On behalf of:
Federal Ministry for the Environment, Climate Action, Nature Conservation and Nuclear Safety
of the Federal Republic of Germany

INTERNATIONAL CLIMATE INITIATIVE

Implemented by
Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH

Modelling Cost-Effective Bulk Green Hydrogen Delivery Networks

For South Africa and Namibia

International PtX Hub

On behalf of:
Federal Ministry
for the Environment, Climate Action,
Nature Conservation and Nuclear Safety
of the Federal Republic of Germany

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Pretoria, January 2026

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ABBREVIATIONS

AEL	Alkaline electrolysis
CAPEX	Capital expenditure
CBAM	Carbon Border Adjustment Mechanism
CGH2	Compressed gaseous hydrogen
DBT	Dibenzyltoluol
DCEDA	Northern Cape Economic Development Agency
DWT	Deadweight tonnage
EUR	Euro
GDP	Gross Domestic Product
GH2	Green hydrogen
GHCS	Green Hydrogen Commercialisation Strategy
GIS	Geographic Information System
HP	High pressure
km	Kilometer
LCOH	Levelised cost of hydrogen
LH2	Liquefied hydrogen
LHV	Lower heating value
LOHC	Liquid organic hydrogen carrier
LP	Low pressure
mm	Millimeter
MP	Medium pressure
Mt	Million tonnes
Mtpa	Million tonnes per annum

MWh	Megawatt-hours
MWh/a	Megawatt-hours per annum
NH3	Ammonia
OPEX	Operational expenditure
PEM	Proton exchange membrane
PtX	Power-to-X
PV	Photovoltaic
SADC	Southern African Development Community
SANRAL	South African National Roads Agency
Sc	Scenario (developed and considered in this study)
SDGs	Sustainable Development Goals
SEA	Strategic Environmental Assessment
SIP	Strategic Integrated Project
tpa	Tonnes per annum
USD	United States Dollar
WACC	Weighted average cost of capital
Wesgro	Western Cape Tourism, Trade, and Investment Agency
ZAR	South African Rand

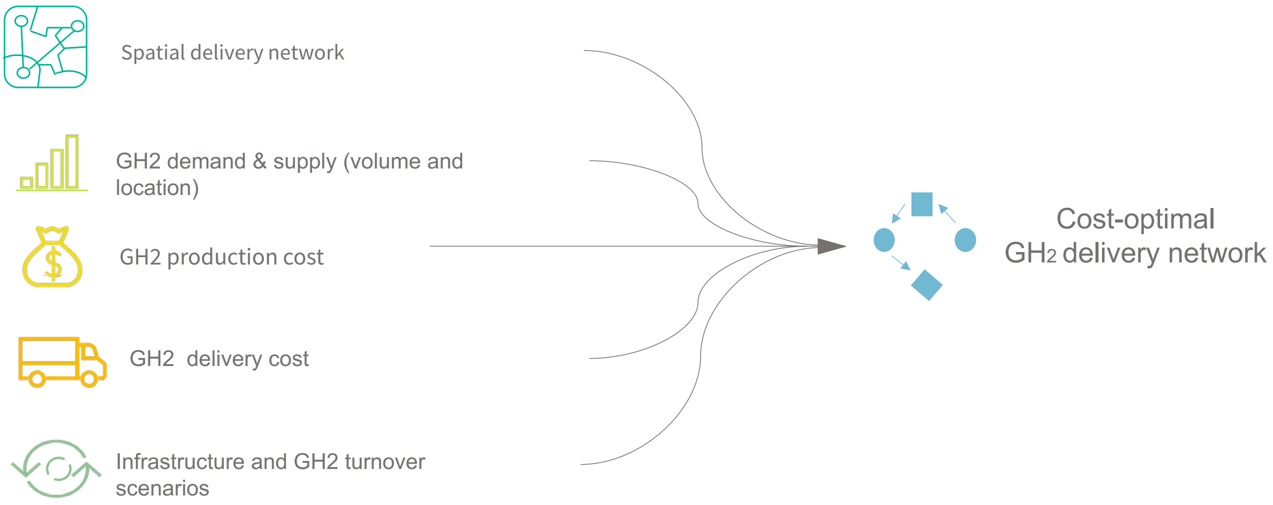
Executive Summary

Background and Scope of the Study

The aim of this study was to develop a modelling approach to investigate **possible cost-effective networks for the bulk delivery/transport of green hydrogen (GH_2) in South Africa linking Namibia** under different infrastructure development and GH_2 utilisation scenarios. Such a network contains the consolidated origin-to-destination flows of GH_2 between supply and demand points. More specifically, it represents the suggested quantities to transport between each node pair, and the routes, transport modes, and carrier types to utilise to minimise the overall network cost.

The scope focuses specifically on the **bulk delivery of GH_2** as either **compressed gaseous hydrogen (CGH_2), liquefied hydrogen (LH_2), green ammonia (NH_3)**, or **Liquid Organic Hydrogen Carriers (LOHC)** via **pipeline, road, rail and ship for domestic use and export in South Africa and Namibia**. Supply nodes constitute various proposed GH_2 production programmes and projects in **South Africa** and **Namibia**. Demand is assumed to be the **export market** and potential **domestic use** by various industrial sectors aggregated to selected nodes in South Africa and two key planned GH_2 production regions in Namibia, namely Lüderitz and Walvis Bay.

A cost optimisation model using GH_2 supply, demand, production and delivery costs within a spatial delivery network for various infrastructure and GH_2 turnover scenarios was developed.



Summary of the main components used to model potential cost-optimal delivery networks for local and export GH_2 demand in South Africa and Namibia. (own illustration)

Scenarios

The infrastructure and GH_2 turnover scenarios analysed were:

- **Sc0 – Existing infrastructure:** Scenario 0 represents the current baseline and seeks to answer the question: "How would GH_2 be delivered using only existing infrastructure (road, rail, pipeline, coastal shipping routes)?"
- **Sc1 – Unconstrained infrastructure expansion, excluding Boegoebaai.** Scenario 1 assumes that delivery infrastructure (road, rail, pipeline) is an available option wherever a delivery pathway exists, and seeks to explore "How would GH_2 be delivered if any infrastructure theoretically existed along every delivery pathway, but the Port of Boegoebaai did not yet exist?"; and
- **Sc2 – Unconstrained infrastructure expansion, including Boegoebaai:** Scenario 2 assumes that delivery infrastructure (road, rail, pipeline) is an available option wherever a delivery pathway exists, and explores a future in which the proposed Port of Boegoebaai has been realised. It thus seeks to answer the question: "How would GH_2 be transported if any infrastructure theoretically existed along every delivery pathway and the Port of Boegoebaai was operational?"

Key Findings

When interpreting the results, it is important to recognise the assumptions underlaying data and scenarios, and to be aware of the limitations of the model and data.

Four key messages are derived from the results:

1. **The market will dictate PtX product (GH_2 carrier) and volumes, in turn the product and volume will dictate delivery infrastructure.** This study shows that delivery of NH_3 via rail is a relevant option for PtX delivery in and from South Africa and Namibia. However, this assumes that the off taker wants to buy NH_3. Ultimately the market (what the off taker wants) will be a determining factor in the transport infrastructure requirements.
2. **It is worth aligning GH_2 ecosystem activities between South Africa and Namibia, especially to strengthen the Northern Cape province of South Africa's GH_2 proposition before the proposed Port of Boegoebaai is developed.**
3. **GH_2 delivery by rail could play an important role, especially along a central north-south corridor.** Whilst both South Africa and Namibia have ambitions to export GH_2 and may be considered competitors, an integrated GH_2 ecosystem could benefit both countries. This does not necessarily have to focus strictly on pipelines, but could also include rail to leverage early anchor GH_2 projects such as those proposed in Prieska, South Africa.
4. **The GH_2 economy of the highveld interior of South Africa (Sasolburg, OR Tambo, Secunda) may operate relatively independently.** The production and transport of PtX product in South Africa's interior could occur in a relatively independent system. However, these areas are generally limited in land and renewable energy resources, implying that renewable energy be produced elsewhere and thus requires capable electricity grid infrastructure. Alternatively, GH_2 could be produced in resource-rich areas and transported inland, which may prove more feasible or cost-effective depending on infrastructure readiness, transport economics and demand volumes.

