Front. Energy 2025, 19(6): 1072–1092
https://doi.org/10.1007/s11708-025-1013-5

RESEARCH ARTICLE

Life cycle assessment of green ammonia production at a coastal facility in South Africa

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Abstract A just energy transition (JET) to low-carbon fuels, such as green hydrogen, is critical for mitigating climate change. Countries with abundant renewable energy resources are well-positioned to meet the growing global demand for green hydrogen. However, to improve the volumetric energy density and facilitate transport and distribution over long distances, green hydrogen needs to be converted into an energy carrier such as green ammonia. This study conducted a comparative life cycle assessment (LCA) to evaluate the environmental impacts of green ammonia production, with a particular focus on greenhouse gas (GHG) emissions. The boundary of the study was from cradle-to-production gate, and the design was based on a coastal production facility in South Africa, which uses renewable energy to desalinate seawater, produce hydrogen, and synthesise ammonia. The carbon intensity of production was 0.79 kg CO_2-eq per kg of ammonia. However, if co-products of oxygen, argon and excess electricity are sold to market and allocated a portion of GHG emissions, the carbon intensity was 0.28 kg CO_2-eq per kg of ammonia. Further, without the sale of co-products but excluding the embodied emissions of the energy supply system, as defined in the recent international standard (ISO/TS 19870), the carbon intensity was 0.11 kg CO_2-eq per kg of ammonia. Based on the hydrogen content of ammonia, this is equivalent to 0.60 kg CO_2-eq per kg of hydrogen, which is well below the current threshold for certification as a low-carbon fuel. The process contributing most to the overall environmental impacts was electrolysis (68%), with particulate matter (55%) and global warming potential (33%) as the dominant impact categories. This reflects the energy intensity of electrolysis and the carbon intensity of the energy used to manufacture the infrastructure and capital goods required for green ammonia production. These findings support the adoption of green ammonia as a low-carbon fuel to mitigate climate change and help achieve net-zero carbon emissions by 2050. However, achieving this goal requires the rapid decarbonisation of energy supply systems to reduce embodied emissions from manufacturing infrastructure.

Keywords greenhouse gas emissions (GHGs), just energy transition (JET), life cycle assessment (LCA), power-to-X (PtX), standards and certification

1 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 [1]. Renewable energy sources, such as wind and solar power, are increasingly harnessed to supply low-carbon energy for the transition to a more sustainable development path. However, the intermittent nature and uneven distribution of these renewable energy resources necessitates the development of efficient energy storage and energy carrier systems. Power-to-X (PtX) technology, which produces low-carbon fuels from renewable electricity (e-fuels), has the potential to play a crucial role in this energy transition by providing energy carriers that enable the storage and transportation of energy from regions with abundant renewable resources to distant energy markets [2]. This provides an opportunity for sustainable development through a just energy transition (JET) that not only mitigates the global risks of climate change, but also creates job opportunities

Received Jul. 23, 2024; accepted Mar. 25, 2025; online Jun. 10, 2025
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to foster inclusive economic growth [3].

In this context, green ammonia has emerged as a promising low-carbon energy carrier due to its high energy density and ease of storage and transport [4–6]. Ammonia has a volumetric hydrogen density of approximately 123 kg hydrogen/m^3, which surpasses alternatives such as metal hydrides (25 kg hydrogen/m^3), liquefied hydrogen (71 kg hydrogen/m^3), and methanol (99 kg hydrogen/m^3), allowing it to store more hydrogen in a given volume [7]. The liquefication of ammonia is relatively straightforward and achieved through mild compression (1 MPa at ambient temperature) or cooling (−33 °C at atmospheric pressure), while the liquefication of hydrogen requires cryogenic cooling to an extreme temperature of −253 °C. Furthermore, the high chemical stability and low flammability of ammonia compared to pure hydrogen enhances ease of handling and safety. Green ammonia is an energy carrier that has various end-use applications, including electricity generation, industrial process heat and cooling, and as a transportation fuel [8].

There is a growing global demand for green hydrogen and its derivatives. Over 50 countries have national hydrogen strategies aimed at producing 27–35 million tonnes of low-emission hydrogen by 2030, and global green hydrogen trade is expected to reach up to 70 million tonnes by 2050. There are numerous green hydrogen projects at various stages of development, with a combined production target of 31 million tonnes, of which 16 million tonnes are from countries who intend to export (February 2024) [4,9,11]. Countries such as those in the European Union and Japan have strong policy support for hydrogen and are expected to be net importers due to limited domestic production potential relative to their future demand for low-carbon energy [10,11]. These countries will rely on regions with abundant renewable energy sources, such as Australia, South America, Middle-East and Africa, that are well-positioned to become key exporters of green hydrogen [11]. A recent study on the production potential in Africa indicates that Egypt, Morocco, and South Africa have abundant renewable energy resources and access to coastal ports, thereby providing an excellent opportunity to develop PtX for export markets, improve energy security, and mitigate climate change [12,13].

The South African Hydrogen Society Roadmap and the Green Hydrogen Commercialisation Strategy places hydrogen as a key driver for a just energy transition (JET) that diversifies energy sources, increases exports, stimulates economic growth, creates jobs opportunities, and reduces GHG emissions in alignment with international climate commitments [14,15]. Studies in various countries indicate that green ammonia produced with renewable energy sources can dramatically reduce GHG emissions, compared to conventional ammonia production methods [16–21]. Previous estimates of the carbon intensity of ammonia production ranges from 0.09 to 0.70 kg CO_2-eq per kg of ammonia (equivalent to 1.36–3.97 kg CO_2-eq per kg of hydrogen, based on the hydrogen content of ammonia) [17–19], which can reduce GHG emissions by up to 91% compared to ammonia produced from natural gas [16]. The energy source used for ammonia production is a key determinant of its carbon intensity [20,21], with a high proportion of renewable energy in the electricity supply or carbon capture and storage necessary for achieving significant reductions in carbon emissions [16]. Although several studies have assessed the environmental impacts of green hydrogen and green ammonia production, none have examined lifecycle impacts in the developing country context of South Africa, particularly within the global framework of a JET.

Further, the methods for assessing and accounting for the environmental impacts of PtX production which underpins policy support and certification schemes, remains inconsistent [10]. The certification schemes for PtX fuels, such as green hydrogen and green ammonia, are still developing, and there are discrepancies in the environmental impact category criteria, thresholds, and boundaries for emissions accounting across the different schemes. In addition, some certification schemes or policy require 100% renewable energy supply and the additionality of energy to ensure that renewable energy is built for, and dedicated to, the production of green hydrogen and associated energy carriers [22,23]. However, the main criteria for certification schemes are the GHG emissions or carbon intensity of production, which is required to meet market specifications and fulfil climate mitigation targets for 2050. These targets include the Announced Pledges Scenario with a carbon intensity below 3 kg CO_2-eq per kg of green hydrogen, and the Net Zero Scenario with a carbon intensity less than 1 kg CO_2-eq per kg of hydrogen [5,9]. Several certification schemes for green hydrogen are under development, with varying thresholds of carbon intensity. For example, the Green Hydrogen Organization sets a threshold of 1.0 kg CO_2-eq per kg of hydrogen, while the Japan Basic Hydrogen Strategy and the European Union Renewable Energy Directive (EU-RED II) set a 70% reduction compared to grey hydrogen, or a threshold of 3.4 kg CO_2-eq per kg of hydrogen, while the China's Alliance sets the threshold at 4.9 kg CO_2-eq per kg of hydrogen [9,10]. These discrepancies could lead to certification schemes not being recognized between exporting and importing jurisdictions, which would limit the development of global markets and trade of hydrogen and associated energy carriers [23,24].

This study aims to contribute to the ongoing discourse on renewable energy strategies and a JET by providing a detailed LCA of the environmental impacts of green ammonia produced at a coastal facility in South Africa. Specifically, the LCA explores how the GHG emissions of green ammonia production are influenced by assumptions regarding the boundary and scope of the study, particularly concerning embodied emissions from the manufacturing renewable energy infrastructure and the production of co-products (oxygen, argon and electricity). It also conducts a comprehensive environmental impact assessment to understand the types and magnitude of impacts across the green ammonia lifecycle. This study aims to clarify the boundary and scope assumptions necessary for a robust comparison of the environmental performance of green ammonia production, ultimately improving the interoperability of certification schemes for green ammonia and other PtX fuels. Furthermore, it provides *ex-ante* insights into the design of green ammonia production to help ensure that it meets the specifications and market requirements of potential importing countries.

2 Methods

This study employed an attributional LCA in accordance with the principles, framework, requirements and guidelines set by the International Organisation for Standardization (ISO 14040 and ISO 14044, 2006) [25]. Accordingly, it follows the main stages of goal and scope definition, life cycle inventory (LCI) analysis, life cycle impact assessment, and interpretation. The ReCiPe environmental impact assessment method was used [26], which includes the IPCC method to assess GHGs and the global warming potential over 100 years [27]. The SimaPro 9.5 software [28], along with the Ecoinvent 3.9.1 database [29,30] were used to conduct the modelling and the assessment.

The following assumptions were made in the LCA:

- Global supply of materials and technology: Materials were sourced from global markets, while construction and operation processes were localized in South Africa. Data sets were adjusted to reflect South Africa’s energy supply (fuels and electricity) for these processes.
- Infrastructure: The infrastructure was included, considering the stages of commissioning, operational lifetime, decommissioning, and waste treatment. However, in Scenario 3, renewable energy infrastructure was specifically excluded from the analysis.
- Recycling: The recycling of metals (nickel, copper, iron, and aluminium) was included based on established practices and recycling rates in South Africa [31–34]. However, the recycling of solar photovoltaics (PVs) and wind infrastructure was not considered, as these components currently lack an established recycling in South Africa.
- Fugitive hydrogen emissions: The global warming potential of fugitive hydrogen emissions was not included in the impact assessment, as hydrogen is not currently recognised as a GHG in the Intergovernmental Panel on Climate Change (IPCC) methodology [27]. However, recent research suggests that hydrogen may be an indirect GHG with a global warming potential over 100 years estimated to be 12.8 times that of carbon dioxide [35].

