% reduction compared to grey hydrogen from natural gas, which represents a threshold of 3.4 kg CO_2-eq/kg hydrogen.**

The **cradle-to-production gate** GWP for GNH_3 produced and stored at Saldanha bay port was 0.790 kg CO_2-eq/kg GNH_3. If oxygen, argon and excess electricity are sold to market and allocated a portion of GHG emissions, then the GWP of ammonia is 0.276kg CO_2-eq/kg GNH_3. If embodied emissions associated with capital infrastructure of the energy supply system are excluded in accordance with the recommended methodology for the certification of hydrogen as a low-carbon fuel, then the GWP is 0.106 CO_2-eq/kg ammonia or **0.599 kg CO_2-eq/kg hydrogen** when expressed in terms of hydrogen content of ammonia[12].

Therefore, **GNH_3 produced from coastal production in South Africa are well within this threshold and will achieve certification as a low-carbon fuel.**

In terms of other environment impacts for cradle-to-production gate, GNH_3 has greater impacts than grey and/or black ammonia in some categories, notably eco-toxicity (human, freshwater and marine), human toxicity (carcinogenic and non-carcinogenic), land-use, eutrophication (freshwater and marine) and acidification which could be a concern. However, when these environment impact indicators are normalised and

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[12] *The hydrogen content of ammonia is 17.75%. Therefore, 1 kg hydrogen = 5.67 kg ammonia.*

aggregated to express the damage to areas of protection, GNH$_3$ **has reduced damage to human health, ecosystems and resources.** GNH$_3$ has a reduced damage to human health ($0.21x10^{-05}$; $0.04x10^{-05}$ and $0.04x10^{-05}$ DALY[13] for scenario 1, 2 and 3 respectively), compared to black ammonia ($1.19x10^{-05}$ DALY) or grey ammonia ($0.28x10^{-05}$ DALY); a reduced damage to ecosystems for scenario 1, 2 and 3 ($0.67x10^{-08}$; $0.12x10^{-08}$ and $0.11x10^{-08}$ species.yr[14] for scenario 1, 2 and 3 respectively), compared to black ammonia ($2.92x10^{-08}$ species.yr) and grey ammonia ($0.81x10^{-08}$ species.yr); and reduced damage to resources ($0.49x10^{-01}$; $0.09x10^{-01}$ and $0.06x10^{-01}$ USD2013[15] for scenario 1, 2 and 3 respectively), compared to black ammonia ($2.35x10^{-01}$ USD2013) or grey ammonia ($2.86x10^{-01}$ USD2013).

A **contribution analysis of cradle-to-gate GNH$_3$ production** indicates that the most significant impact categories in contributing to the total environmental impact of GNH$_3$ production is particulate matter (55%), followed by GWP (33%) and water (4%). These impacts are related to the embodied emissions from fossil fuels (coal, oil, natural gas) that were used to generate electricity for the manufacturing of infrastructure in the GNH$_3$ value chain. In addition, the processes or lifecycle stages that have the greatest contribution to the overall environmental impacts are electrolysis (68%), air separation (15%) and ammonia synthesis (13%), which reflects the energy intensity of these processes.

The **extended lifecycle includes transport, distribution and use in heavy duty transport in Germany.** The **cradle-to-grave** GWP of GNH$_3$ was 0.0967 kg CO$_2$-eq/km travelled. If oxygen, argon, and excess electricity are sold and allocated a portion of GWP on a mass basis, then the GWP of GNH$_3$ is 0.0467 kg CO$_2$-eq/km travelled (scenario 2). If embodied emissions associated with the capital infrastructure of the energy supply system are excluded, then the GNH$_3$ carbon emissions are **0.0427 kg CO$_2$-eq/km travelled, which is a >70% reduction compared to grey hydrogen, black hydrogen or diesel fuel, and will likely receive certification as a low carbon fuel.** However, the transportation, cracking, distribution incurs additional carbon emissions of 3.522 kg CO$_2$-eq/kg hydrogen and this may negate the carbon savings of GNH$_3$ production and pose a risk for the certification as a low-carbon fuel. There is uncertainty to the risk of certification, since EU-REDII and TÜV SÜD specifies a 70% reduction from the reference of natural gas which amounts to 3.4 kgCO$_2$-eq /kg hydrogen. If this absolute threshold, rather than a percentage reduction from the appropriate reference fossil fuel is used and applied at the point of consumption (re-fuelling station, cradle-to-tank or well-to-tank) or end-use (cradle-to-grave or well-to-tank), then GNH$_3$ may not achieve certification as a low carbon fuel under EU-RED II and TÜV SÜD schemes since it exceeds these thresholds. However, the threshold for the EU CertifHy scheme is 4.4 kgCO$_2$-eq /kg hydrogen at the point of consumption (See Appendix S8) and GNH$_3$ would meet this threshold. This highlights the current lack of a clarity and uncertainty

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[13] *Disability-adjusted life years (DALY)*

[14] *Biodiversity loss, measured as species lost over time (species.yr)*

[15] *Impacts to resources leading to resource depletion and increasing costs of extraction, US dollars in 2013 (USD2013)*

in the certification schemes needed to meet green market requirements, as well as the lack of interoperability between schemes; which represents a substantial risk to investment and global trade.