Whilst the results from the scenarios analysed in this study are relevant, **the development of the model to achieve the results is the main value-add output from this work**. It provides a framework as a point of departure for future investigation of GH_2 delivery networks as the global market establishes itself and grows.

The study concludes with recommendations to research, industry and policymaker stakeholders that aim to strengthen the capability of the model to explore additional questions and yield more robust results, and better understand the infrastructural and policy realities and interventions required towards functional and efficient GH_2 delivery networks in South Africa and Namibia.

1

Introduction

Globally, the transition from fossil fuels towards renewable energy is taking place at increasing pace and urgency. The global shift is driven by commitments to greenhouse gas reduction targets (IPCC, 2019) and the Sustainable Development Goals (SDGs) (Raman et al., 2022), plus the geopolitical need to develop new, sustainable energy supply chains and partnerships (Zakeri et al., 2022). The production of green hydrogen (GH_2) and Power-to-X (PtX) products may play a pivotal role in this transition. The PtX process enables the conversion of electricity into high energy density carriers like hydrogen and synthetic fuels, which could replace fossil fuels in traditionally “hard-to-abate“ sectors, like heavy-duty transport (e.g. shipping) and aviation.

South Africa and Namibia’s renewable energy resources and extensive coastlines provide a potentially competitive advantage in cost-effective GH_2 production. The geographical distribution of optimal GH_2 production (renewable energy and water) and off taker locations means that a connective network for the bulk delivery of GH_2 will require significant investment and must form part of these countries’ GH_2 vision and planning.

Multiple options to connect GH_2 supply and demand [1] exist, and there are ongoing questions about the comparative advantages and disadvantages of moving electricity and water from resource rich areas to on-site GH_2 production facilities at demand centres, or to produce GH_2 proximal to resources centres and delivering it to demand centres (Ortiz et al., 2022).

1.1 Scope and aim

This study developed a modelling approach to investigate **cost-effective networks for the bulk delivery/transport of GH_2 in South Africa and Namibia** under different possible infrastructure development and GH_2 utilisation scenarios. Such a network contains the consolidated origin-to-destination flows of GH_2 between supply and demand points. More specifically, it represents the suggested quantities to transport between each node pair, and the routes, transport modes, and carrier types to utilise in order to minimise the overall network cost.

The scope is focussed specifically on the **bulk delivery/transport of GH_2** as either **compressed gaseous hydrogen (CGH_2), liquefied hydrogen (LH_2), green ammonia (NH_3)** or **Liquid Organic Hydrogen Carriers (LOHC)** via **pipeline, road, rail and ship**. Supply nodes constitute various proposed GH_2 production programmes and projects in **South Africa** and **Namibia**. Demand is assumed to be the **export market** and potential **domestic use** by various industrial sectors aggregated to selected nodes in South Africa and two key planned GH_2 producing regions in Namibia, namely Lüderitz and Walvis Bay.

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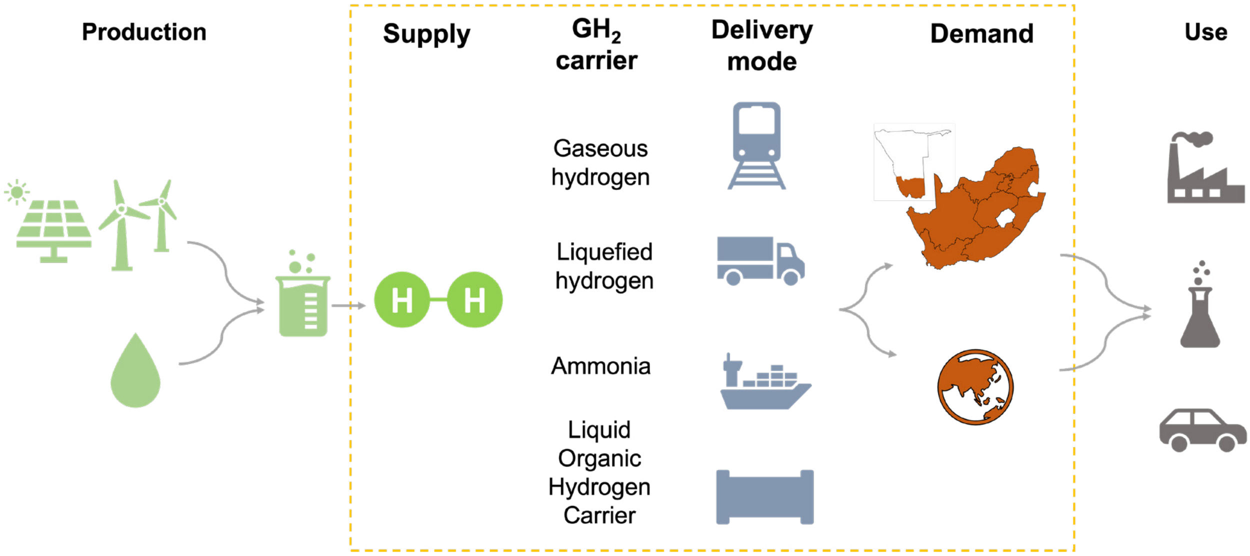
[1] Connecting hydrogen supply and demand is often interchangeably referred to as hydrogen ‘delivery’, ‘logistics’ or ‘transport’, not to be confused with the use of hydrogen in logistics or transport (i.e. hydrogen-powered vehicles). For the purpose of this study, we use the terminology **‘hydrogen delivery’**.

The work developed an initial modelling framework for bulk delivery of GH_2 in South Africa and Namibia, ultimately towards:

- Identifying, at a strategic and national level, cost-effective pathways for the bulk delivery of GH_2 to meet the future needs of South Africa's domestic and export markets, with links to Namibia.
- Support decisions on where future GH_2 infrastructure development may need to be prioritised to meet South Africa's GH_2 ambitions.

Figure 1: The scope of work for this study focusses on the bulk delivery of GH_2 via road, rail, ship and pipeline from supply in South Africa and Namibia to meet domestic and export demand (yellow dashed outline).



Source: CSIR, 2025

2

Background

2.1 The South African context

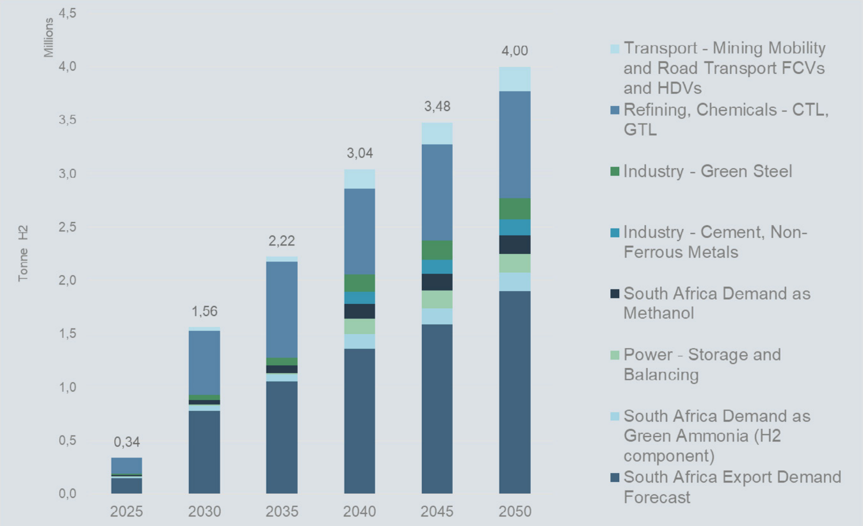
2.1.1 Green hydrogen demand and export potential

Countries with insufficient renewable energy resources and limited by land to deploy commercial GH_2 and PtX projects are looking to import GH_2 from countries like South Africa and Namibia that are endowed with resources like solar and wind energy as well as abandoned or unusable land. The cumulative market potential for exports to the European and Asian markets are estimated at 12 Mtpa by 2030 (Uhorakeye et al., 2024).

Increased domestic demand for GH_2 will be driven by overarching policy developments, such as the Paris Agreement and the more recently introduced Carbon Border Adjustment Mechanism (CBAM). The CBAM will initially apply to commodities exported to the European market such as cement, iron and steel, and aluminium. Vasileva (2024) notes that infrastructure, particularly pipelines are critical to driving GH_2 demand and enabling offtake.