2.1 Goal

The goal of the study is to assess the environmental impacts of green ammonia produced in South Africa at a coastal production facility using renewable energy from wind and solar. A total of 18 environmental impact categories were assessed, with a primarily focus on GHG emissions and the climate change impacts related to its certification as a low-carbon fuel. The study compares the carbon emission reductions of green ammonia production to the conventional production of grey ammonia from natural gas (Asia) and black ammonia from coal (South Africa).

The findings of this study aim to inform researchers, project developers, certifying bodies and policymakers about the environmental impacts of green ammonia and its potential role in supporting a JET.

2.2 Scope

The system boundary is defined as cradle-to-gate, or more accurately, cradle-to-production gate. The product system includes all inputs, resources, and processes required to produce green ammonia in South Africa at a coastal facility, using renewable energy from wind and solar PVs. The functional unit is the production of 1 kg of green ammonia.

The life cycle stages of green ammonia production include:

- Raw material extraction: This stage involves the extraction and purification of seawater for the electrolyser, and air for nitrogen production. It also includes the raw materials required for infrastructure and the energy needed for acquiring these raw materials.
- Renewable electricity generation: Electricity is generated from solar PVs and wind power, with lithium-ion battery storage.
- Hydrogen production: Hydrogen is produced via water electrolysis, followed by hydrogen storage.
- Nitrogen production: Nitrogen is produced in an air separation unit and stored.
- Ammonia synthesis: The synthesis of ammonia and its storage.

To explore different assumption regarding the system boundary and scope, several scenarios were developed to assess the impacts of green ammonia production. In particular, the scenarios investigated include the inclusion of co-products (oxygen, argon, and excess electricity sold to market) and the exclusion of embodied emissions from the manufacturing of renewable energy infrastructure. The green ammonia production scenarios (Fig. 1) are as follows:

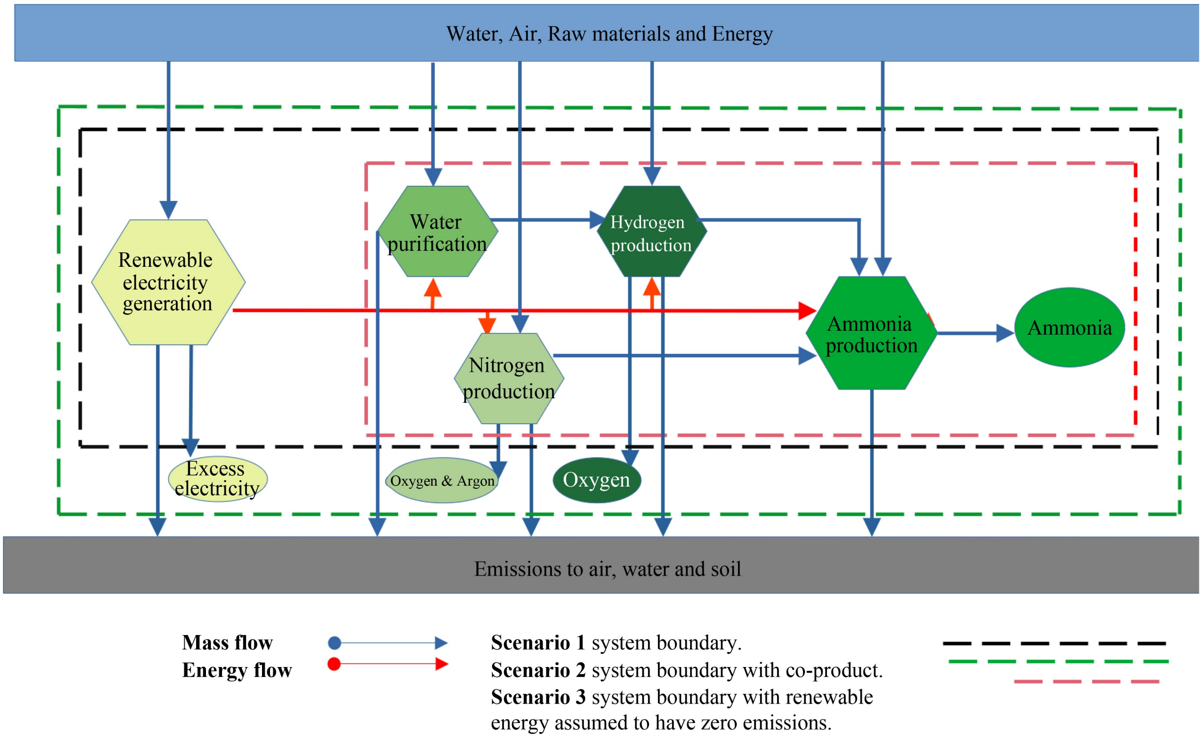

Fig. 1 Scope and system boundary of the green ammonia production Scenarios 1, 2, and 3.

Scenario 1: Renewable energy is used to produce hydrogen through electrolysis of seawater, and ammonia is synthesised as the only product.

Scenario 2: Renewable energy is used to produce hydrogen through the electrolysis of seawater, with ammonia synthesis and the additional co-products of electricity, oxygen, and argon.

Scenario 3: Renewable energy is used to produce hydrogen through electrolysis of seawater, with ammonia synthesis as the only product. In this scenario, the embodied emissions associated with the capital infrastructure of the energy supply system are excluded by assuming the renewable energy supply has zero emissions. This follows the recommended methodology for determining the greenhouse gas emissions of hydrogen, which is being developed into an international standard (ISO/TS 19870). According to this standard: "*Greenhouse gas impact of electricity used for hydrogen production shall be restricted to Scope 1 and 2 emissions, and partial Scope 3 assumptions (excluding emissions associated with manufacturing of power generation facilities). As a result of this assumption, the greenhouse gas impact of electricity generation from wind, solar photovoltaic, hydropower and geothermal will be assumed to be zero*" [36,37].

2.3 Design of green ammonia production facility and the product system

The process design and associated data for this study were based on a techno-economic pre-feasibility study of green ammonia production in South Africa, using Saldanha Bay as a case study. Saldanha Bay is a designated Special Economic Zone (SEZ) and is located near a Renewable Energy Development Zone (REDZ). The REDZ are geographical areas identified by the national Department of Forestry, Fisheries, and the Environment (DFFE) as having a good solar and/or wind potential, while also being free from sensitive or protected areas so that renewable energy development regulatory processes can be streamlined [38].

The product system encompasses all the inputs, resources, and processes required to produce 280 kilotonnes (kt) of green ammonia annually. The green ammonia plant is connected to the national electricity grid only to allow the export of excess electricity, with no import or supply of electricity from the national grid. Since the ammonia production needs to operate with available renewable energy and ammonia synthesis requires a capacity factor above 95%, the renewable energy supply was oversized by 200% relative to the electrolyser, and the electrolyser was oversized by 100% relative to the ammonia plant. Battery storage was incorporated to further improve the availability of energy for ammonia production.

The design of the green ammonia production facility was based on techno-economic studies [39, and Roos, unpublished], as outlined in Table 1.

Renewable electricity for the production of green ammonia was provided through combination of solar PVs

Table 1 Processes design of the green ammonia production facility [39, and Roos, unpublished].

Process	Technology	Parameter	Value	Unit
Renewable energy generation	Wind and solar farm	Solar farm capacity	1515	MW
		Wind farm capacity	379	MW
		Combined capacity factor	0.26	
		Renewable energy generation	4311	GWh/a
Water treatment	Seawater reverse osmosis	Specific energy consumption	4.1	kWh/m^3
		Annual production	717000	m^3 of treated water
		Energy consumption per year	2.9	GWh
Electrolyser	Alkaline water electrolysis	Design output	150.3	t H_2/d
		Specific energy consumption	49.11	kWh/(kg·H_2)
		Annual capacity factor	0.63	
		Annual production	52000	t H_2/a
		Energy consumption per year	1609	GWh/a
		Capacity	660	t N_2/d
Air separation unit	Cryogenic air separation	Design power demand	6.8	MW
		Specific energy consumption	0.243	kWh/(kg·N_2)
		Capacity factor	0.82	
		Energy consumption per year	60	GWh/a
		Annual production	242000	(t·N_2)/a
		Capacity	294000	(t·N_2)/a
Ammonia plant	Haber-Bosch synthesis	Design power demand	15.57	MW
		Specific energy consumption	0.44	kWh$_e$/(kg·NH_3)
		Annual production	280000	(t·NH_3)/a
		Annual capacity factor	0.95	
		Energy consumption per year	123.3	GWh/a

and wind turbines located at an inland site near Moorreesburg (−33.150, 18.667). This site was connected to the coastal ammonia synthesis facility in Saldanha (−33.012, 17.944) via a high-voltage electrical transmission grid [40]. Water was provided through seawater reverse osmosis, with brine wastewater discharged to the sea [41].

Hydrogen production was performed by electrolysis of water using an alkaline electrolyser [42]; with the oxygen co-product either vented to the atmosphere (Scenario 1 and 3) or sold to market (Scenario 2). Nitrogen was produced using a cryogenic air separation unit, and the co-products of oxygen and argon were either vented to the atmosphere (Scenarios 1 and 3) or sold to the market (Scenario 2).

Ammonia synthesis was carried out in a Haber-Bosch reactor using nitrogen and hydrogen gases, with an iron catalyst [43]. To capture heat from ammonia synthesis and generate dispatchable electricity, a steam turbine was incorporated. A utility-scale lithium-ion battery was incorporated to improve the availability of electricity for ammonia synthesis. Hydrogen, nitrogen, and ammonia were stored in tanks, with electricity inputs for compression and cooling [44,45].

Hydrogen leakage during storage was estimated at 0.1% per day, equating to 52 kt per year for the production facility [46]. Ammonia was assumed to be stored for 5 days, with boil-off losses of 0.006% per day, resulting in 84 t of ammonia vented to the atmosphere annually. Additionally, 0.02% per day leakage during pumping and storage resulted in 56 t of ammonia evaporating into the atmosphere per year [17].

Based on the design details for the 280 kt per year green ammonia production (Table 1), the process flow diagram, along with the mass and energy balance for the production of 1 kg of green ammonia, is shown in Fig. 2.