In terms of other environment impacts for cradle-to-grave, GNH$_3$ has greater impacts than grey and/or black ammonia in some categories, notably eco-toxicity (human, freshwater and marine), Human toxicity (carcinogenic and non-carcinogenic), land-use, eutrophication (freshwater and marine) and acidification which could be a concern. However, when these environment impact indicators are normalised and aggregated to express the damage to areas of protection, **GNH$_3$ has reduced damage to human health, ecosystems and resources.** GNH$_3$ has a reduced damage to human-health ($2.23x10^{-07}$; $0.88x10^{-07}$ and $0.87x10^{-07}$ DALY for scenario 1, 2 and 3 respectively), compared to black ammonia ($9.62x10^{-07}$ DALY) or grey ammonia ($2.80x10^{-07}$ DALY); reduced damage to ecosystems for scenario 1, 2 and 3 ($0.72x10^{-09}$; $0.28x10^{-09}$ and $0.27x10^{-09}$ species.yr for scenario 1, 2 and 3 respectively), compared to black ammonia ($2.54x10^{-09}$ species.yr) and grey ammonia ($0.83x10^{-09}$ species.yr); and reduced damage to resources ($0.52x10^{-02}$; $0.19x10^{-02}$ and $0.17x10^{-02}$ USD2013 for scenario 1, 2 and 3 respectively), compared to black ammonia ($2.02x10^{-02}$ USD2013) or grey ammonia ($2.44x10^{-02}$ USD2013).

The most significant impact categories contributing to the overall environmental impact for GNH$_3$ cradle-to-grave lifecycle are particulate matter (51%), global warming (39%), and water (3%). These impacts are related to the embodied emissions of manufacturing infrastructure using fossil fuels. The stages/process that make the greatest contribution to the cradle-to-grave overall environmental impacts score are electrolysis (37%), cracking (16%), compression and storage (15%), and air separation process (8%). It is noteworthy that considerable impacts of the cradle-to-grave lifecycle of GNH$_3$ are related to the transport, cracking and distribution to end users in Germany, due to the loss of hydrogen in cracking and the energy intensity of compression and storage.

In conclusion, the transition from fossil fuels, such as coal and natural gas, to GH$_2$ /GNH$_3$ fuels can reduce greenhouse gas emissions in the heavy-duty transport sector and help to mitigate climate change. Compared to fossil fuels such as coal and natural gas, GH$_2$/GNH$_3$ has lower environment impacts in most impact categories and can thereby reduce the damage to human health, ecosystems and resource depletion.

Recommendations

This lifecycle assessment determined the environment impacts of GH_2/GNH_3 production, distribution and use, and provided insight where technology selection, process optimisation and value chain design could substantially influence the environmental impacts. Some recommendations and suggestions for further research are:

- Confidence and consensus building is needed to effectively **inform policy and the certification standards for GH_2/GNH_3.** Currently, a common methodology is being established for **low-carbon fuels** as per scenario 3 (IPHE 2023, and ISO/TS 19870, 2023), but there are different thresholds of carbon intensity of fuel in various certification systems, and inconsistent lifecycle boundaries to define the point of measurement (Sieler and Dörr 2023). The **lack of harmonisation of various certification schemes** creates a risk for mutual recognition and interoperability which represents a **substantial risk to investment and global trade.** In addition to having low GHG emissions, **other environment or socio-economic criteria may be needed to achieve certification.** Identifying and defining these requirements in policy and the certification standards for GH_2/GNH_3 will build confidence in certification and the local and global market, and thereby support low-carbon ammonia in the Just Energy Transition (Denton *et al*. 2022). In this regard, the Green Hydrogen Organisation is paving the way for harmonisation of a global Green Hydrogen Standard to help ensure unanimous project-level certification and accreditation (www.gh2.org and GHS, 2023).
- Green ammonia requires a **substantial energy supply from renewables** to assure a low environment impact, including a low-carbon footprint. This requires that:
    i. **Renewable energy is used for all stages of the product lifecycle.** In particular, this study revealed that renewable energy is needed not only for the production of GH_2 and GNH_3, but also for the transport of GNH_3 and distribution of GH_2 to the end user. The energy intensity in the distribution of hydrogen to end-use, as well as the hydrogen lost in cracking, can incur substantial carbon emissions that could negate many of the carbon savings from the production of GNH_3. Moreover, this presents a risk of not achieving certification as a low-carbon fuel and/or facing additional fuel levies from the EU Carbon Border Adjustment Mechanism (CBAM, 2023). This presents a significant investment and development risk, since if GH_2/GNH_3 does not attract a green price premium in the market it may well be deemed unsuitable as a fuel for decarbonisation in the transport sector. A solution to reduce the transport related impacts could be the use of GH_2/GNH_3 as a maritime fuel, while reducing the distribution related impacts could involve the use of pipelines for the distribution of GH_2 or the GNH_3 fuel used directly in heavy vehicles that incorporate on-board cracking (www.amogy.co). The environment lifecycle impacts of different GH_2/GNH_3 distribution and use options warrants further research.