The domestic market for GH_2 in South Africa is currently centred on decarbonising hard-to-abate industries, such as mining, steel, cement and chemicals. South Africa's domestic demand for GH_2 has been estimated under a 'low' scenario and a 'high" scenario according to the Green Hydrogen Commercialisation Strategy (GHCS). In the low scenario, domestic GH_2 demand is estimated at 1.5 Mtpa by 2050, with a high estimate of 2.1 Mtpa (DTIC, 2022). The addressable export market according to the GHCS is 1.25 Mtpa in the low scenario and 1.9 Mtpa in the high scenario. The combined domestic and export demand trajectory estimates according to the high scenario is depicted in Figure 2.

Figure 2: South African GH_2 export and domestic demand (high scenario).



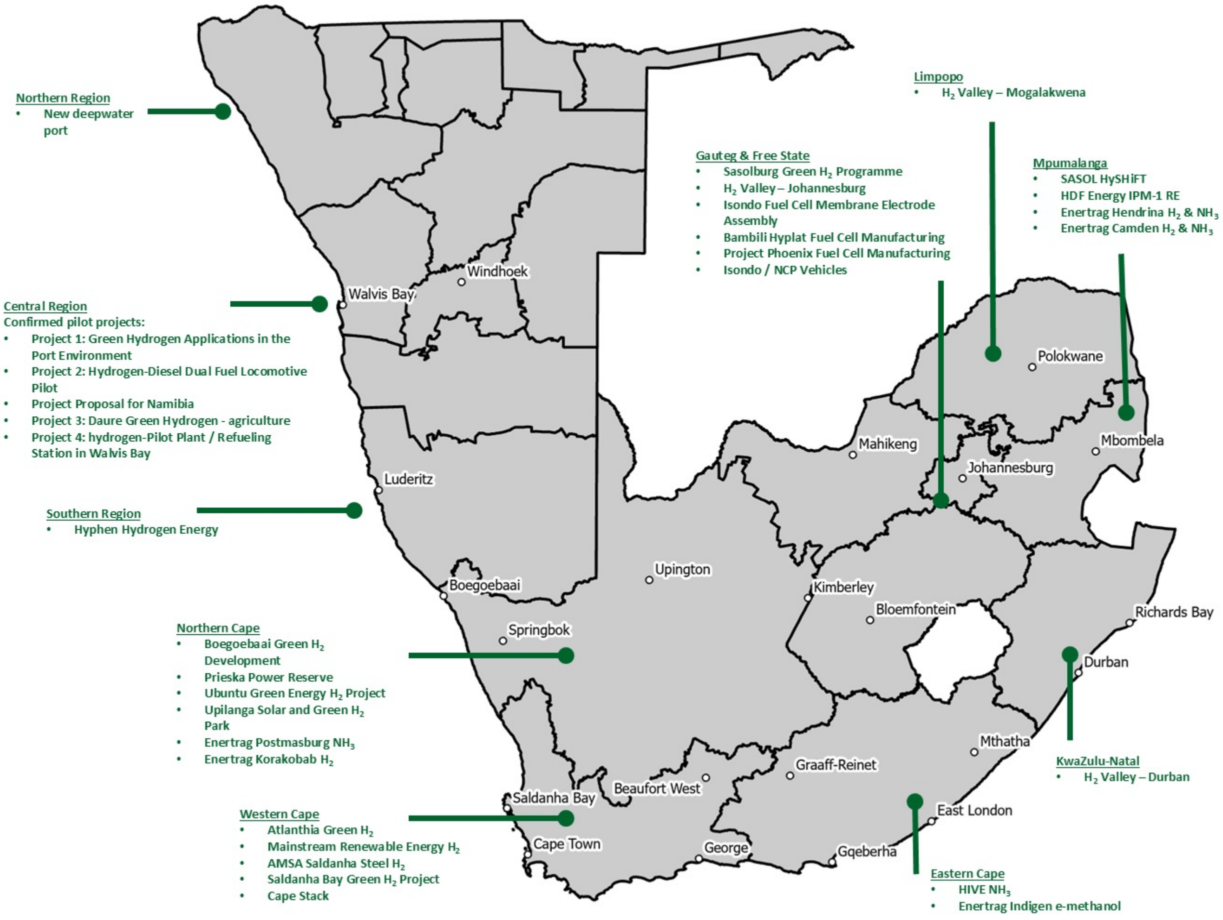
Source: Rebel Group, 2025 (based on data in DTIC, 2022).

It should be noted that, due to the nascency of global PtX markets, there is considerable uncertainty in both the export and domestic demand estimates. In terms of exports, the GHCS adopted a relatively conservative estimate when compared to more ambitious scenarios that project export demand as high as 8 Mtpa [2].

2.1.2 Green hydrogen supply

South Africa's ambition is to produce 3.8 Mtpa of GH_2 by 2040 and 7 Mtpa by 2050 (DTIC, 2022). Several GH_2 and PtX production and related supply chain projects (e.g. fuel cell manufacturing) had been announced, with several being prioritised by the South African government as Strategic Integrated Projects (SIPs). Notable GH_2 production proposals are located at Saldanha Bay, Boegoebaai (conceptual), Coega, and inland at Prieska near Upington, Secunda and Sasolburg (Figure 3).

Figure 3: Planned GH_2 and PtX projects (including indirect value chain initiatives) in South Africa and Namibia.



Source: CSIR, 2025 (based on data from DSI, 2022; South Africa, 2022; MME, 2022).

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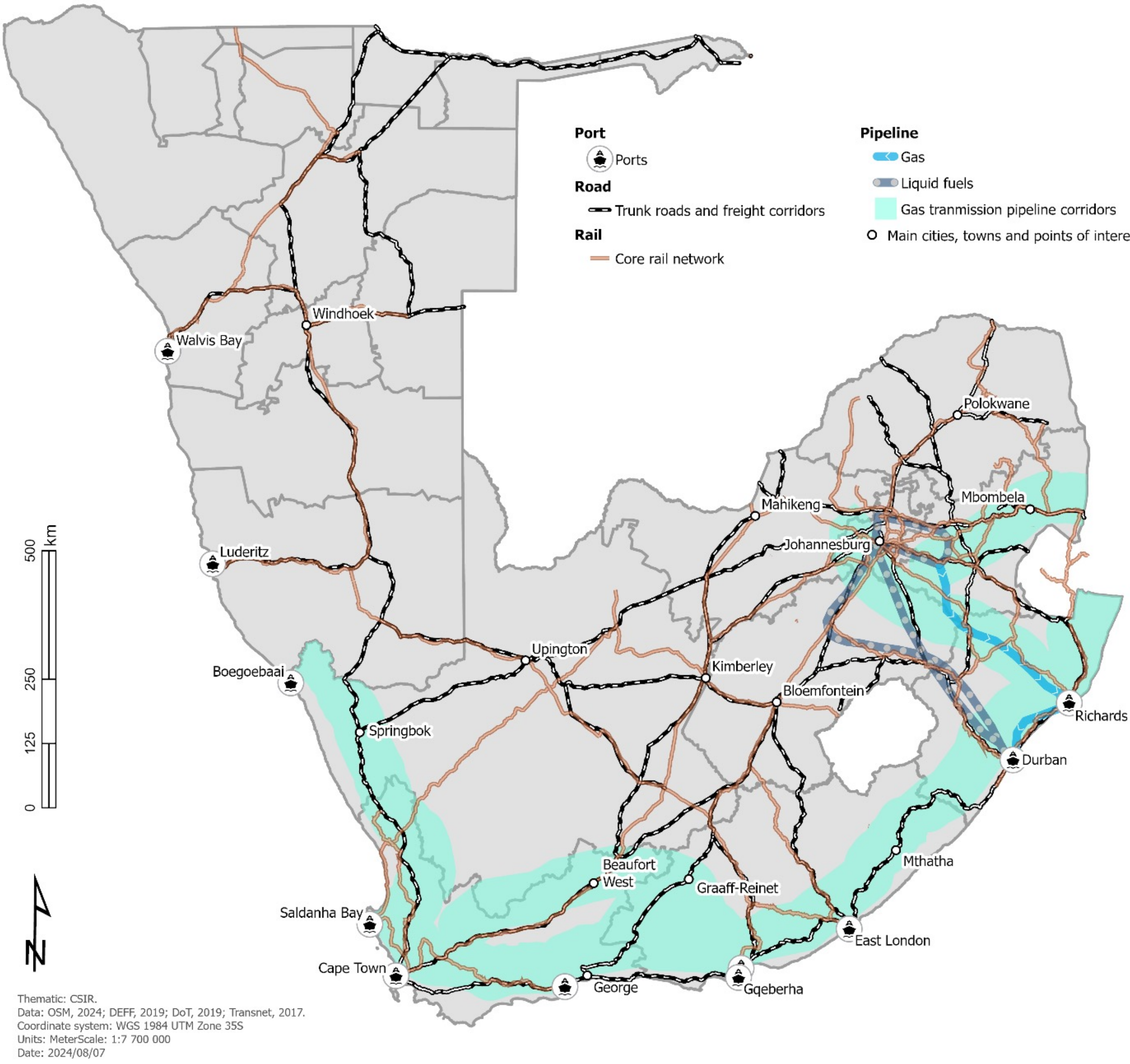
[2] SASOL Ambitious Scenario as documented in the GHCS.