2.4 LCIs

The LCIs were based on the on the process design (Table 1) and the corresponding mass and energy required to produce 1 kg of green ammonia, in accordance with the boundaries and scope defined in the green hydrogen scenarios (Figs. 1 and 2). The life cycle of green ammonia production was modelled using a combination of background datasets from the Ecoinvent database [29], adapted to represent the local context where appropriate, and foreground datasets that were specifically built to represent the relevant processes.

Green ammonia production was compared to the

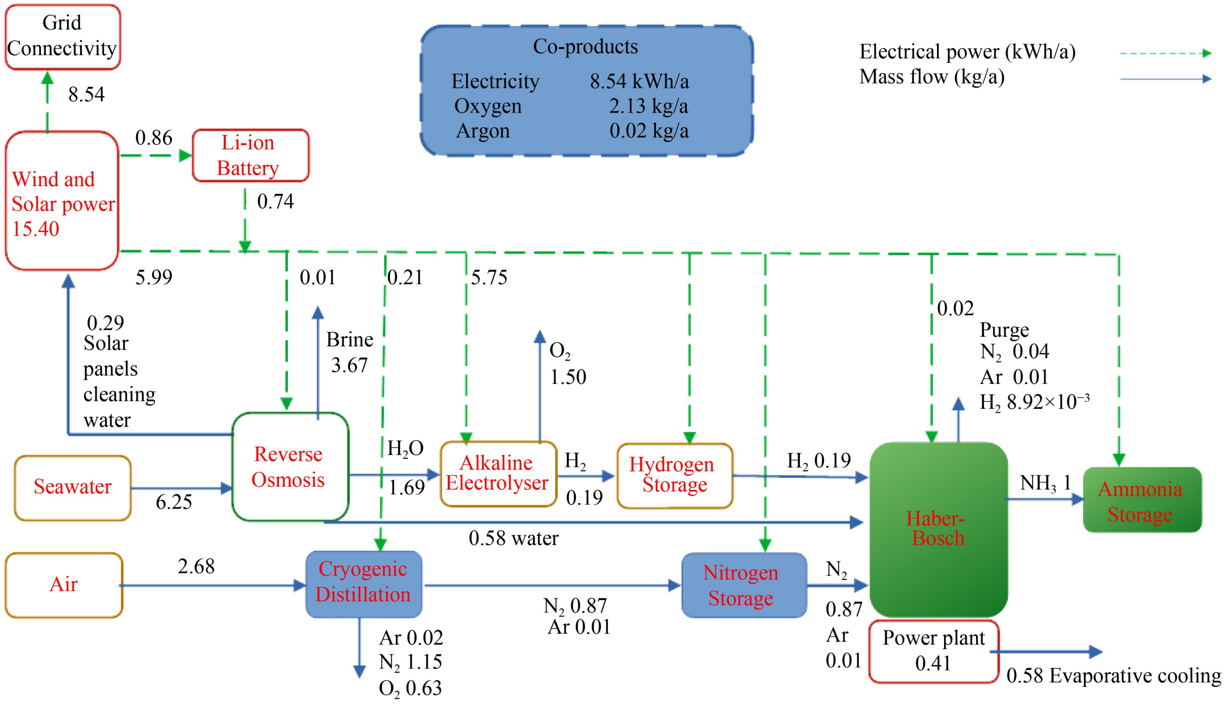

Fig. 2 Process flow diagram for production of 1 of kg green ammonia with mass and energy flows shown (minor material and energy flows < 0.5% omitted).

current business-as-usual scenario, which uses fossil fuels for ammonia production, with data sets representing black ammonia produced from coal and grey ammonia produced from natural gas [29,30]. Specifically:

Grey ammonia production: The dataset for grey ammonia (*Ammonia, anhydrous, liquid {UN-OCEANIA}| ammonia production, steam reforming, liquid | APOS, U)* is modelled using steam reforming of natural gas with a catalyst (molybdenum with zinc oxide) for sulphur removal. This dataset represents the production of 1 kg of liquid ammonia from the Oceania region (Australia, New Zealand, and Pacific).

Black ammonia production: The dataset for black ammonia (*Ammonia, anhydrous, liquid {ZA}| synthetic fuel production, from coal, high temperature Fisher-Tropsch operations | APOS, U)* uses Sasol's proprietary coal-to-liquid Fisher-Tropsch synthesis, using high temperature and an iron-based catalyst. The dataset represents the production of 1 kg of liquid ammonia from coal in South Africa (ZA).

Table 2 provides the LCI for the production of 1 kg of green ammonia, grey ammonia, and black ammonia, based on the functional unit and scenarios defined earlier. Further details of the LCI are provided in the Supplementary Materials.

The inventory of inputs for green ammonia Scenario 1, grey ammonia and black ammonia is as shown. For Scenario 2, the outputs (emissions) from green ammonia production were allocated among green ammonia and co-products. For green ammonia Scenario 3, the emissions from the renewable electricity were removed in accordance with the standard methodology for determining the GHG emissions associated with the production, conditioning and transport of hydrogen to consumption gate (ISO/TS 19870, 2023), which states that GHG impact of electricity generation from wind, solar photovoltaic, hydropower and geothermal will be assumed to be zero.

This study used the allocation at point of substitution (APOS) system model [29]. In cases of system multi-functionality; such as the co-production of electricity, oxygen, and argon (Scenario 2), allocation must be applied to distribute the environmental impacts among the primary product and various co-products. A mass-based allocation method was chosen, with electricity being converted to primary energy and the amount of coal required for electricity generation in South Africa. The rationale behind the use of mass-based allocation and its influence on the results is discussed in the sensitivity analysis (see Section 3.4).

The recycling of materials from infrastructure and technology at the end-of-life was modelled as a multi-functional process, and waste treatment required to produce recyclate as a valuable secondary material included in the system boundary. For the recycling of valuable metals, such as copper in electricity transmission lines and other electrical components, aluminium in solar PVs and other infrastructure, nickel in the electrolyser, and iron and steel in the building infrastructure, a closed-loop approximation was used. This model assumes these

Table 2 LCI for production of 1 kg of green ammonia, grey ammonia and black ammonia

Inputs from technosphere	Value
Green ammonia production, 1 kg	
Chemical factory, organics {RoW}| construction | APOS, U	4×10^{-10} p
Aluminium oxide, metallurgical {RoW}| market for aluminium oxide, metallurgical | APOS, U	2.68×10^{-10} kg
Hydrogen, liquid {RER}| potassium hydroxide production | APOS, U	8.94×10^{-11} kg
Magnetite {GLO}| market for | APOS, U	8.58×10^{-9} kg
Nitrogen gas	0.87 kg
Hydrogen gas	0.19 kg
Renewable electricity mix (solar and wind)	0.44 kWh
Emissions to air	
Nitrogen, atmospheric	0.04 kg
Argon-40/kg	0.03 kg
Hydrogen	9.43×10^{-3} kg
Waste treatment	
Steel and iron (waste treatment) {GLO}| recycling of steel and iron by (EAF) | APOS, U	2.68 g
Copper scrap, sorted, pressed {RoW}| treatment of copper scrap by electrolytic refining | APOS, U	0.11 g
Aluminium scrap, post-consumer, prepared for melting {RoW}| treatment of aluminium scrap, post-consumer, prepared for recycling, at remelter | APOS, U	0.32 g
Grey ammonia production, 1 kg	
Chemical factory, organics	4×10^{-10} p
Heat, district or industrial, natural gas	8.28 MJ
Natural gas, high pressure	0.625 m^3
Nickel, class 1	0.00035 kg
Solvent, organic	3×10^{-5} kg
Tap water	0.721 kg
Inputs from environment	
Water, cooling, unspecified natural origin	0.14 m^3
Emissions to air	
Carbon dioxide, fossil	1.44 kg
Nitrogen oxides	0.0007 kg
Water	0.0544 m^3
Emissions to water	
Nitrogen	0.00012 kg
Water	0.0865 m^3
Black ammonia production, 1 kg	
Chemical, inorganic	0.298 kg
Electricity, medium voltage	0.527 kWh
Hard coal	2.96 kg
Natural gas, high pressure	0.0944 m^3
Petroleum refinery	6.04×10^{-10} p
Inputs from environment	
Occupation, industrial area	0.00596 m^2/a
Oxygen	0.93 kg
Transformation, from unspecified	6.72×10^{-5} m^2
Transformation, to industrial area	6.72×10^{-5} m^2
Water, river	0.00672 m^3

Table 2 LCI for production of 1 kg of green ammonia, grey ammonia and black ammonia *(continued)*

Inputs from technosphere	Value
Emissions to air	
Carbon dioxide, fossil	4.14 kg
Hydrogen sulphide	0.0047 kg
Methane, fossil	0.00802 kg
Nitrogen oxides	0.011 kg
Particulate matter, > 10 µm	0.000723 kg
Sulphur dioxide	0.0146 kg
VOC, volatile organic compounds	0.00296 kg
Water	0.00423 m^3

metals are recycled without any changes in the properties of the material [25].