ii. There is **additionality of the renewable energy** to ensure that new renewable energy is generated for, and dedicated to, the energy required for GNH_3 production, as described in EU RED-II legislation for Renewable Fuels of Non-Biological Origin (Lexology 2023, EC 2024, EUR-Lex 2023). This is the case for the Saldanha bay case study with islanded production and self-consumption increased with battery storage and a steam turbine, with only unidirectional export to the connected grid. However, in cases where the GH_2/GNH_3 production is grid-connected and imports electricity from the grid, a renewable energy certificate (REC) with proven temporal and spatial matching of energy supply and demand is needed (Lexology 2023, EC 2024).

iii. **Renewable energy is used for the manufacture of capital,** namely the solar PV and wind power infrastructure, which implies a rapid transition of manufacturing countries to a have a high percentage of renewables in the country energy supply mix. The increased **recycling of infrastructure** with avoid some future burdens by displacing the need for virgin metal and materials production. Of note, any plant design should consider recycling of the foreseen large scale solar PV and wind power infrastructure, particularly since attaining recycling targets for electrical and battery sector is mandated in South Africa's recent Extended Producer Responsibility legislation (EPR 2020). Recycling could also reduce resource depletion with the recovery of critical raw materials used in the renewable energy infrastructure (solar PV, wind power and battery), such as aluminium, copper, iron, lead, nickel, zinc, silver, cadmium, molybdenum, selenium, tin, tellurium dysprosium and neodymium (Carrara *et al*. 2020). Further research with techno-economic and environment assessments of recycling critical raw materials is needed.

- The techno-economic optimisation of GNH_3 production to increase **energy self-sufficiency and energy availability** for the ammonia synthesis plant effectively used solar PV plus wind power, a Li-ion battery for electricity storage, and additional electricity generation from a steam turbine utilising the waste heat from ammonia synthesis. However, the installation of the steam turbine with wet cooling increases the **water demand** by 24%, which amounts to 162 000 m^3 per annum or 0.648 litres per kg GNH_3 produced. This freshwater requirement was met by the reverse osmosis of seawater, but this could be considered a poor use of water resources in semi-arid regions, such as many parts of South Africa. Utilising once-through wet-cooling with seawater is a potential solution, but the thermal impacts to aquatic life would be a concern. The use of dry cooling could reduce the water requirement by an order of magnitude, although at a substantial added cost (WRC, 2021). Alternatively, **other renewable energy supply and storage systems** can be considered in future optimisation.