2.1.3 Green hydrogen delivery infrastructure

Modes of transporting freight and associated enabling infrastructure in South Africa and Namibia consists of ports, road, rail and gas and liquid fuel pipelines (Figure 4). Pipeline infrastructure is isolated to the area between Gauteng and Durban, whilst road and rail infrastructure are more established, including South Africa-Namibia links.

Figure 4: Existing port, road, rail and gas pipeline infrastructure in South Africa and Namibia.



Thematic: CSIR.
Data: OSM, 2024; DEFF, 2019; DoT, 2019; Transnet, 2017.
Coordinate system: WGS 1984 UTM Zone 35S
Units: MeterScale: 1:7 700 000
Date: 2024/08/07

Source: CSIR, 2025 (based on data from OSM, 2024; DEFF, 2019; Dot, 2019; Transnet, 2017).

Road

Nearly 85% of freight payload is transported by road in South Africa (StatsSA, 2024). The country has several defined freight corridors[3], consisting of freight mass transported roughly 56 % by road, 42 % by rail and 2 % by pipelines (DoT, 2019). Most of the roads in the national freight corridors are developed, maintained and managed by the South African National Roads Agency (SANRAL), whilst in some cases provincial and local government may be responsible for roads.

Rail

Approximately 15 % of freight payload in South Africa is transported by rail (StatsSA, 2024). Transnet's core rail network consists of four main systems (Transnet, 2017:47):

- **Iron ore and manganese systems:** Heavy haul lines linking the Northern Cape with Saldanha and Port Elizabeth/ Ngqura predominantly export iron ore and manganese ore to Saldanha and domestic manganese ore, domestic iron ore and containers to Port Elizabeth/Ngqura. Train size is predominantly heavy.
- **Coal system:** Feeder lines from the Lephalale and Mpumalanga areas to domestic destinations and Ermelo-Suid; main line from Ermelo-Suid to Richards Bay; Komatipoort through Eswatini to Richards Bay, including the proposed Eswatini link. Main commodities are export coal, domestic coal, chrome and magnetite. Train size is predominantly heavy.
- **North-eastern system:** General freight lines from Gauteng to Komatipoort, Gauteng to Musina and Groenbult to Kaapmuiden. Main commodities are agricultural products and fuel, with coal and minerals from Limpopo. Train size is light to medium.
- **Intermodal and general freight systems:**
  - **Gauteng to Durban system:** General freight lines including Freight Ring from Pyramid South to Houtheuwel; Natcor from Rietvallei to Booth. Main commodities are containers, domestic coal, fuel and other general freight. Train size is light to medium.
  - **Gauteng to Cape Town system:** General freight line including Houtheuwel to Kamfersdam, De Aar to Cape Town, Vereeniging to Noupoort. Predominantly transports containers and domestic coal. Some containers and automotive transport linked to Gqeberha. Train size is light to medium.

In recent years, the South African freight rail network's performance has been declining with transported volumes reducing from 226 Mt in 2017/18 to approximately 150 Mt (2022/23) – as a result, there has been a substantive shift to road freight, which compromises greenhouse gas emission reduction goals (DoT, 2023).

Pipeline

South Africa's existing pipeline network is located in the eastern part of the country and services delivery of liquid petroleum and methane-rich gas. Transnet's pipeline network consists of: 1) multi-product lines that carry a range of refined petroleum products like diesel, petrol, jet fuel, and kerosene for from coastal refineries in Durban to inland terminals and distribution centres across the country; and 2) a gas pipeline that carries methane-rich gas from Secunda to Durban with off take points at Newcastle, Empangeni, and along the route (Transnet, 2017).

Transnet's pipelines conform to an American code of practice (ASME B31.4) and have diameters ranging from six inches (nominally 150 mm) to 20 inches (nominally 508 mm). Pressures in the pipeline network are permanently monitored at the control centre at the Transnet head office in Durban (Transnet, n.d.).

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[3] "A freight corridor is defined as a coordinated bundle of transport and logistics infrastructure and services that facilitates multi-modal trade and transport flows between major points of production and consumption, linking South Africa with regional and global markets." (DOT, 2019) (https://freight.transport.gov.za/#!/corridormain)).

In 2019, a Strategic Environmental Assessment (SEA) was undertaken to identify and pre-assess suitable gas transmission pipeline corridors to facilitate a streamlined environmental assessment process for the development of such energy infrastructure (DEFF, 2019) (see Figure 4). The assessment focused on the future gas transmission pipeline plans of iGas, PetroSA and Transnet, but at that time, a pipeline linkage between Gauteng and the Northern Cape was not prioritised.

The outcomes of the SEA have been formalised in South African law such that “the development and related operation of facilities or infrastructure for the bulk transportation of dangerous goods in gas, liquid or solid form using pipelines” (South Africa, 2017) within the identified corridors that require Environmental Authorisation enjoy a shortened assessment and decision-making process (South Africa, 2021a) and have a pre-existing Environmental Management Programme that need only be populated with site-specific information (South Africa, 2021b).

The development of new pipelines for bulk delivery of GH_2 within the strategic gas pipeline corridors will benefit from this regulatory streamlining during the Environmental Impact Assessment and authorisation stage.

Ports and shipping

South Africa boasts eight commercial ports (Figure 4), managed by the Transnet Ports Authority (TNPA), with an additional new port proposed at Boegoebaai in the Northern Cape.

The ports of Saldanha Bay, Coega/Ngqura and Richards Bay of the ports are considered to be currently viable for GH_2 and PtX product export (Uhorakeye et al., 2024). The proposed new deepwater port at Boegoebaai is strategically put forward as a GH_2 hub (NCEDA, 2023). The ports of Durban, Cape Town and Port Elizabeth (Gqeberha) may be constrained for bulk production and export of GH_2 as they are in urban centres, whilst the shallow draughts of the ports of East London and Mossel Bay are currently unsuitable for GH_2 export (Uhorakeye et al., 2024).

2.2 Namibian context

2.2.1 Namibia’s Green Hydrogen Strategy

The ‘Namibia Green Hydrogen and Derivatives Strategy’ outlines Namibia’s ambitions to become a global leader in GH_2 production by leveraging its abundant renewable energy resources, particularly solar and wind (MME, 2022). Key targets and goals include:

1. GH_2 production: Namibia aims to produce 10 to 15 million tonnes per annum (Mtpa) of GH_2 equivalent by 2050. Interim targets include 1-2 Mtpa by 2030 and 5-7 Mtpa by 2040.
2. Export focus: While Namibia will develop domestic GH_2 use, the primary focus is on exporting GH_2 derivatives like NH_3, methanol, and synthetic kerosene to regions including Europe, Japan, South Korea, and China.
3. Economic impact: By 2030, the GH_2 industry is expected to contribute \$6 billion to Namibia‘s Gross Domestic Product (GDP) and create up to 80 000 jobs, with further growth anticipated by 2040.
4. GH_2 valleys: Three key GH_2 valleys will be developed in the Southern, Central, and Northern regions, with shared infrastructure and synergies with neighbouring countries for regional growth.
5. Green growth goals: The GH_2 industry will contribute to decarbonising Namibia‘s economy, with a domestic demand target of 95 000 tonnes of GH_2 by 2040.