2.5 Impact assessment methods

The ISO14040/14044 standards [25] do not specify particular life cycle impact assessment (LCIA) methods but require that the chosen method be internationally recognised. In this study, the environmental impacts were assessed using the ReCiPe 2016 method, which is a harmonised life cycle impact assessment method that evaluates both midpoint and endpoint levels and has been a widely applied in LCA studies [26,27]. The ReCiPe method includes 18 midpoint impact categories, including the global warming potential that is estimated from from GHG emissions and calculated over a 100-year period. Additionally, it aggregates these midpoint impacts to three endpoint categories related to damage to three areas of protection: human-heath, ecosystems, and resources. The method also provides a composite single

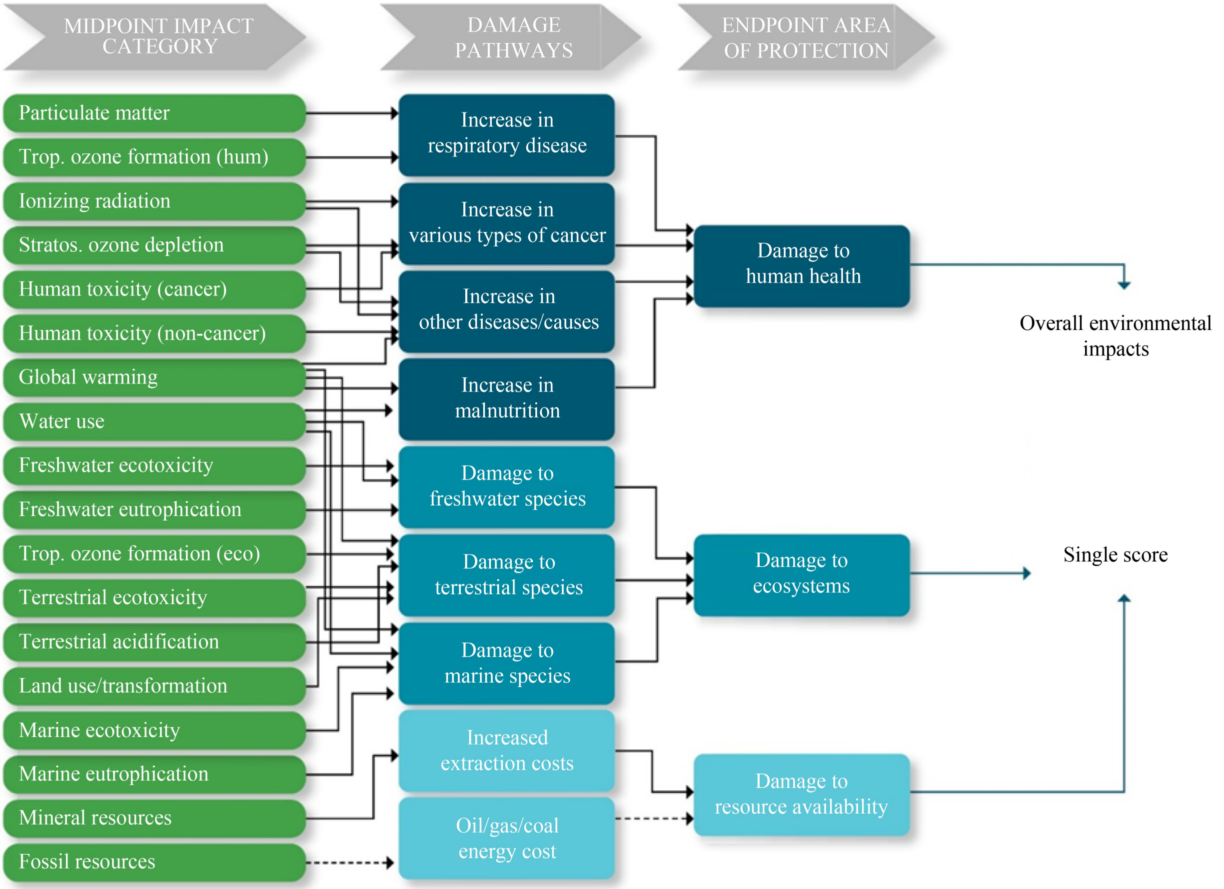

Fig. 3 Overview of the impact categories that are covered in the ReCiPe 2016 methodology and their relation to the areas of protection (adapted from ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint levels [26]).

score representing total environmental impacts or the environmental footprint (see Fig. 3 and Table 1).

The single score is derived by combining the damage to the areas of protection through normalisation and weighting. The weighting was performed using the hierarchist perspective, which is based on the most common and widely accepted policy principles with regards to timeframes and other considerations [26] (see Tables 3 and 4).

3 Results

The results of the cradle-to-production gate life cycle impact assessment for the production of 1 kg of green ammonia are summarised inTable 5. This includes all 18 midpoint impact categories, endpoint areas of protection, and the single score representing total impacts. Additionally, the GHG emissions, expressed in carbon dioxide equivalents per kg of green ammonia, are converted to carbon dioxide equivalents per kg of hydrogen (based on the 17.8% hydrogen content of ammonia). This conversion allows for a direct comparison with the proposed thresholds set by hydrogen certification schemes or national policies.

3.1 GHG emissions and global warming potential

Table 3 ReCiPe method showing the impacts category that are assessed at midpoint, endpoint and single score (Further details of emission factors and characterisation factors for the impact categories are provided in ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint levels)

	Unit	Description
Mid-point impact category		
Global warming potential	Carbon dioxide equivalent (kg CO_2-eq)	Contributions to climate change, primarily through GHG emissions, such as CO_2, CH_4, and N_2O
Stratospheric ozone depletion	Chlorofluorocarbon-11 equivalent (kg CFC11-eq)	Damage to the ozone layer from emissions of CFCs, HCFCs, etc., critical for filtering UV radiation
Ionising radiation	Cobalt-60 equivalent (kg Co-60-eq)	Human and ecosystem exposure to ionising radiation from emissions
Ozone formation, human health	Nitrogen oxide equivalent (kg NO_x-eq)	Emissions contributing to ground-level ozone formation affecting respiratory health
Fine particulate matter formation	Particulate matter < 2.5 µm (kg $PM_{2.5}$-eq)	Emissions of fine particulates causing respiratory and cardiovascular diseases
Ozone formation, terrestrial ecosystem	Nitrogen oxide equivalent (kg NO_x-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, NO_x) 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
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 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)	Evaluation of 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		
Human health	Disability Adjusted Life Years (DALY)	Damage to human health, expressed in terms of loss of productivity and disability adjusted life years
Ecosystems	Biodiversity loss (Species. year)	Damage to ecosystems expressed in terms of biodiversity loss over time
Resources	US dollars, 2013 (USD)	Impacts to resources leading to resource depletion and increasing costs of extraction
Single score indicator		
Total damage	Points (Pt)	Total damage in terms of human health, ecosystems and resources

The global warming potential of green ammonia production was found to be 0.79 kg CO_2-eq per kg of ammonia in Scenario 1 (Fig. 4). However, if oxygen, argon, and excess electricity are sold and the GHG emissions allocated on a mass basis, the GHG emissions for green ammonia production drop to 0.28 kg CO_2-eq per kg of ammonia (Scenario 2). Further, if the embodied GHG emissions from renewable energy infrastructure are assumed to be zero in accordance with the methodology for assessing low-carbon fuels [36,37], the GHG emissions decrease to 0.11 kg CO_2-eq per kg of ammonia, or 0.60 CO_2-eq per kg of hydrogen, based on the hydrogen content of ammonia (Scenario 3).

Table 4 Normalisation and weighting values used in the ReCiPe 2016 method for the single score of total impacts with the hierarchist perspective (H/A) [26]

Damage category	Normalisation	Weighting
Human health	42.1	400
Ecosystems	1396	400
Resources	0.0000357	200

The thresholds for carbon intensity in current certification schemes vary, ranging from as low as 1.0 CO_2-eq per kg of hydrogen in the Green Hydrogen Organization standard, to 3.4 kg CO_2-eq per kg of hydrogen in the Japan Hydrogen Association standard and EU-RED II for RFNBO, and up to 4.9 kg CO_2-eq per kg of hydrogen in the China Hydrogen Alliance standard [9,10,23]. Therefore, the green ammonia produced at a coastal facility in South Africa has a carbon intensity below the most stringent thresholds and is likely to meet global market requirements for certifications as a low-carbon fuel.

A South African standard for Green and Low-carbon hydrogen is currently being developed to align with international certification schemes and importing country requirements and thereby support opportunities for export and the transition of industry to low-carbon energy. The

Table 5 LCA results for the production of 1 kg green ammonia (Scenarios 1, 2, and 3), grey ammonia and black ammonia.

	Units	Green ammonia			Grey ammonia	Black ammonia
		Scenario 1	Scenario 2	Scenario 3		
Mid-point **Impact category**						
Global warming potential	kg CO_2-eq	0.79	0.28	0.11	2.29	5.83
Stratospheric ozone depletion	($\times 10^{-6}$) kg CFC11-eq	0.34	0.12	0.06	0.28	2.98
Ionising radiation	($\times 10^{-2}$) kBq Co-60-eq	4.81	1.65	0.54	1.19	5.57
Ozone formation, human health	($\times 10^{-2}$) kg NO_x-eq	0.23	0.08	0.04	0.17	1.77
Fine particulate matter formation	($\times 10^{-3}$) kg $PM_{2.5}$-eq	1.95	0.69	0.35	0.83	9.08
Ozone formation, terrestrial ecosystems	($\times 10^{-2}$) kg NO_x-eq	0.23	0.08	0.04	0.18	1.78
Terrestrial acidification	($\times 10^{-2}$) kg SO_2-eq	0.44	0.16	0.09	0.24	2.97
Freshwater eutrophication	($\times 10^{-3}$) kg P-eq	0.49	0.19	0.09	0.09	4.68
Marine eutrophication	($\times 10^{-4}$) kg N-eq	0.44	0.15	0.07	0.08	2.95
Terrestrial ecotoxicity	kg 1,4-DCB	0.19	0.07	0.03	0.03	0.20
Freshwater ecotoxicity	($\times 10^{-2}$) kg 1,4-DCB	0.67	0.23	0.09	0.08	2.76
Marine ecotoxicity	($\times 10^{-2}$) kg 1,4-DCB	0.95	0.33	0.12	0.11	3.88
Human carcinogenic toxicity	($\times 10^{-4}$) kg 1,4-DCB	3.18	1.14	0.60	1.84	2.50
Human non-carcinogenic toxicity	($\times 10^{-2}$) kg 1,4-DCB	4.55	1.64	0.86	0.76	10.25
Land use	($\times 10^{-2}$) m^2/a crop-eq	26.00	8.55	0.85	1.49	9.28
Mineral resource scarcity	($\times 10^{-2}$) kg Cu-eq	1.49	0.55	0.33	0.49	2.36
Fossil resource scarcity	kg oil-eq	0.20	0.07	0.03	0.80	2.02
Water consumption	($\times 10^{-2}$) m^3	4.74	1.54	3.17	5.59	2.27
End point **Area of protection**						
Human health	($\times 10^{-5}$) DALY	0.21	0.04	0.04	0.28	1.12
Ecosystems	($\times 10^{-8}$) species. yr	0.67	0.12	0.11	0.81	2.92
Resources	($\times 10^{-2}$) USD	4.86	0.87	0.57	28.59	23.46
Single score **Total impacts**						
Total impacts	($\times 10^{-3}$) Pt	47.00	15.00	6.00	54.40	196.00