- The optimisation of a GNH_3 plant design could benefit **from additional renewable energy and battery storage oversizing,** as well as exploring **different battery chemistries** such as vanadium redox flow batteries that have advantages at utility scale (Capital10x, 2023; Karrech, 2024). Furthermore, the electricity demand could decrease through the **effective use of process heat** from ammonia synthesis, which could be used to purify seawater by distillation instead of reverse osmosis and/or to generate hydrogen using solid state electrolysers instead of alkaline electrolysers (Shamet and Antar 2023).
- The results reveal the environment benefits of co-products (electricity, argon and oxygen) in the sense that the impacts are allocated amongst the product and co-products, and therefore GNH_3 receives a portion of the overall lifecycle impacts. The production of electricity is valuable co-product in South Africa where there is incomplete electrification and national electricity supply is already constrained. However, achieving a favourable price requires that generation matches demand, which is a challenge since the supply of excess electricity from the renewable energy is intermittent. The combined solar PV and wind power produces most electricity in excess of requirements around midday, and therefore the offtake market may be limited. In addition, the GNH_3 is a bulk commodity with high market volumes, while the oxygen and argon that is co-produced is a fine chemical or specialty chemical commodity with low to medium market volume. In other words, while there are existing markets for oxygen and argon co-products, the market potential may be limited. More detailed research and market analysis is needed to estimate the potential of these co-products.
- There is also a unique opportunity to produce water as a co-product. South Africa is a semi-arid country and has already faced threatening water shortages in the Western Cape. Therefore, all electricity in excess of that required for GNH_3 production could be used for desalination and the pure water sold for potable, domestic or industrial consumption. In addition, the brine from desalination is a waste sent back to sea and, while these marine impacts are largely unknown and require further impact assessment studies, there is also perhaps an opportunity to use brine as a source of several valuable metals since sodium, magnesium, calcium and boron are found at high concentrations, and lithium, rubidium, strontium or gallium at minor concentrations (del Villar *et al*. 2023).
- Upscaling the Saldanha bay 280 kt per annum GNH_3 production plant to the region through further research with strategic environmental site selection studies to determine maximum feasible potential is highly desirable. **Upscaling is needed to obtain the economies of scale of production and compete in the growing global markets for PtX fuels or e-fuels** (Markets and markets 2030). If the Saldanha bay prototype can be replicated in the region, and beyond, a significant share of the growing global hydrogen market can be achieved, perhaps beyond that foreseen by the South African Hydrogen Commercialisation strategy, which has a target GH_2

annual production of 0.5 Mt per annum by 2030, and to double the share of the global market to 4% by 2050 (McKinsey 2023, and DST 2021). A new and dedicated renewable energy supply is required, since electricity availability and the national grid is constrained in South Africa and there is an additionality requirement for GNH_3 to be certified as a low-carbon fuel. Therefore, additional renewable energy capacity coupled to a micro-grid connecting several GNH_3 production centres could be a unique value proposition, since it may serve to:

i. increase the availability of renewable energy and thereby reduce the unit cost of GNH_3 production,

ii. reduce the costs of storage and distribution, since it is generally more cost-effective to move electricity than GH_2/GNH_3, and

iii. supplement and extend the existing electricity grid infrastructure to stimulate secondary socio-economic benefits from local rural electrification. For example, a micro-grid connecting Saldanha bay SEZ to Atlantis, Boegoebaai and/or Musina could be explored.

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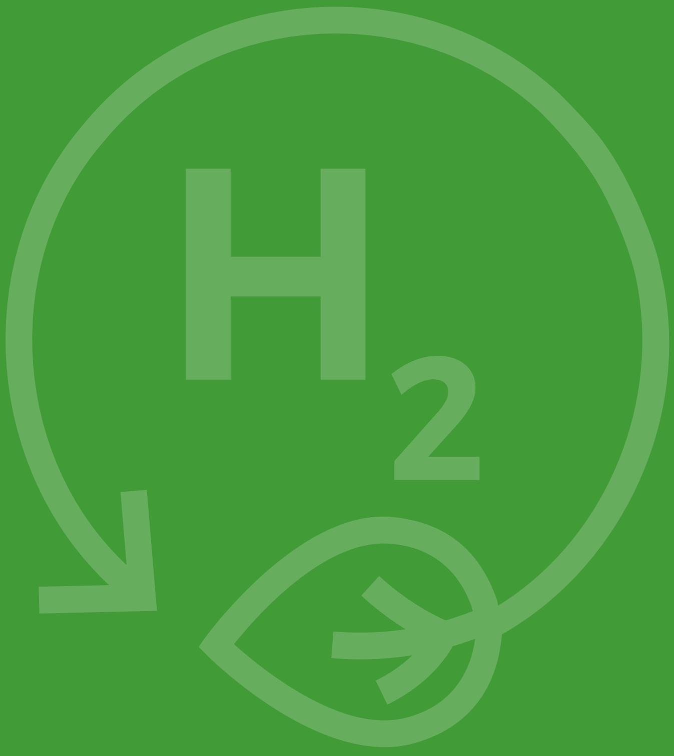

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Supplementary information

Supplementary information

Table 5: Overview of Saldanha bay GNH$_3$ production

Process Unit	Technology	Parameter	Value	Unit	Reference
Renewable Energy Generation Plant	Wind and Solar Farm	Solar Farm Capacity	1515	MW	
		Wind Farm Capacity	379	MW	
		Combined Capacity Factor	0.26		
		Renewable Energy generation	4311	GWh/year	
Water Treatment	Seawater Reverse Osmosis (SWRO)	Specific energy consumption	4.1	KWh/m^3	(Pinto ,2020)
		Annual Production	717 000	m^3 of Treated water	
		Energy consumption per Annum	2.9	GWh	
Electrolyser	Alkaline Water Electrolysis	Design Output	150.3	t H_2/day	
		Specific energy consumption	49.11	KWh/kg H_2	(PFS)
		Annual Capacity Factor	0.630		
		Annual Production	52 000	t H_2/year	
		Energy consumption per Annum	1609	GWh/year	
		Capacity	660	t N_2/day	
Air Separation Unit	Cryogenic Air Separation	Design Power Demand	6.8	MW	
		Specific energy consumption	0.243	kWh/kg N_2	(PFS)
		Capacity Factor	0.82		
		Energy consumption Per Annum	60	GWh/year	
		Annual Production	242 000	t N_2/year	
		Capacity	294 000	t N_2/year	