2.2.2 Green hydrogen demand and export potential

Namibia‘s GH_2 strategy is primarily focused on serving global markets, with limited domestic demand expected in the near term. The country anticipates that its domestic GH_2 demand could reach approximately 95 000 tonnes per annum by 2040, driven by sectors such as mining (e.g., GH_2-fuelled trucks), transport (including GH_2 -powered tugboats and trains), and local industrial applications (MME, 2022). These early projects will support decarbonisation and green industrialisation in Namibia.

On the export side, Namibia’s competitive advantage in renewable energy production positions it to become a major supplier of PtX products, particularly NH_3, methanol, synthetic kerosene, and hot-briquetted iron (HBI). The country aims to meet the growing demand from leading international markets, including Europe, Japan, South Korea, and China, all of which have ambitious GH_2 import targets as part of their decarbonisation plans. Europe‘s GH_2 import demand, for example, is expected to be driven by the EU’s REPowerEU strategy, which targets 10 Mt of GH_2 imports by 2030, with Germany expected to need 15 Mt by 2050 (MME, 2022).

Namibia’s competitive GH_2 production costs make it a viable partner for these markets despite the relatively large distance from these markets. The country‘s GH_2 export potential will be realised through its ability to deliver cost-competitive GH_2 derivatives, benefiting from existing and planned export infrastructure at Walvis Bay and Lüderitz ports. Additionally, Namibia is fostering partnerships with countries like Germany[4], Belgium[5], the Netherlands[6], and Japan[7] to secure long-term export agreements and develop the necessary regulatory frameworks to facilitate international trade.

Namibia’s domestic demand and export potential for GH_2 is summarised in Table 1.

Table 1: Namibian GH_2 domestic demand and export potential.

Year	Domestic Demand (tonnes/year)	Export Potential (mtpa)
2030	22 635	1-2
2040	172 635	5-7
2050	172 635	10-15

Source: MME (2022) and announcements on projects requiring pure GH_2 including O&L group - CMB.TECH hydrogen hub, Renewstable Swakopmund and Oshivela DRI project, Phase 1 and 2.

2.2.3 Green hydrogen supply

Namibia’s GH_2 supply strategy is centred around its vast renewable energy resources and the development of three key GH_2 production regions, or „hydrogen valleys,“ which will contribute to the country‘s overall GH_2 production targets respectively. By 2050, Namibia aims to produce 10–15 Mtpa of GH_2 equivalent, with exports being the primary focus.

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[4] “German-Namibian cooperation on hydrogen.” (GIZ,2023) (https://www.giz.de/en/worldwide/155834.html)

[5] Belgium commits to long-term clean energy partnership with Namibia. (Mining & Energy, 2024) (https://miningandenergy.com.na/belgium-commits-to-long-term -clean-energy-partnership-with-namibia/)

[6] “EU, Netherlands pledge N$258 million to Namibia’s green hydrogen fund.” (The Brief, 2025) (https://thebrief.com.na/2025/04/eu-netherlands-pledge-n258-million-to-namibias-green-hydrogen-fund/)

[7] “Namibia and Japan Forge Green Pathway in Hydrogen and Minerals” (Energy News, 2023) (https://energynews.biz/namibia-and-japan-forge-green-pathway-in-hydrogen-and-minerals/)

Southern Region (Kharas)

The Southern Hydrogen Valley is expected to be the largest GH_2 production hub in Namibia. The region's strong wind and solar resources, coupled with existing and planned infrastructure, position it as the main driver of GH_2 production, with an estimated 5 Mtpa of GH_2 equivalent by 2050. The Lüderitz port will serve as the primary export facility for GH_2 derivatives from this region, with planned upgrades to accommodate large-scale exports of green NH_3, methanol, and other PtX products.

Central Region (Walvis Bay and Windhoek)

The Central Hydrogen Valley, including Walvis Bay and the capital Windhoek, is expected to contribute up to 3 Mtpa of GH_2 equivalent by 2050. This region benefits from a combination of solar and wind energy, but will scale production more gradually compared to the Southern region. Walvis Bay, as a well-established port, will play a critical role in exporting PtX products such as synthetic fuels and NH_3. In addition to exports, GH_2 produced in this region may be used for domestic applications, including transport and agriculture.

Northern Region (Kunene)

The Northern Hydrogen Valley has the potential to produce 5 Mtpa of GH_2 equivalent by 2050. However, development in this region will require significant investment in infrastructure, including the construction of a new port. Once developed, this valley will complement the other two regions, contributing to the overall GH_2 supply and exporting PtX products primarily via the new port facility in the northern region.

Namibia's GH_2 production estimates for the three regions from 2030 to 2050 is summarised in Table 2.

Table 2: Namibia GH_2 production estimates for different regions from 2030 to 2050

Year	Southern Valley (mtpa)	Central Valley (mtpa)	Northern Valley (mtpa)	Total (mtpa)
2030	0.63	0	0.59	1.22
2035	1.24	0.36	1.26	2.86
2040	2 .4	1	2.3	5.7
2045	3 .4	1.6	3.3	8.3
2050	5	3.2	4.8	13

Source: MME, 2022 (based on Exhibit 13: Green valley evolution to 2050 in Namibia).

2.2.4 Green hydrogen delivery infrastructure

Namibia's GH_2 supply chain is closely tied to its export infrastructure. The country will leverage its strategic coastal locations, with Lüderitz and Walvis Bay being the key ports for GH_2 exports. The Southern region's supply will primarily flow through Lüderitz, while the Central region's exports will be handled by Walvis Bay. The development of a port in the Northern region will further enhance Namibia's export capacity, enabling it to meet the growing international demand for PtX.

Road

Namibia’s road network facilitates the movement of goods and trade, connecting its coastal regions with both domestic and international markets, particularly South Africa. The B4 and B1 highways are key components of this network, playing an important role in supporting heavy freight transport, including minerals, fuel, agricultural products, and containerised goods, across Namibia’s trade routes.

Namibia’s road network is extensive and generally well-maintained. Trunk roads, such as the B1, provide the primary north-south routes, while main roads, such as the B4, link coastal towns like Lüderitz to the interior. The B1 connects Keetmanshoop to the Ariamsvlei border post, where it continues into South Africa along the N7 highway, providing a direct route to Cape Town. Additionally, the Trans-Kalahari Corridor and other routes extend Namibia’s road links eastward, connecting the country with Botswana, South Africa’s Gauteng region, and other southern African countries.

Road link from Lüderitz

The B4 highway links Lüderitz, a coastal town and export hub, to Keetmanshoop in central Namibia. From Keetmanshoop, the B1 highway offers two main routes for cross-border transport:

1. South to Cape Town: From Lüderitz, freight can travel along the B4 to Keetmanshoop, and from there, the B1 leads south to the Ariamsvlei border post with South Africa. Once across the border, the N7 highway connects to Springbok and continues south to Cape Town, with a total distance of approximately 800 km via trunk roads.
2. East to Gauteng: Alternatively, the B4 and B1 provide an eastward route to Gauteng, South Africa’s industrial hub. This route extends Namibia’s road connections to important economic regions in southern Africa.

The B4 and B1 highways are designed to accommodate various types of heavy freight, including:

- Minerals: Manganese and other minerals like copper and zinc are transported from South African mines to Lüderitz for export.
- Fuel: The B1 serves as a route for fuel transport, particularly between Namibia’s ports and its central regions.
- Agricultural products: Namibia exports agricultural goods, such as beef and fish, along these routes, facilitating trade with South African markets.
- Containerised goods: Containerized freight moves between Walvis Bay, Lüderitz, and industrial hubs like Gauteng.

These roads support heavy loads, with trucks allowed to carry up to 56 tonnes of gross vehicle mass, in line with Southern African Development Community (SADC) transport regulations. Weight and axle load restrictions are enforced to preserve the road infrastructure, and rolling restrictions may be applied during extreme weather to prevent road damage.

Rail

The Namibian rail network runs centrally from north to south, also connecting Walvis Bay and Lüderitz. In the south, it connects to South Africa’s Upington and Kakamas. Both countries use the same gauge. Currently, passenger, bulk freight and container services are run on the Namibian rail network. Data on capacity is not available.