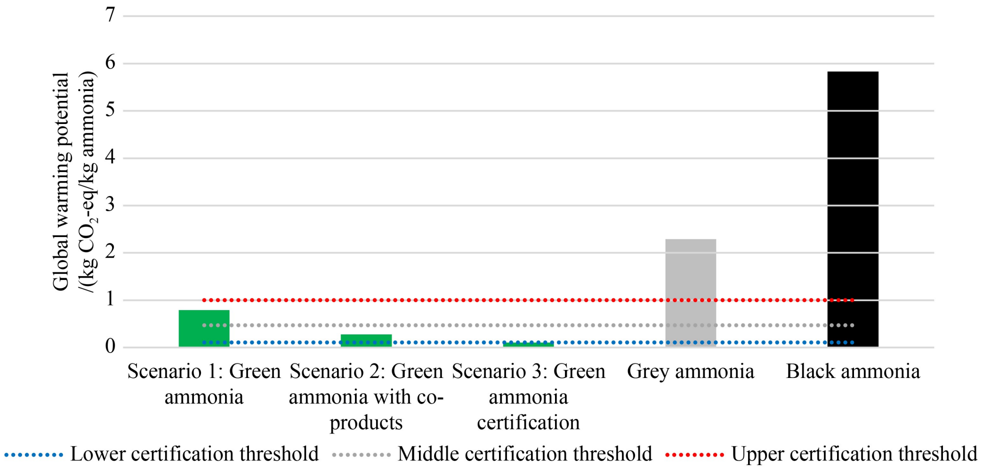

Fig. 4 GHG emissions of green ammonia production, with the thresholds for various certification systems shown (dashed line). These thresholds range from 0.20 to 0.87 kg CO_2-eq per kg of ammonia, which corresponds to 1.0 to 4.9 kg CO_2-eq per kg of hydrogen, based on the hydrogen content of ammonia. Upper certification of 4.9 kg CO_2-eq per kg of hydrogen (China Hydrogen Alliance standard). Middle certification threshold of 3.4 kg CO_2-eq per kg of hydrogen (Japan Basic Hydrogen Strategy and EU-REDII for RFNBO). Lower certification threshold of 1 kg CO_2-eq per kg (Green Hydrogen Organization standard) [9,10,23]).

carbon emission reductions of green ammonia can also be assessed by comparing it to conventional ammonia production from fossil fuels—either grey ammonia produced from natural gas or back ammonia produced from coal gasification. Green ammonia has a 95% reduction in GHG emissions compared to grey ammonia from natural gas (2.29 kg CO_2-eq per kg of ammonia) and a 98% reduction in GHG emissions compared to black ammonia from coal (5.83 kg CO_2-eq per kg of ammonia).

A comparison between Scenario 1 and Scenario 3 reveals that the embodied carbon emissions associated with manufacturing the energy supply infrastructure (solar PVs and wind infrastructure) amount to 0.68 kg CO_2-eq per kg of ammonia, which reflects the carbon-intensive nature of the current energy supply systems used for the manufacturing. However, as the energy supply systems in manufacturing countries are increasingly decarbonised, these embodied emissions are expected to decrease in the future. This is a key rationale behind the exclusion of embodied emissions from renewable energy supply in the ISO/TS 19870 standard [36,37].

Given that many countries, including South Africa, aim for net-zero carbon emissions by 2050, the entire value chain must be optimised to meet this goal [47]. A prospective view of the complete GHG emissions can be modelled as a progressive transition from Scenario 1 to Scenario 3, which represents a fully decarbonised energy supply by 2050 (Fig. 5). The carbon intensity of green ammonia, which is currently 0.79kg CO_2-eq per kg of ammonia in Scenario 1 (equivalent to 4.4 kg CO_2-eq per kg of hydrogen), is expected to gradually decrease as the energy supply is decarbonised. By 2025, it is projected to surpass the upper certification of 4.9 kg CO_2-eq per kg of hydrogen (China Hydrogen Alliance standard), by 2034 it will meet the middle certification threshold of 3.4 kg CO_2-eq per kg of hydrogen (Japan Hydrogen Association standard and EU-REDII RFNBO). By 2048 the carbon intensity will reach the lower certification threshold of 1.0 kg CO_2-eq per kg of hydrogen (Green Hydrogen Organisation), and in 2050, the carbon intensity is expected to reach 0.11 kg CO_2-eq per kg of ammonia (or 0.62 kg CO_2-eq per kg of hydrogen), as per Scenario 3.

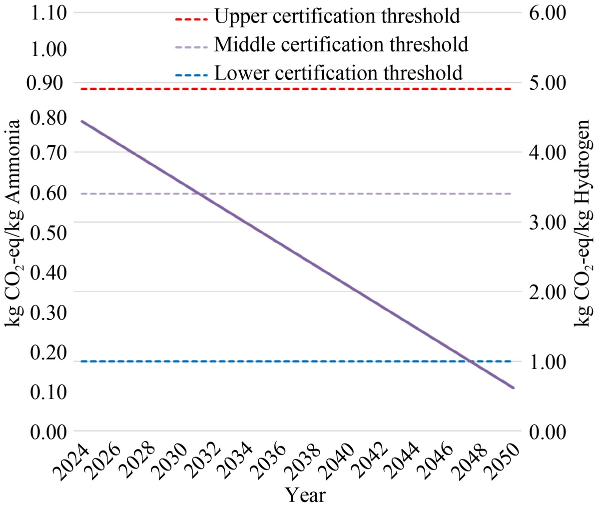

Fig. 5 Prospective carbon intensity of green ammonia production—now and in 2050, based on the gradual decarbonisation of energy supply system until 2050, which reduces the embodied emissions of green hydrogen production (manufacturing renewable energy infrastructure) (Upper certification threshold of 4.9 kg CO_2-eq per kg of hydrogen (China Hydrogen Alliance standard). Middle certification threshold of 3.4 kg CO_2-eq per kg of hydrogen (Japan BHS and EU-REDII for RFNBO. Lower certification threshold of 1 kg CO_2-eq/kg (Green Hydrogen Organisation standard)).

3.2 Total environmental impacts and damage to areas of

protection

A comparison of green ammonia production (Scenarios 1, 2, and 3) with grey and black ammonia across all impact categories provides a comparative view of the environmental performance (Fig. 6). When compared to black ammonia, green ammonia had decreased impacts in 15 out of 18 midpoint impact categories for Scenario 1, in all 18 midpoint impact categories for Scenario 2, and in 17 out of 18 midpoint impact categories for Scenario 3. The midpoint impact categories where green ammonia had greater impacts than black ammonia were water use (in Scenarios 1 and 3), human carcinogenic toxicity, and land use (Scenario 1 only).

When compared to grey ammonia, green ammonia had decreased impacts in 4 out of 18 midpoint impact categories for Scenario 1, in 13 out of 18 midpoint impact categories for Scenario 2 and in all 18 midpoint impact categories for Scenario 3. The midpoint impact categories where green ammonia had greater impacts than grey ammonia were mainly related to ecotoxicity (terrestrial, freshwater, and marine), human non-carcinogenic toxicity, land use, and eutrophication (both freshwater and marine).

Although green ammonia has greater impacts than grey and/or black ammonia for several midpoint impact categories, this does not indicate a negative overall environmental outcome. However, when these midpoint categories are normalised and aggregated to reflect the damage to human health, ecosystem, and resources, the results show that green ammonia consistently performs better, with reduced damage to all areas of protection, compared to both grey and black ammonia (Fig. 7).

Green ammonia has a reduced damage to human health damage (0.21×10^{-5} DALY/kg ammonia for Scenario 1, 0.04×10^{-5} DALY/kg ammonia for Scenario 2, and 0.04×10^{-5} DALY/kg ammonia for Scenario 3), compared to black ammonia (1.12×10^{-5} DALY/kg ammonia) and grey ammonia (0.28×10^{-5} DALY/kg ammonia),

Green ammonia also has reduced damage to ecosystems (0.67×10^{-8} species.yr/kg ammonia) for Scenario 1, 0.12×10^{-8} species.yr/kg ammonia for Scenario 2, and 0.11×10^{-8} species.yr/kg ammonia for Scenario 3), compared both black ammonia (2.92×10^{-8} species.yr/kg ammonia) and grey ammonia (0.81×10^{-8} species.yr/kg ammonia).

Similarly, green ammonia has reduced damage to resource availability, compared to black ammonia (23.46×10^{-2} \$/kg ammonia) and grey ammonia damage (28.59×10^{-2} \$/kg ammonia). The damage to resource availability for green ammonia is 4.86×10^{-2} \$/kg ammonia in Scenario 1, 0.87×10^{-2} \$/kg ammonia in Scenario 2, and 0.57×10^{-2} \$/kg ammonia in Scenario 3.

When all the damage to human-health, ecosystems and resources is aggregated to a single score, green ammonia has a reduced total score (47.00×10^{-3} Pt/kg ammonia for Scenario 1, 15.00×10^{-3} Pt/kg ammonia for Scenario 2, and 6.00×10^{-3} Pt/kg ammonia for Scenario 3), compared to both grey ammonia (54.40×10^{-3} Pt/kg ammonia) and black ammonia (196.00×10^{-3} Pt/kg ammonia), which confirms the overall environmental benefits of green ammonia production.

3.3 Contribution analysis

The single score of total environmental impacts was used to explore the key impact categories (Fig. 8) and processes (Fig. 9) that make the greatest contributions to the overall environmental impacts of green ammonia production.