Process Unit	Technology	Parameter	Value	Unit	Reference
Ammonia Plant	Haber-Bosch synthesis	Design Power Demand	15.57	MW	
		Specific energy consumption	0.44	kWh_e/ kg_{NH3}	(PFS)
		Annual Production	280 000	t NH_3/year	
		Annual Capacity Factor	0.95		
		Energy consumption Per Annum	123.3	GWh/year	

Table 6: Metal recycling process for GH_2 /GNH_3 infrastructure

Metals	Process description	Data source Ecoinvent
Aluminium	The model starts with the reception of prepared post-consumer Aluminium scrap, remelting and ends with wrought Aluminium billets	Aluminium scrap, post-consumer, prepared for melting {RoW}| treatment of aluminium scrap, post-consumer, prepared for recycling, at remelter | APOS, U
Copper	The model includes the collection, handling and the refining of copper scrap to copper cathodes	Copper scrap, sorted, pressed {RoW}| treatment of copper scrap by electrolytic refining | APOS, U
Nickel	The modelling start upon delivery of nickel-rich materials including the electrorefining of nickel rich materials end with the production of nickel, class 1.	Nickel, class 1 {GLO}| processing of nickel-rich materials | APOS, U
Steel	Iron scrap, sorted, pressed, smelting, and refining to produce hot rolled steel	Hot Rolling Steel recyclate from steel scrap processed with Electric Arc Furnace (EAF) (Birat ,2020)

Table 7: LCI for each process in the production of GNH_3, transport, distribution and use in heavy duty transport

Renewable energy mix		Amount	Modification
Output	Renewable Electricity Mix-NO INVERTER	1 KWh	
Input	Electricity, low voltage {RoW-ZA water} | electricity production, photovoltaic, 570kWp open ground installation, multi-Si | APOS, U	KWh	Modified by removing the inverter, electronic-grade silicon from casted silicon production mix inputs, silicon carbide from silicon wafer production inputs and polystyrene from silicon wafer production inputs.
	Electricity, high voltage {ZA}| electricity production, wind, >3MW turbine, onshore | APOS, U	0.2 KWh	Material of construction replaced with South African material
Waste treatment	Steel and iron (waste treatment) {GLO}| recycling of steel and iron by (EAF) | APOS, U	2.48 g	Represent steel recycling process UNEP (2020), BIR (2019).
	Aluminium scrap, post-consumer, prepared for melting {RoW-}| treatment of aluminium scrap, post-consumer, prepared for recycling, at remelter | APOS, U	0.597 g	Represent aluminium recycling process UNEP (2020)
	Copper scrap, sorted, pressed {RoW}| treatment of copper scrap by electrolytic refining | APOS, U	0.039 g	Represent copper recycling process UNEP (2020) International Copper Association, (2020).
	Nickel (waste treatment) {GLO}| recycling of nickel scrap | APOS, U	3.96E-6 g	Represent nickel recycling process UNEP (2020) Reck B. (2015)

Notes: The solar PV in the Ecoinvent database for South Africa was based on a 2009 source with outdated technologies solar PV and was modified as described.

Water treatment		Amount	Modification
Output	Treated water	9	
Input	Water works, capacity 6.23E10l/year {GLO}| water works construction, capacity 6.23E10l/year, seawater reverse osmosis, ultrafiltration pre-treatment | APOS, U	4.82E-12 p	Represent SWRO process. Material of construction replaced with South Africa material
	Water, process, salt, ocean	21.4 kg	None
	Renewable Electricity Mix-NO INVERTER	0.0369 KWh	
Emissions to Water	Water, ZA	11.6 l	Ortega Méndez *et al* 2012, suggest the composition of brine and this was calculated and modelled based on the water rejected/effluent from SWRO. This was added to emissions to water (see below)
	Sodium	232.0746 g	
	Chloride	437.999 g	
	Sulphate	68.32586 g	
	Magnesium	27.69292 g	
	Calcium	13.05658 g	
	Potassium (I)	10.9709 g	
	Bicarbonate, ion	3.43542 g	
	Silicon dioxide	0.5394 g	
	Carbonate	0.062 g	
	Nitrate	0.15376 g	
	Nitrite	0.00062 g	
	Ammonium, ion	0.00186 g	
	Iron (II)	0.00124 g	
Waste treatment	Aluminium scrap, post-consumer, prepared for melting {RoW-}| treatment of aluminium scrap, post-consumer, prepared for recycling, at remelter | APOS, U	0.003 g	Represent aluminium recycling process UNEP (2020)
	Steel and iron (waste treatment) {GLO}| recycling of steel and iron by (EAF) | APOS, U	0.00825 g	Represent steel recycling process UNEP (2020) BIR (2019).