The stretch of rail from the South African border to Lüderitz runs from the border post at Nakop in South Africa through Ariamsvlei and Keetmanshoop and extends to Lüderitz on Namibia‘s southern coast. This line, originally completed in 1915, was partially decommissioned in the late 1990s due to poor track conditions. However, the rail line was rehabilitated in the 2010s, with test trains running to Lüderitz in 2014 and 2018. Currently, the line is operational and primarily used to transport manganese ore from South African mines to Lüderitz for export. The line’s capacity is part of the broader upgrade plans by TransNamib, but it still faces load limitations, as sections of the network have not yet been upgraded to meet the SADC axle load standard of 18.5 tonnes.

Pipeline

Pipelines to transport GH_2 within Namibia to connect hinterland PtX production sites to coastal export facilities (e.g. for the Central Hydrogen Valley (FICHTNER 2024) are being discussed, in the scope of the Hyphen project in the Southern Hydrogen Valley (HYPHEN 2022)) and to connect Namibian to South African GH_2 activities. A feasibility study is currently conducted for a GH_2 pipeline connecting the Namibian Port Lüderitz with the South African northern cape region, potentially extending to other regions in South Africa.

In June 2024, Namibia and South Africa have signed a Memorandum of Understanding (MoU) to explore the feasibility of Africa's first cross-country GH_2 pipeline. The proposed pipeline would connect Lüderitz in Namibia with South Africa's Northern Cape and potentially extend to the Western Cape, creating a corridor for the transport and trade of GH_2.

The MoU was signed at the 2024 World Hydrogen Summit and includes participants such as Wesgro (Western Cape Tourism, Trade, and Investment Agency), NCEDA (Northern Cape Economic Development Agency), Namibia's Green Hydrogen Programme, Gasunie, and Climate Fund Managers. The study assessed various technical, financial, environmental, and operational aspects of the project. The pre-feasibility study was completed in December of 2024 with a positive outcome.

Ports and shipping

Lüderitz and Walvis Bay have been identified as the main ports for Namibia's GH_2 exports in the near future. Namport has analysed the infrastructure at both ports to assess their current and future capacities for handling green fuel exports (2024), focusing on necessary upgrades and expansion to meet expected demand. A new port in the north of the country, near Cape Fria, is being considered for future expansion, but for now, the emphasis remains on these two southern ports.

At **Walvis Bay**, the port has already developed liquid bulk handling capabilities, with two 90 000 DWT[8] berths in place. These facilities can manage up to 10 Mtpa of gases and liquids, including GH_2 derivatives like NH_3 and methanol. Additionally, 350 hectares of land has been zoned specifically for GH_2-related activities. Three project developers have secured land for NH_3 bunkering and export terminals. Namport's analysis suggests that this infrastructure will be sufficient to handle GH_2 exports for at least the next 10 years, with room for further expansion as the sector grows.

The port of **Lüderitz** faces limitations in its current infrastructure, which is fully utilised. However, Namport's assessment has led to plans for an expansion of 6 to 15 hectares of land and an additional 250 to 700 meters of quay wall at Robert Harbour, which could be available by 2027. Furthermore, the Angra Point expansion is being planned to accommodate 2 Mtpa of GH_2 exports by 2028, with a total potential capacity of **18 Mtpa**. This expansion will also include facilities for NH_3 production, storage, and a desalination plant to support GH_2 production.

While Walvis Bay and Lüderitz will handle Namibia's GH_2 exports in the coming years, there are plans for a new port in northern Namibia near Cape Fria. Although still in the planning phase, this future port is intended to further enhance the country's export capacity as GH_2 production continues to scale.

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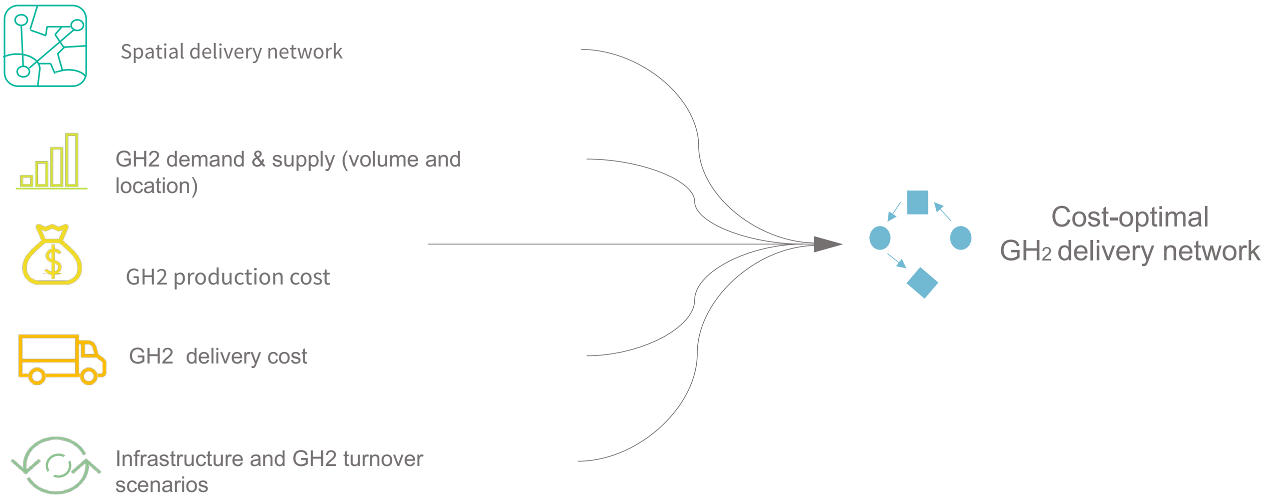
[8] Deadweight tonnage (DWT) refers to the maximum weight a vessel can safely carry before it submerges to its maximum allowable draft.

3

Approach

This work focuses specifically on the assessment of bulk delivery of GH_2 as CGH_2, LH_2, NH_3 and LOHC via pipeline, road, rail and ship (refer to Figure 1) for different demand-supply volumes. To achieve this, a cost optimisation model using GH_2 supply, demand, production and delivery costs within a spatial delivery network for various infrastructure and GH_2 turnover scenarios was developed (Figure 5). There is a total of 20 GH_2 supply and demand nodes defined in the optimisation model of which two are located in Namibia, two representing export ambitions and 16 nodes located in South Africa. Details can be found in Section 4.1. As the future development of GH_2 supply and demand volumes are highly uncertain, three levels of GH_2 turnover are defined, as low, medium and high, which correlates to the time horizons of 2030, 2040 and 2050.

Figure 5: Summary of the main components used to model potential cost-optimal delivery networks for local and export GH_2 demand in South Africa and Namibia.



Source: CSIR, 2025.

The delivery network is discussed in section 3.1. Details on supply and demand figures are elaborated in section 3.2. Techno-economic assumptions and model input data are presented in section 3.3. Assumptions, methodology and input data on GH_2 transport technology are discussed in section 3.4., Section 3.5 presents the defined supply, demand and infrastructure development scenarios and details on the optimisation model are included in section 3.5

3.1 Spatial hydrogen delivery network

3.1.1 Delivery pathways

The PtX delivery network for South Africa and Namibia was constructed in a Geographic Information System (GIS) using available spatial data of existing road, rail and pipeline infrastructure (Table 3). Coastal and export shipping were assumed from commercial ports in South Africa (including the proposed port of Boegoebaai) and the southern and central regions of Namibia (Lüderitz and Walvis Bay).

Table 3: Spatial data of existing infrastructure used to construct the PtX delivery pathways network for South Africa and Namibia.

Pathway feature	Data source/s
Road	Open Street Map Contributors. 2024. South Africa. https://download.geofabrik.de/africa/south-africa.html
Rail	Open Street Map Contributors. 2024. South Africa. https://download.geofabrik.de/africa/south-africa.html Verified against “core rail” network in the Transnet Rail Development Plan (Transnet, 2017)
Pipeline	Derived from the Transnet Pipeline Development Plan (Transnet, 2017).
Shipping	Generated as lines along the coast for the purpose of this study.

The road and rail lines were simplified using a 10 km threshold to reduce extraneous detail (e.g. small bends in roads) in the national-scale networks whilst maintaining enough detail to express relative distances between potential nodes (see section 4.1.2). Existing pipeline infrastructure, limited to the eastern part of South Africa, was derived from Transnet (2017) and broadly aligned with the road and rail network.