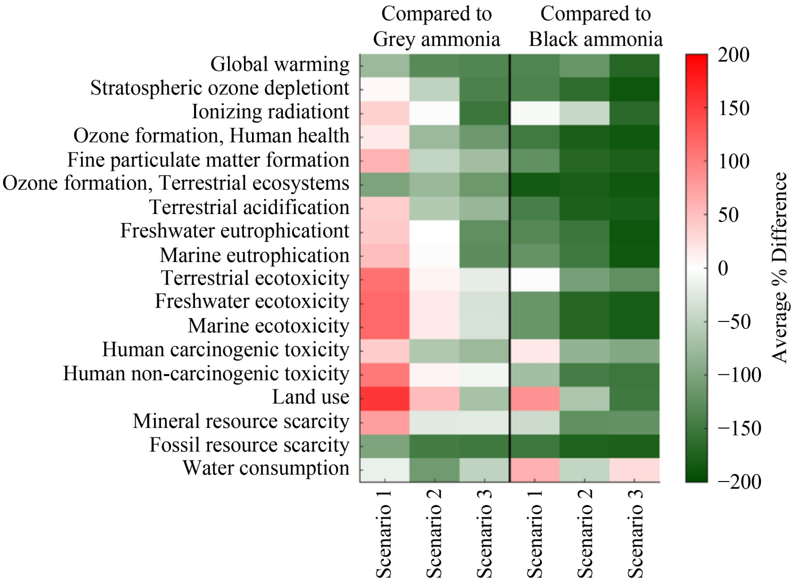

Fig. 6 Comparison of green ammonia with black and grey ammonia across all impact categories using average percentage difference.

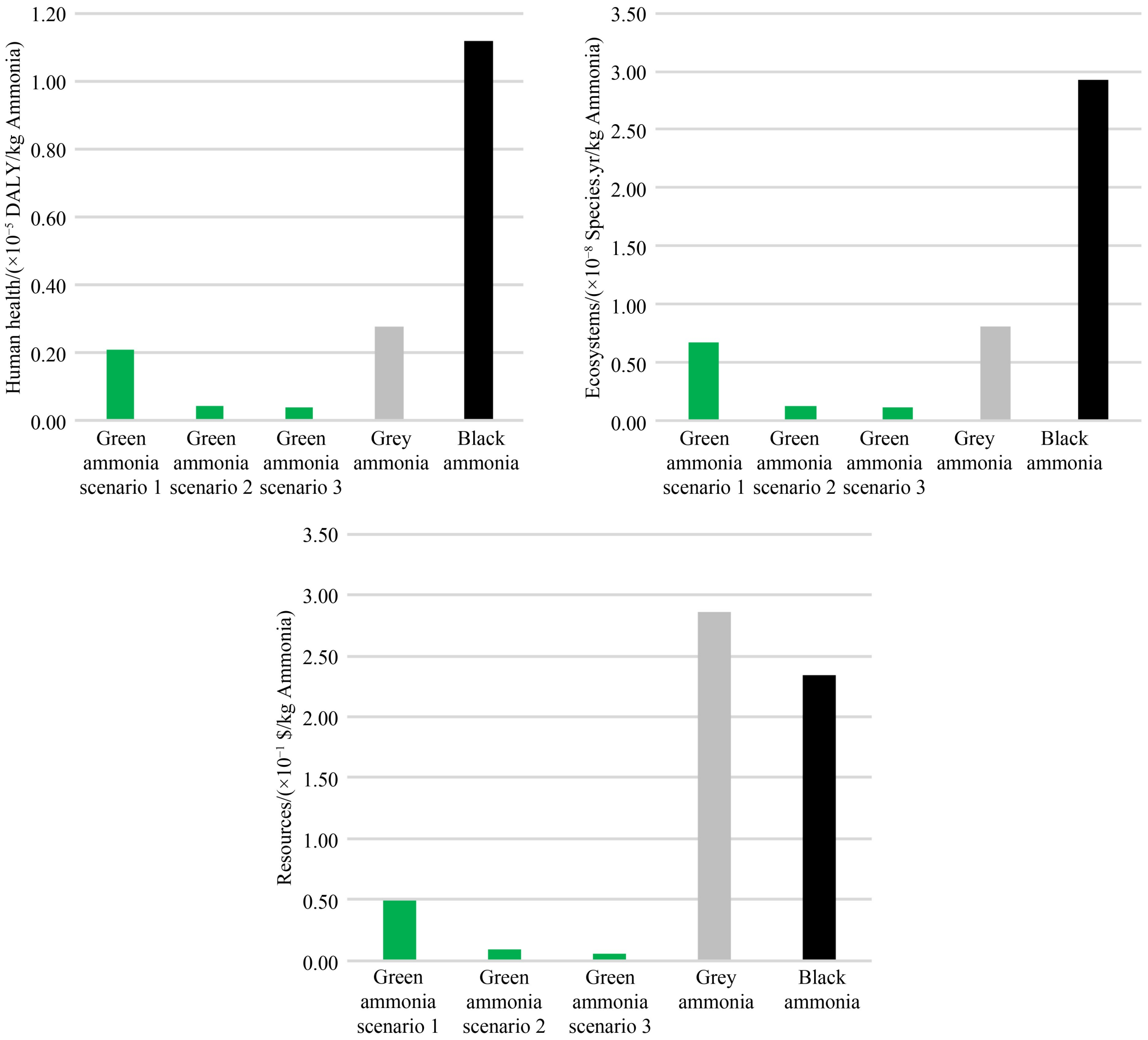

Fig. 7 Comparison of green ammonia with black and grey ammonia in terms of damage to areas of protection (human health, ecosystems, resources).

Among the impact categories, fine particulate matter (55%) and global warming potential (33%) were the largest contributors to the overall environmental impacts in the life cycle of green ammonia production (Fig. 8), followed by water consumption (5%).

In terms of life cycle stages, the electrolysis of water was the greatest contributor, responsible for 68 % of the total impacts, followed by the air separation units (15%), ammonia synthesis (13%) and hydrogen storage (2%) (Fig. 9).

These contribution analyses reveal that electricity is the main factor driving the total environmental impacts, primarily due to the embodied energy involved in manufacturing the renewable energy infrastructure.

3.4 Sensitivity analysis

For the co-products analysis (Scenario 3), mass-based allocation was applied since it was considered the most appropriate for the system under study. Although energy-based allocation might appear to be a logical choice given the fact that green ammonia is an energy carrier, the oxygen and argon co-products have no energy value and therefore would be allocated zero environmental impact. Economic allocation could be another option, but the markets for green hydrogen and energy carriers such as green ammonia are not yet well-established and the market prices, market size and price elasticity of green ammonia, oxygen and argon are uncertain.

In contrast, mass-based allocation can be applied to all co-products, including electricity, which is converted into primary energy demand in terms of coal equivalents, based on the coal dominated electricity generation mix in South Africa. Mass-based allocation is also an appropriate choice since the proportions of the (co-)products are physically constrained by the production system and

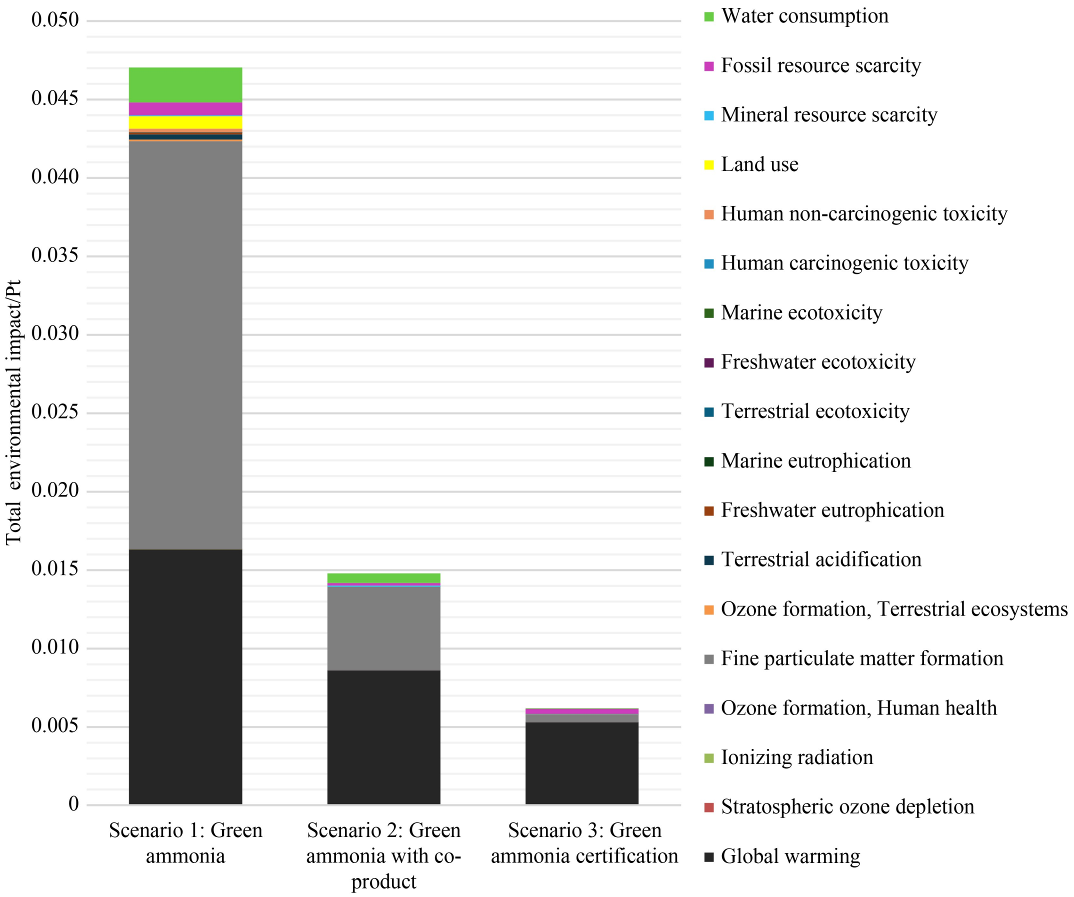

Fig. 8 Impact category contribution to the life cycle impacts of green ammonia production.