Notes: The plant is assumed to have a 30-year lifetime. The average production of the reverse osmosis. SWRO plant is 170 500 m3/day of treated water. Recovery rate of the reverse osmosis system is 41%.

Seawater/ocean water was not available as input from nature, Water, process, salt, ocean was used to represent Seawater/ocean water.

Hydrogen production		Amount	Modification
Output	Hydrogen gas	1 kg	
	Oxygen gas	8 kg	
Input	Treated water	9 kg	
	Electrolyser. Consisting of:	0.596 kg	Electrolyser unit was modelled according to Zhao *et al.* (2020) that provides the raw materials to construct a 1 m^2 electrolyser with a production of 19 tonne/ m^2 H_2 over its lifetime of 15 years.
	Nickel, class 1 {ZA}| platinum group metal, extraction and refinery operations | APOS, U	0.366 kg	
	Steel, stainless 304, flat rolled coil/kg/ RNA	0.123	
	Zirconium oxide {GLO}| market for | APOS, U	5.01x10-3 kg	
	Polysulfone {GLO}| market for | APOS, U	8.8ex10-4 kg	
	Electricity, medium voltage {ZA}| market for | APOS, U	7.26x10-5 KWh	
	Polyphenylene sulfide {GLO}| market for | APOS, U	0.102 kg	
	Hydrogen, liquid {RER}| potassium hydroxide production | APOS, U	3.7E-5 kg	None
	Chemical factory, organics {RoW}| construction | APOS, U	4.0E-10 p	Represent the building that house the electrolyser. Material of construction replaced with South Africa material
	Transport, freight, lorry 7.5-16 metric ton, EURO2 {ZA}| market for transport, freight, lorry 7.5-16 metric ton, EURO2 | APOS, U	0.0207 tkm	Diesel used replaced with South Africa diesel.
	Renewable Electricity Mix-NO INVERTER	49.11	KWh
Waste treatment	Steel and iron (waste treatment) {GLO}| recycling of steel and iron by (EAF) | APOS, U	2.99 g	Represent aluminium recycling process UNEP (2020) BIR (2019).
	Aluminium scrap, post-consumer, prepared for melting {RoW}| treatment of aluminium scrap, post-consumer, prepared for recycling, at remelter | APOS, U	0.353 g	Represent aluminium recycling process UNEP (2020)

Hydrogen production		Amount	Modification
Waste treatment	Copper scrap, sorted, pressed {RoW}| treatment of copper scrap by electrolytic refining | APOS, U	0.12 g	Represent copper recycling process UNEP (2020) International Copper Association, (2020).
	Nickel (waste treatment) {GLO}| recycling of nickel scrap | APOS, U	0.000115 g	Represent nickel recycling process UNEP (2020) Reck (2015)

Hydrogen gas storage		Amount	Modification
Output	Stored Hydrogen gas	1 kg	
Input	Hydrogen gas	1 kg	
	Liquid storage tank, chemicals, organics {RoW}| production // Kolobe//| APOS, U	$7.74E^{-12}$	Material of construction replaced with South African material
	Renewable Electricity Mix-NO INVERTER	1.7 KWh	
Waste treatment	Steel and iron (waste treatment) {GLO}| recycling of steel and iron by (EAF) | APOS, U	0.0996 g	Represent steel recycling process UNEP (2020), BIR (2019).
	Copper scrap, sorted, pressed {RoW}| treatment of copper scrap by electrolytic refining | APOS, U	0.000284 g	Represent copper recycling process UNEP (2020); International Copper Association, (2020).
	Aluminium scrap, post-consumer, prepared for melting {RoW}| treatment of aluminium scrap, post-consumer, prepared for recycling, at remelter | APOS, U	0.000823 g	Represent aluminium recycling process UNEP (2020)

Note: 14 days of storage and 0.1% hydrogen loss per day (Andersen and Grönkvist 2019)