The presence of the available transport modes for each pathway segment (road, rail, pipeline and shipping) is indicated and the segment length between nodes were calculated in kilometres in the GIS software [9].

3.1.2 Nodes

Intersections at pathway segments represent nodes. Three different node types exist:

- Supply node* – where GH_2 will be produced. A single node can act as both a supply and demand node.
- Demand node* – where GH_2 will be consumed. A single node can act as both a supply and demand node.
- Connecting node – intersection between the different pathways that are not necessarily associated with GH_2 supply or demand but may present a transport mode change.
- *Note that the node types are not mutually exclusive, meaning that a node could be classified as one or more node type (e.g., a GH_2 could be produced and consumed at the same node).

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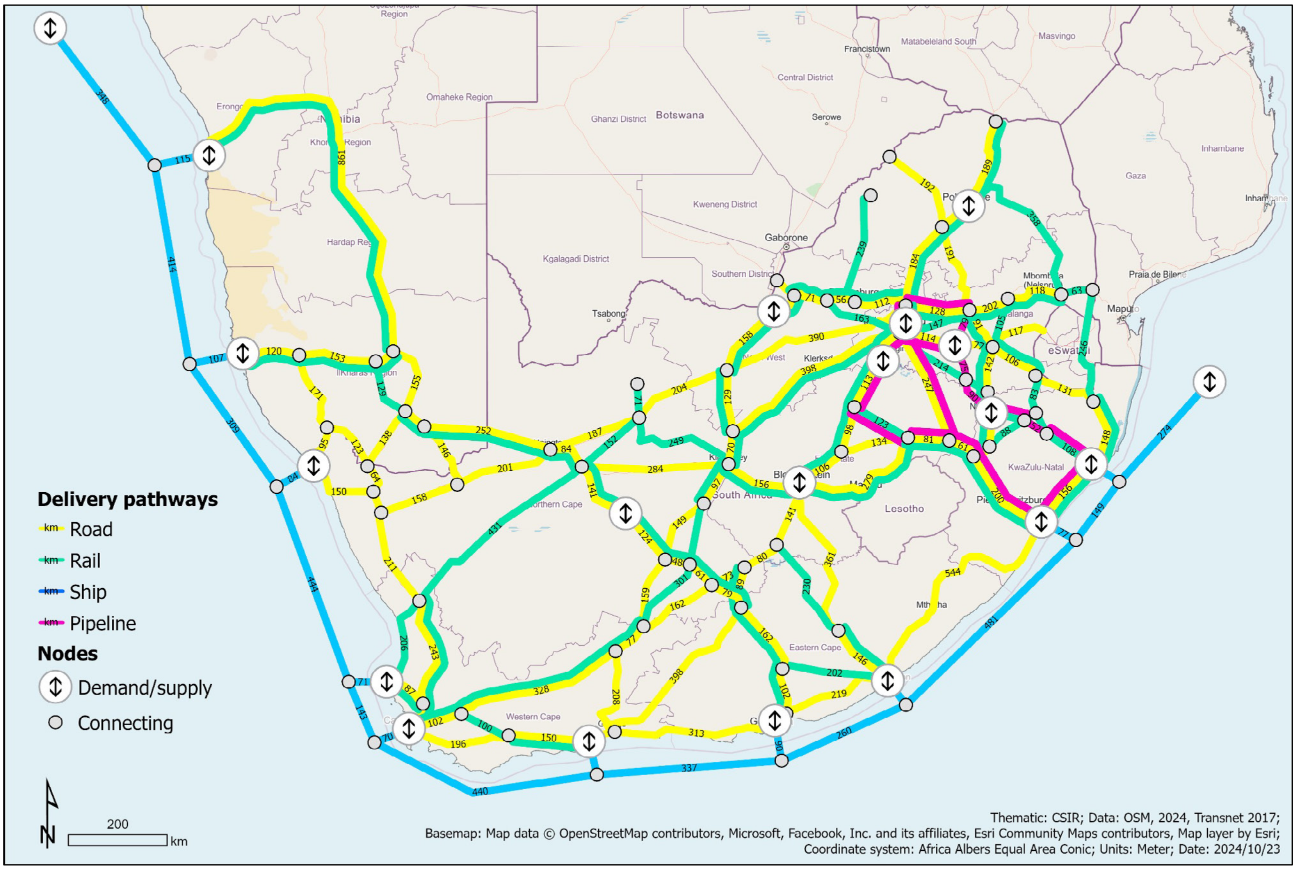
[9] Esri ArcGIS Pro 3.2.1.

Figure 6: Spatially defined PtX delivery network for South Africa and Namibia considering existing road, rail and pipeline infrastructure. The length (km) of possible delivery pathways is indicated for each pathway segment (min: 22 km; max 860 km; mean 160 km). Nodes are located at the intersection of delivery pathways and are either connecting (i.e. no associated GH_2 demand/supply, but representing a delivery mode change) or representative of GH_2 demand/supply areas.



Thematic: CSIR; Data: OSM, 2024, Transnet 2017;
Basemap: Map data © OpenStreetMap contributors, Microsoft, Facebook, Inc. and its affiliates, Esri Community Maps contributors, Map layer by Esri;
Coordinate system: Africa Albers Equal Area Conic; Units: Meter; Date: 2024/10/23

Source: CSIR, 2025

The network consists of 92 nodes representative of South Africa and Namibia in the context of GH$_2$. Twenty (20) of the 92 nodes were preliminarily identified as supply/demand nodes:

Eastern Cape:	1. East London
	2. Gqeberha
Free State:	3. Bloemfontein
	4. Sasolburg
Gauteng:	5. OR Tambo
KwaZulu-Natal:	6. Durban
	7. Newcastle
	8. Richards Bay
Limpopo:	9. Polokwane
Mpumalanga:	10. Secunda

Northern Cape:	11. Boegoebaai
	12. Prieska
North West:	13. Mahikeng
Western Cape:	14. Cape Town
	15. Mosselbay
	16. Saldanha Bay
Namibia:	17. Lüderitz
	18. Walvis Bay
	19. Asia (export to)
	20. Europe (export to)

The supply and demand nodes were apportioned GH$_2$ volumes in line with the methodology outlined in section 4.2.

3.2 Hydrogen supply and demand volumes

Currently, no geographically explicit data exists for future GH$_2$ demand or supply in South Africa or Namibia. While both countries have developed national GH$_2$ strategies with aggregate supply and demand estimates, these are not spatially resolved. However, planning for a delivery network necessarily requires geographically defined nodes of supply and demand. This section describes the approach used to construct such spatial estimates based on available national targets, sectoral breakdowns, and additional supporting datasets.

3.2.1 Data sources

We adopted national strategy documents as the primary reference point:

- **South Africa**: Green Hydrogen Commercialisation Strategy (GHCS) (DTIC, 2022), which provides sectoral estimates of domestic demand and export potential under low and high scenarios, as well as total production ambitions.
- **Namibia:** Green Hydrogen and Derivatives Strategy (MME, 2022), which outlines future production capacity targets and a high-level projection of domestic use.

To spatially allocate demand and supply, the following secondary sources and proxies were used:

- **South African Green Hydrogen Potential Atlas[10]:** location suitability for GH_2 production and industrial offtake
- **IEA Hydrogen Projects Database[11]:** lists of known projects and proposed capacities
- **Strategic Integrated Projects (SIPs):** South African projects identified under the GH National Programme
- **World Bank study on Green Marine Fuels[12]:** estimates of potential demand for hydrogen-derived bunker fuels at South African ports
- **Sector-specific proxies:** e.g. diesel consumption (for transport), electricity consumption (for energy storage), foundry and cement plant locations (for industrial demand)
- **Project-specific engagement:** including Sasol production estimates and methanol market data

3.2.2 Demand estimation

South Africa – spatial allocation of sectoral demand

The GHCS provides sectoral estimates of domestic GH_2 demand. For modelling purposes, we adopted the high scenario as a reference case and spatially allocated each sector's demand to specific nodes in the delivery network. Table 4 summarises the allocation approach.