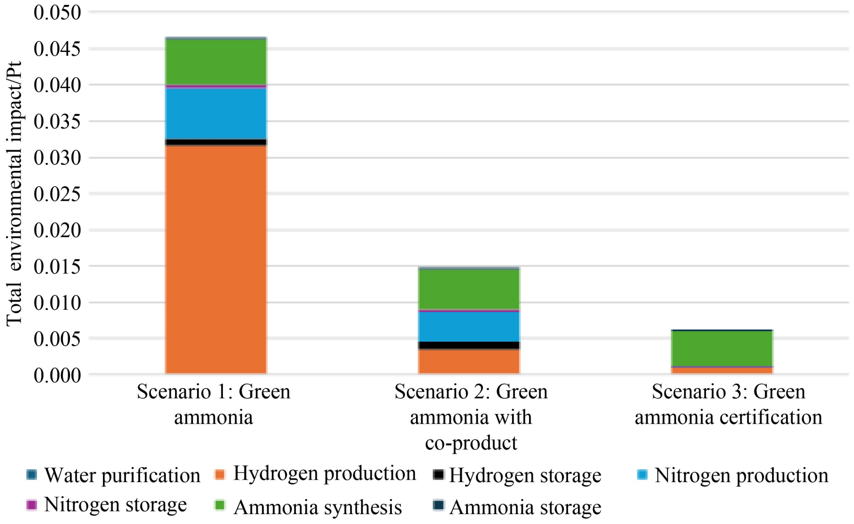

Fig. 9 Process contribution to the life cycle impacts of green ammonia production.

cannot be adjusted according to prevailing market prices.

To assess the impact of different allocation choices, a sensitivity analysis was performed. This compared the carbon intensity of green ammonia under various allocation methods: mass (based on amounts of products), economic value (based on revenue from products), energy (based on the lower heating value of products) and system expansion and substitution of existing products in the market (allocation at the point of substitution). Table 6 provides the data for the products and co-products, while Fig. 10 presents the results of the sensitivity analysis for each allocation choice.

Table 6 Data to explore different allocation methods for co-products, with the amount (kg), energy (lower heating value, MJ), unit price (US dollars per kg), and revenue (US dollars) per product.

Products	Amount/kg	Energy/MJ	Unit price/ ($\$\cdot\mathrm{kg}^{-1}$)	Revenue per product/$
Ammonia	1.00 kg	18.80	1.00 [4]	1.00
Excess electricity[a]	4.40 kg	30.80	0.16 [48]	0.70
Oxygen	2.13 kg	0.00	3.00 [49]	6.33
Argon	0.03 kg	0.00	1.62 [50]	0.05

Notes: [a] Excess electricity was 8.55 kWh per kg green ammonia produced. This requires 4.40 kg of coal, based on 1 kWh electricity requiring 0.515 kg coal with a Lower Heating Value of 20 MJ/kg (South Africa's coal power plant with 35% conversion efficiency, Eskom 2021 [51]).

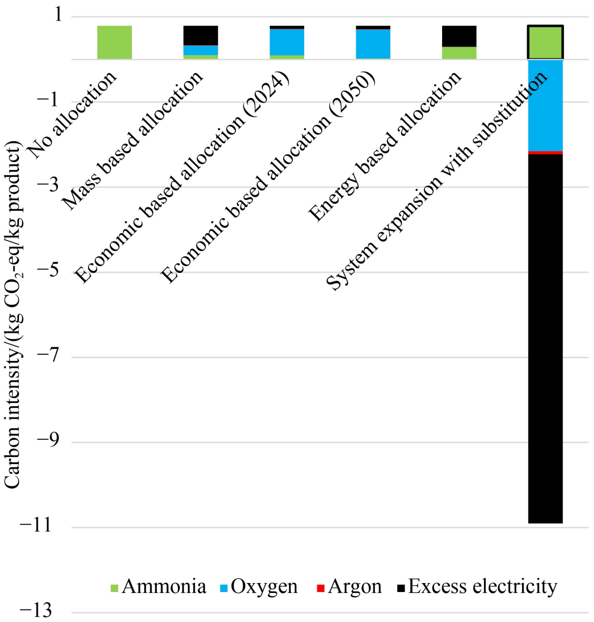

Fig. 10 Sensitivity analysis showing carbon intensity of green ammonia production using allocation based on mass, economic value, energy or system expansion and substitution.

The production of co-products and mass-based allocation results in a carbon intensity of 0.102 kg CO_2-eq per kg of green ammonia. If economic allocation is applied, using estimated current market prices, the carbon intensity decreases to 0.098 kg CO_2-eq per kg of ammonia, which is half that of mass-based allocation. However, the current price of green ammonia is estimated to be \$1.00 per kg of green ammonia (equivalent to \$5.6 per kg of green hydrogen) [4], but is expected to decrease in the future due to technological advancements, policy support, and increased market penetration. By 2050, the pricecould fall to \$0.23 per kg green ammonia (equivalent to \$1.30 per kg green hydrogen) [51]. As a result, the economic-based allocation of emissions to green ammonia would decrease, resulting in a carbon intensity of 0.024 kg CO_2-eq per kg of ammonia by 2050.

In contrast, applying system expansion with allocation at the point of substitution, results in a carbon intensity of 0.79 kg CO_2-eq per kg of ammonia, but there are substantial emission reductions from the co-products displacing market products produced from fossil fuels (coal, oil, and natural gas). This results in a net negative carbon intensity of −10.91 kg CO_2-eq per kg of ammonia. Such confusing results have led several LCA practitioners to recommend that system expansion and product substitution be applied only in consequential LCA studies, not attributional LCA as conducted in this study [52–55].

4 Discussion

Green ammonia is an energy carrier that that holds promise for addressing the global challenge of mitigating climate change by facilitating the distribution of renewable energy from production areas to regions with high energy demand [56,57]. However, although green ammonia is a fuel containing zero carbon, the life cycle of green ammonia production involves embodied GHG emissions and other potential environmental impacts from manufacturing infrastructure.

The energy source plays a key role in determining the carbon intensity of ammonia production. Currently, most ammonia is produced from fossil fuels, with over 70% generated via steam methane reforming of natural gas (carbon intensity of 2.5–2.9 kg CO_2-eq per kg of ammonia) and 26% from coal (carbon intensity of 5.2–7.8 kg CO_2-eq per kg of ammonia) [18,19,57]. While carbon emissions from fossil fuels can be reduced by shifting from coal to natural gas and incorporating carbon capture and storage, substantial carbon emission reductions and sustainable production will require the switch to renewable energy resources [19,58,59]. Green ammonia produced using renewable energy to power electrolysis achieves a carbon intensity of 0.1–0.7 kg CO_2-eq per kg of ammonia, with offshore wind and hydropower enabling emissions as low as 0.1 kg CO_2-eq per kg of ammonia [16–21]. This LCA study for South Africa is consistent with previous findings and indicates the significant carbon abatement potential in the transition from black ammonia to green ammonia production. Black ammonia, produced from coal gasification, has a carbon intensity of 5.83 CO_2-eq per kg of ammonia, while green ammonia produced from hybrid renewable energy (solar-wind) has a carbon intensity of 0.79 CO_2-eq per kg of ammonia. Furthermore, excluding the embodied emissions of the energy supply system as defined in the recent international standard (ISO/TS 19870), the carbon intensity of green ammonia is 0.11 kg CO_2-eq per kg of ammonia, which is well below the current threshold for certification as a low-carbon fuel. This underscores the significant embodied GHG emissions from manufacturing the infrastructure required for green ammonia production, and highlights the need for a rapid transition to renewable energy sources in manufacturing countries in order to achieve near-zero carbon fuels by 2050 [9]. In addition, increasing the lifetime of assets and improving the recovery and recycling of renewable infrastructure at the end of life can reduce embodied emissions by avoiding the need for virgin materials, as well as avoiding the depletion of critical raw materials used in the manufacturing of renewable energy infrastructure, such as solar, wind power, and battery components [60].

This study also revealed that the carbon intensity of green ammonia could be further reduced if there is co-production with the sale of oxygen, argon, and electricity to market. In this case, the co-products share the environmental impacts and are allocated a portion of GHG emissions, which results in a carbon intensity of 0.28 kg CO_2-eq per kg of ammonia. In practical terms, co-production is only a reality when there is a tangible market and known value for these co-products, otherwise they are vented to atmosphere as waste. Currently, the market size and price elasticity of green ammonia, oxygen and argon are highly uncertain. In addition, while mass-based allocation among (co-) products is arguably the most appropriate for this system, the choice of allocation method by the researcher substantially influences the results. This aspect of allocation among (co-) products is often poorly addressed in certification schemes and policy, despite being recognised as causing large variations in the results of LCA studies [24]. This issue should be addressed and clarified in future updates to the standard methodology for determining the GHG emissions associated with hydrogen production, conditioning, and transport of hydrogen to consumption gate (ISO/TS 19870, 2023).

Technology advancements could further reduce the environmental impacts of green ammonia production. For instance, advances in solar PVs and wind-power technologies are significantly improving efficiency, which in turn reduces the associated environmental impacts of green ammonia production [61]. Previous LCA studies have found that GHG emissions for green ammonia produced using wind power are 0.24–0.54 kg CO_2-eq per kg of ammonia, while GHG emissions of green ammonia produced using solar are 0.59–0.70 kg CO_2-eq per kg of ammonia [17–21], which would favour wind as the preferred renewable energy resource. However, the combined use of wind and solar resources can reduced energy supply intermittency and thereby increase the energy available for ammonia production. Furthermore, integrating battery energy storage and a steam turbine to utilise process heat from the ammonia synthesis improves production efficiency while increasing energy self-sufficiency (no supply of electricity from the carbon-intensive national electrical grid). This also helps to fulfil the additionality requirement of several hydrogen policy and certification schemes, which requires validated temporal and spatial matching of renewable energy generation with hydrogen production to ensure that the renewable energy supply is built for- and dedicated to- the production of green hydrogen and derivatives [9,10,23,24].