Nitrogen production		Amount	Modification
Output	Nitrogen liquid	0.234	kg
Input	Argon-40/kg	0.00985	Kg
	Nitrogen, atmospheric	0.531	Kg
	Oxygen	0.163	Kg
	Water, cooling, unspecified natural origin, RoW	0.0214	kg
	Air separation facility {GLO}| market for | APOS, U	4.432E-10 p	Material of construction replaced with South Africa material (Aluminium)
	Renewable Electricity Mix-NO INVERTER	0.563 KWh	
Emissions to air	Nitrogen, atmospheric	0.296 kg	Added to emissions to air
	Argon-40/kg	5.5E-5 kg	Added to emissions to air
	Oxygen	0.162 kg	Added to emissions to air
	Water/m3	0.00828 M^3	None
Emissions to Water	Water, RoW	0.0131 M^3	None
Waste treatment	Aluminium scrap, post-consumer, prepared for melting {RoW}| treatment of aluminium scrap, post-consumer, prepared for recycling, at remelter | APOS, U	0.00286 g	Represent aluminium recycling process UNEP (2020)
	Steel and iron (waste treatment) {GLO}| recycling of steel and iron by (EAF) | APOS, U	0.0201 g	Represent steel recycling process UNEP (2020); BIR (2019).

Notes: Oxygen and argon were added to emissions to air. 2% w/w argon was added to the nitrogen stream. Electricity supply to ASU was replaced with on-site renewable

Liquid nitrogen storage		Amount	Modification
Output	Liquid nitrogen stored	4.6 kg	
input	Liquid nitrogen	4.6 kg	
	Liquid storage tank, chemicals, organics {RoW}| production | APOS, U	$7.11E^{-9}$ p	Material of construction replaced with South African material
	Renewable Electricity Mix-NO INVERTER	0.431 KWh	
Waste treatment	Steel and iron (waste treatment) {GLO-Kolobe}| recycling of steel and iron by (EAF) | APOS, U	2.25 g	Represent steel recycling process UNEP (2020) BIR (2019).

Liquid ammonia production		Amount	Modification
Output	Liquid ammonia	5.3 kg	
Input	Chemical factory, organics {RoW}| construction | APOS, U	2.12E-9 p	Electricity supply was replaced with on-site renewable energy
	Aluminium oxide, metallurgical {RoW}| market for aluminium oxide, metallurgical | APOS, U	$1.422E^{-9}$ kg	None
	Hydrogen, liquid {RER}| potassium hydroxide production | APOS, U	$4.74E^{-10}$ kg	None
	Magnetite {GLO}| market for | APOS, U	4.55E-8 kg	None
	Nitrogen gas	4.6 kg	
	Hydrogen gas	1 kg	
	Renewable Electricity Mix-NO INVERTER	2.33 KWh	
Emissions to air	Nitrogen, atmospheric	0.229 kg	None
	Argon-40/kg	0.178 kg	None
	Hydrogen	0.05 kg	None
Waste treatment	Steel and iron (waste treatment) {GLO}| recycling of steel and iron by (EAF) | APOS, U	14.2 g	Represent steel recycling process UNEP (2020) BIR (2019).
	Copper scrap, sorted, pressed {RoW}| treatment of copper scrap by electrolytic refining | APOS, U	0.568 g	Represent copper recycling process UNEP (2020) International Copper Association, (2020).
	Aluminium scrap, post-consumer, prepared for melting {RoW}| treatment of aluminium scrap, post-consumer, prepared for recycling, at remelter | APOS, U	1.68 g	Represent aluminium recycling process UNEP (2020)

Notes: Chemical factory, for the ammonia synthesis (Haber-Bosch) includes land use, building and facilities (including dismantling) of an average chemical plant. It represents the building and reactor needed to produce ammonia. The chemical factory has an annual production volume of 50E6 kg of product. and a 50-year lifespan.

Liquid ammonia storage		Amount	Modification
Output	Liquid ammonia stored	5.3 kg	
Input	Liquid ammonia	5.3 kg	
	Liquid storage tank, chemicals, organics {RoW}| production | APOS, U	10E-9 P	Material of construction replaced with South African material
	Renewable Electricity Mix-NO INVERTER	0.000376 KWh	
Waste treatment	Steel and iron (waste treatment) {GLO}| recycling of steel and iron by (EAF) | APOS, U	2.74 g	Represent aluminium recycling process BIR (2019). UNEP (2020)

Transportation and storage		Amount	Modification
Output	Ammonia Transported and stored	5.3 kg	
Input	Transport, freight, sea, tanker for liquefied natural gas {GLO}| market for transport, freight, sea, tanker for liquefied natural gas | APOS, U	71.2 tkm	None
	Liquid storage tank, chemicals, organics {RoW}| production | APOS, U	10E-9 p	None
	Liquid ammonia storage	5.3 kg	

Ammonia cracking		Amount	Modification
Output	Hydrogen from cracking	0.797 kg	
Input	Chemical factory, organics {RoW}| construction | APOS, U	2.12e-9 p	None
	Liquid ammonia storage	5.3 kg	
	Electricity, medium voltage {DE}| market for | APOS, U	1.54 KWh	None
Emissions to air	Hydrogen	0.141 kg	

Notes: Chemical factory, for the ammonia cracking includes land use, building and facilities (including dismantling) of an average chemical plant. It represents the building and ammonia cracker needed to ammonia to hydrogen. The chemical factory has an annual production volume of 50E6 kg of product. and a 50-year lifespan.

Hydrogen storage		Amount	Modification
Output	Compressed hydrogen	0.6778 kg	
Input	Air compressor, screw-type compressor, 4kW {RER}| production | APOS, U	5.46E-6 p	None
	Liquid storage tank, chemicals, organics {RoW}| production | APOS, U	2.6e-8 p	None
	Hydrogen from cracking	0.797 kg	
	Electricity, medium voltage {DE}| market for | APOS, U	0.119 kg	None
Emissions to air	hydrogen	0.119 kg	

Hydrogen distribution		Amount	Modification
Output	Hydrogen distributed in Germany	0.6778 kg	
Input	Hydrogen from compression	0.6778 kg	
	Transport, freight, lorry >32 metric ton, euro6 {RER}| market for transport, freight, lorry >32 metric ton, EURO6 | APOS, U	0.31 tkm	None

Hydrogen utilisation		Amount	Modification
Output	Distance/Kilometres travelled	64.7 Km	Based on vehicle energy efficiency of 96.5 km/kg H$_2$ (Peterson *et al*. 2024)
Input	Hydrogen distribution	0.6778 kg	
	Heavy-duty hydrogen fuel cell electric vehicle. Consisting of:	4.43x10^{-04} kg	Heavy duty fuel-cell vehicle was based on PEM fuel cell stack process in Ecoinvent of 110 kg (Patterson *et al*., 2014), which was scaled up for a heavy-duty truck, Toyota Mirai, that required 228 kg fuel cell (Yoshida and Kojima, 2015), 130 kg Li-ion battery, 145 kg electric motor (Marcinkoski *et al*., 2016) and 5092 kg glider components. The energy for assembly is 1977 kWh electricity and 2974 MJ heat (Wolff *et al*., 2020).
	Fuel cell, polymer electrolyte membrane, 2kW electrical, future {GLO}| market for | APOS, U	8.58x10^{-08} p	
	Glider, passenger car {GLO}| production | APOS, U	4.20x10^{-04} kg	
	Electric motor, vehicle {RoW}| production | APOS, U	1.20x10^{-05} kg	
	Battery, Li-ion, NCA, rechargeable, prismatic {RoW}| battery production, NCA, Li-ion, rechargeable, prismatic | APOS, U	1.07x10-05 KWh	
	Electricity, medium voltage {DE}| market for | APOS, U	1.63x10-04 kg	
	Heat, district or industrial, natural gas {DE}| heat and power co-generation, natural gas, conventional power plant, 100MW electrical | APOS, U	2.43E-05 MJ	
Emissions to air	Water	6.1 kg	

Table 8: Carbon certification schemes and thresholds Data from Sieler and Dörr (2023)

Further information at: https://www.iea.org/reports/global-hydrogen-review-2024/table-overview-of-existing-and-planned-certification-systems-and-regulatory-frameworks

Certifying body or standard or Country Policy	Hydrogen carbon intensity (kg CO_2-eq/kg H_2)	Ammonia carbon intensity (kg CO_2-eq /kg NH_3)[1]	Energy carbon intensity (g CO_2-eq /MJ)[2]
US, Threshold for highest possible tax credit (US, well-to-gate)	0.45	0.08	3.75
US threshold for lowest tax credit (US, well-to-gate)	3.96	0.70	33
EU Standard for RFNBO RED-II (EU, well-to-wheel)	3.38	0.59	28.2
CertifHy Standard (EU, well-to-gate)	4.37	0.78	36.4
TÜV Süd (Germany, well-to-wheel)	3.38	0.59	28.2
Proposed Standard Japan Hydrogen Association (Japan, well-to-gate)	3.40	0.60	28.3
Hydrogen Alliance Suggestion (China, well-to-wheel)	4.92	0.87	41
Tentative Certification Threshold (Korea, well-to-gate)	5.04	0.89	42

1. *The hydrogen content of ammonia is 17.65%. Therefore, 1 kg hydrogen = 5.67 kg ammonia*
2. *Hydrogen=120 MJ/kg*

Notes

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