Future improvements in energy management and the use of hybrid power systems with energy storage could increase energy self-sufficiency, and thereby reduce the impacts associated with green ammonia production [62]. Process and value chain optimisation also presents opportunities for efficiency improvements. For example, the process heat from the ammonia synthesis plant could drive the thermal distillation of seawater through mechanical vapor compression desalination, reducing the electricity demand for desalination or enabling the co-production of additional potable water for human consumption [65,66]. Other technology innovations, particularly regarding the efficiency of the electrolyser can strongly influence the emissions of green ammonia production. Alkaline electrolysers are the most cost-effective option currently available, though their efficiency ranges between 65%–70%. In comparison, proton exchange membrane (PEM) electrolysers achieve 75%–85% efficiency, while solid oxide electrolysers (solid oxide electrolysis cells, SOECs) can exceed 90% efficiency [63,64]. Due to their superior efficiency, SOECs offer significant potential for reducing emissions, especially when integrated with industrial heat sources to enhance their operational efficiency [67,68].

Storage and transportation losses also contribute to the overall carbon footprint. Compressing or liquefying hydrogen for storage increases energy consumption, while ammonia storage and regeneration introduce additional emissions. Long-haul transport of ammonia, particularly for export markets, can raise emissions by 0.05–0.10 kg CO_2-eq per kg of ammonia [69].

Emerging certification schemes and government policies for the production of green hydrogen and derivatives have requirements in terms of carbon intensity and are based on governments aspirational climate mitigation targets for 2050. For instance, the Announced Pledges Scenario aims for global average emissions intensity to fall below 3 kg CO_2-eq per kg of hydrogen and the Net Zero Scenario sets the threshold at less than 1 kg CO_2-eq per kg of hydrogen to mitigate climate change by 1.5 °C [23]. However, these developing certification schemes have different standards and thresholds of carbon intensity. For example, the Green Hydrogen Organization sets a threshold of 1.0 kg CO_2-eq per kg of hydrogen while the Japan Basic Hydrogen Strategy and the European Union Renewable Energy Directive set it at 3.4 kg CO_2-eq per kg of hydrogen, and the China Hydrogen Alliance Standard sets it at 4.9 kg CO_2-eq per kg of hydrogen [10,23]. The study shows that carbon intensity of green ammonia produced from coastal locations in South Africa is 0.11 CO_2-eq per kg of ammonia (or 0.60 kg CO_2-eq per kg of green hydrogen, when expressed in terms of hydrogen content), which is well below these certification thresholds. This provides confidence to investors that green hydrogen and its derivatives can be produced in South Africa with a carbon intensity that meets the requirements of global markets. However, it should be noted that these carbon intensity thresholds are at the green ammonia production gate and there may be additional GHG emissions during processing, transport, and distribution to the point of consumption, as well as during the use or consumption of green ammonia in delivering energy services [69]. This study should therefore be complemented by extending the boundary to the point of consumption (cradle-to-consumption or well-to-tank) and to the final consumption or use (cradle-to-grave or well-to-wheel). Considering the need to either use green ammonia directly as a fuel or to regenerate the hydrogen, additional emissions may raise during transport, distribution, and use. For example, the regeneration of hydrogen from green ammonia by decomposition incurs a 15%–20% loss of hydrogen, leading to a subsequent increase in net GHG emissions [69,70,71,72]. Advances in ammonia decomposition technologies, such as the use of rubidium and nickel catalysts and the enhanced separation using palladium-based and palladium-coated vanadium membranes, could improve the efficiency of hydrogen regeneration and thereby reduce the environmental impacts associated with the transport and distribution life cycle stages of green ammonia [73,74,75]. Alternative energy carriers to ammonia, such as liquid organic hydrogen carriers (LOHCs) dibenzyltoluene and methylcyclohexane, have lower energy requirements to regenerate the hydrogen and are also being explored [76,77]. However, unlike ammonia which is a zero-carbon containing fuel that can be produced using renewable electricity of non-biological origin, these LOHCs contain carbon and therefore are dependent on fossil fuels or biomass resources for their production [78].

The certification of low-carbon fuels is underpinned by a joint understanding of the applied methodology used, and the confidence in certification as well as the interoperability of certification schemes is an important enabler of market development. There are several methodological choices in LCA, such as the boundary, scope definition, allocation of co-products and the additionality requirement, which need to be adequately clarified for certification or to inform policy [10,23,24]. While a common methodology for estimating the carbon intensity of green hydrogen has recently been developed [36,37], the certification schemes are only emerging and have differences in terms of carbon thresholds, the scope definition, and where the boundaries are drawn within the supply chain for emissions accounting. These differences create regulatory and certification hurdles for project developers, requiring them to navigate unique certification processes for each country's domestic market. This increases transaction costs, reduces investor confidence and is likely to restrict trade due to the lack of mutual recognition of these certification schemes. Therefore, governments must collaborate to harmonise certification schemes and establish interoperability between their regulatory frameworks [11,56,79]. This was affirmed in the recent declaration by G20 countries that calls for mutually recognised and interoperable certification schemes for renewable and low-carbon hydrogen in order to build a sustainable and equitable global hydrogen ecosystem that benefits all nations [80]. Accordingly, South Africa is in the process of developing a Green and Low-carbon Hydrogen Standard to provide a regulatory framework that guides the national production of green hydrogen and its derivatives for both domestic use and export, while also establishing clear market signals to align investment decisions, technology development and infrastructure planning with the country's objectives for decarbonisation and sustainable development.

The current certification of green hydrogen derivatives is centred on the carbon intensity threshold, which is significance for adoption as a suitable fuel to assist countries in meeting their carbon emission reduction targets needed to mitigate climate change. However, for the widespread adoption of green hydrogen, a comprehensive assessment covering various impact categories, as conducted in this study, is needed to inform hydrogen energy policy for sustainable development [11,81]. This LCA study shows that green ammonia production has a lower overall environmental compared to black or grey ammonia. The global warming potential and particulate matter were shown to make the greatest contribution to the total environment impacts, which supports the focus on carbon intensity as a performance metric for the certification of green hydrogen and derivatives. However, several impacts can depend on the locality and local context, such as direct and indirect land-use changes (LUC and iLUC), impacts to endemic biodiversity, and the local availability of water. These issues can be addressed through strategic environmental impact assessments, and incorporating multi-functionality into project planning and design, such as optimising land-use though the application of Agrivoltaics [82]. In addition, socio-economic and governance factors are also crucial to reduce project risk and ensure a JET. The socio-economic assessments should include the macro-economic and employment opportunities of green ammonia production with export improving the balance of trade, as well as the benefits from the local use of green ammonia and associated local economic development benefits. Incorporating the environmental, social and economic aspects of sustainability into the assessment presents considerable complexity, but could be addressed through complementary social LCA (sLCA) and life cycle costing (LCC) of the proposed developments, or by multi-objective optimisation and integrated life cycle sustainability assessment (LCSA) [83–86].

Finally, the concept of the resource nexus, which emphasises the interdependencies between different natural resources and systems of provision, provides a useful framework for understanding and managing a JET that aims to help achieve the Sustainable Development Goals (SDGs) [87]. In the context of green ammonia, the resource nexus approach reveals interconnections between water, energy, and food systems. The production of green ammonia requires significant amounts of water, land, and energy, which can have implications for land-use and the allocation of limited resources. Furthermore, since ammonia is used to make chemical fertilsers, there could be competition for green ammonia between the energy and agriculture sectors that could affect crop yields and food security [88]. The land footprint of the renewable energy needed for the production of ammonia could also impact biodiversity and displace fertile lands from food production [89]. Similarly, even though seawater desalination was used to supply the pure water required for electrolysis, the use of freshwater for producing green ammonia for energy may present an opportunity cost in water-scarce regions, since the water could have been used for agriculture, food production, or human consumption. This water, food, and energy nexus necessitates the adoption of intelligent design and careful planning to ensure that green ammonia developments support societal needs while protecting natural resources and ecosystems [65, 90].

5 Conclusions

This LCA study examines the design of a coastal green ammonia production facility in South Africa, using renewable energy from wind and solar PVs to desalinate seawater, produce green hydrogen, and synthesise green ammonia fuel. The carbon intensity of green ammonia production is compared to grey ammonia produced from natural gas and black ammonia produced from coal.

The study assesses three different ammonia production scenarios, each with varying scopes regarding production of possible co-products and the inclusion of embodied emissions from the renewable energy infrastructure. In accordance with methodology for measuring the carbon intensity of hydrogen and its derivatives (ISO/TS 19870, 2023), the carbon intensity of green ammonia production is 0.11 kg CO_2-eq per kg of ammonia (or 0.60 kg CO_2-eq per kg of green hydrogen, when expressed in terms of hydrogen content of ammonia). This value is below the threshold required by several certification schemes or national policies, which indicates that green hydrogen produced at a coastal facility in South Africa will meet global market requirements and can be certified as a low-carbon fuel. Additionally, the sale of co-products such as oxygen, argon, and excess electricity could further reduce the carbon emissions of green ammonia, since a portion of the carbon emissions are allocated to these co-products.

Compared to grey and black ammonia, green ammonia has lower environmental impact in most midpoint impact categories and a reduced overall environmental footprint. However, certain impacts such as direct and indirect land-use change, impacts to endemic biodiversity and the local water availability could be of concern, depending on the specific location and context of the project. The global warming potential and particulate matter were identified as the primary contributors to the overall environmental footprint, underscoring the importance of carbon intensity as a key performance metric for the certification of green hydrogen and its derivatives.

The findings of this study highlight the potential of green ammonia as a fuel to mitigate climate change, help achieve net-zero emissions by 2050, and contribute to the sustainable development goals. However, achieving this potential will require the rapid decarbonisation of energy supply systems to reduce the embodied emissions associated with manufacturing infrastructure.

Acknowledgements This study was part of the project Promoting a South African Green Hydrogen Economy (H2.SA) that is funded by the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ), GmbH and aims to support the South African public and private sectors in realising the potential of a sustainable green hydrogen economy. The interim findings also informed the recommendations of the Research and Development for G20 countries (RD20) Task Force for the Life Cycle Assessment of hydrogen (Tokyo, October 2023).

Competing Interests The authors declare that they have no competing interest.

Electronic Supplementary Material Supplementary material is available in the online version of this article atdoi.org/10.1007/s11708-025-1013-5 and is accessible for authorized users.

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