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[10] CSIR, GFA, DFE and GIZ, South African Green Hydrogen Potentials Atlas https://bit.ly/SAGH2atlas

[11] Hydrogen Production and Infrastructure Projects Database." (IEA, 2024) (https://www.iea.org/data-and-statistics/data-product/hydrogen-production-and-infrastructure-projects-database)

[12] "Creating a Green Marine Fuel Market in South Africa." (World Bank, 2024) (https://openknowledge.worldbank.org/entities/publication/da61a3f6-88b8-41b0-98f9-1e08efa989fd)

Table 4: Spatial allocation methodology for sectoral GH_2 demand in South Africa

Sector	Data source / proxy used	Allocation approach	Key nodes allocated to	Notes
Ammonia production	Existing production centres (SASOL, 2019)	Based on Sasol's current operations	Sasolburg, Secunda	Reflects current large-scale NH_3 use at Sasol plants
Methanol demand	Duma (2023), methanol use by location	Sasolburg assigned entire domestic methanol-linked H_2 demand	Sasolburg	Total demand: 17 500 tpa GH_2 from 140 000 t methanol use
Heavy-duty transport	Provincial diesel sales (2021–2022 averages) (DMRE, 2024)	Proportional allocation based on % of diesel consumption	All provinces (weighted share)	Gauteng: 25.7%, KZN: 21.7%, Western Cape: 20.0%, etc.
Electricity storage	Share of national electricity consumption by province (StatsSA, 2019)	Proportional to annual electricity demand	All provinces	Gauteng, KZN, Western Cape and Mpumalanga dominate; no specific industrial site allocation
Cement & non-ferrous	Cement production data (Agnello, 2023), foundry distribution (DAVIES, 2015)	Weighted average between cement and non-ferrous location shares	OR Tambo, Mahikeng, Prieska, Saldanha, etc.	Node-level shares derived from provincial/ municipal production shares
Refining and chemicals (incl. synfuels)	Sasol grey hydrogen production split (Meridian Economics)	Allocate to Sasol: 80% to Secunda, 20% to Sasolburg	Secunda, Sasolburg	Based on estimated existing grey H_2 use of 2.6 Mtpa. Includes synthetic fuel production; demand assumed to require pure hydrogen
Marine Fuel classified as export	Salgmann, Weidenhammer, and Englert (2024)	Demand allocated to individual ports based on bunker fuel estimates.	Saldanha, Coega, Durban, Richards Bay, Cape Town	Volumes deducted from South Africa's export allocation, not domestic demand

Namibia – Export-Dominated Demand

Namibia's national strategy is primarily export-oriented. Domestic GH_2 use is projected to remain limited (up to 95 000 tpa by 2040), focused on transport, mining, and iron ore reduction.

For this study:

- All supply, domestic demand, and export volumes were spatially allocated to two key coastal nodes: Lüderitz (Southern Valley) and Walvis Bay (Central Valley).
- The planned Cape Fria port in the Northern Valley was excluded from the delivery model. GH_2 produced there is assumed to be exported directly and independently.
- Accordingly, Namibia's total export volume was reduced by the projected contribution of the Northern Valley to avoid double-counting.

This approach reflects infrastructure constraints and near-term priorities and avoids including delivery flows that would not interact with the South Africa–Namibia network under consideration.

3.2.3 Supply estimation

Known and proposed GH_2 supply projects were compiled from the IEA Hydrogen Projects Database (IEA), South Africa's list of SIPs (ISA), and additional industry reports. Each project was assigned to one of the network's predefined nodes based on location.

Where project-level capacity information was available, these were directly included as known supply. In cases where volumes were unspecified, estimates were made based on typical project size or inferred from announcements. All supply values were aligned to the national targets defined in the South African Namibian hydrogen strategies.

3.2.4 Hydrogen carrier and demand assumptions

Hydrogen demand was classified into two categories:

- **Pure hydrogen**: required for refining, methanol and synthetic fuel production, steelmaking, and industrial uses.
- **Ammonia:** used for direct NH_3 applications, marine fuel or GH_2 export.

For modelling purposes:

- **All exports** from both countries were assumed to take the form of NH_3.
- Domestic demand was split between pure GH_2 and NH_3 based on end use (e.g. methanol uses pure GH_2; NH_3 uses remain in NH_3 form).
- This distinction influences conditioning, reconditioning, and delivery costs across the network model.

3.2.5 Demand supply balancing

To assess the alignment between spatially allocated GH_2 demand and available supply, each node's known production potential was compared to its projected demand. Where shortfalls were identified, it was assumed that additional production capacity would be developed locally to close the gap.

The modelling approach adopted in this study assumes **distributed generation** – i.e. GH_2 is produced as close as possible to where it is consumed, even in areas with less favourable renewable energy potential. This approach avoids long-distance delivery and minimises infrastructure requirements in the early stages of market development.

Additional production was assigned directly to high demand nodes, except in Cape Town, Durban, and OR Tambo, where spatial constraints and competing land uses precluded new production capacity. For these nodes, GH_2 was assumed to be delivered from nearby locations using the most cost-effective available transport mode.

This distributed supply configuration was applied across all scenarios modelled, which vary by GH_2 turnover levels (low, medium, high) and infrastructure assumptions.

3.2.6 Supply and demand model input data

To support the delivery network optimisation model, the final supply and demand estimates developed through the methods described above were converted into a format suitable for quantitative modelling. Specifically:

- All supply and demand volumes were converted from 1 Mtpa GH_2 to megawatt-hours per annum (MWh/a) using the lower heating value (LHV) of GH_2. This ensures compatibility with energy-based cost and transport calculations used throughout the model.
- The LHV of GH_2 was taken as 33.33 MWh per tonne and applied consistently across all nodes and scenarios.

The resulting input data are presented below for each of the three GH_2 demand levels considered in the study: low, medium, and high. Each table includes spatially allocated values for supply and demand at the modelled nodes, as well as the breakdown between NH_3-based demand and pure GH_2 demand.

These three demand levels were developed as follows:

- The **low turnover** corresponds to the year 2030, using the low-demand pathway from the GHCS.
- The **medium turnover** approximates the year 2040, using the average of the low and high GHCS estimates.
- The **high turnover** reflects the year 2050, based on the GHCS high demand pathway.

GH_2 turnover is anticipated to increase over time as the market grows and uptake increases, thus the underlying assumptions are low turnover by the year 2030, medium turnover by the year 2040, and high turnover (associated with a mature/established market) by the year 2050. This three-level structure was chosen to maintain analytical tractability while still capturing the evolution of the GH_2 economy over time.

Constructing separate spatial models for each of the three time horizons (2030, 2040, 2050) under both low and high GHCS scenarios would have resulted in six distinct scenario combinations, prior to incorporating the various infrastructure assumptions. This level of complexity was deemed impractical for this stage of analysis, particularly given the high degree of uncertainty in future GH_2 demand, sectoral uptake patterns, and project implementation timelines. This three “GH_2 turnover” framework therefore balances realism, clarity, and feasibility, while still offering robust insights into long-term delivery network needs.

Table 5: Low GH_2 turnover demand and supply estimates.

Supply location:		**Distributed**	**GH_2 turnover:**	**low**	**Unit:**	**MWh/a (LHV)**
Node	**Name**		**Supply**	**Demand**		
			Total		**of which NH_3**	**of which GH_2**
n_01	Mosselbay		6 547	6 547	4 910	1 637
n_02	Prieska		28 011 308	20 153	-	20 153
n_03	Mahikeng		49 980	49 980	-	49 980
n_04	Polokwane		22 571	22 571	-	22 571
n_05	Secunda		14 348 508	14 348 508	800 053	13 548 455
n_06	OR Tambo		-	210 806	-	210 806
n_07	Bloemfontein		53 624	53 624	-	53 624
n_08	Newcastle		-	-	-	-
n_09	Saldanha Bay		8 101 124	1 058 823	44 192	1 014 631
n_10	Boegoebaai		17 097 336	-	-	-
n_11	Gqeberha		12 797 815	126 206	49 102	77 104
n_12	Namibian Exports		-	39 908 189	39 908 189	-
n_13	SA Exports		-	19 964 670	19 964 670	-
n_14	Durban		-	262 031	63 833	198 198
n_15	Richards Bay		85 111	85 111	63 833	21 278
n_16	East London		4 648 253	6 547	4 910	1 637
n_17	Cape Town		-	209 118	44 192	164 926
n_18	Lüderitz		23 584 308	-	-	-
n_19	Walvis Bay		17 078 292	754 411	-	754 411
n_53	Sasolburg		4 404 554	4 404 554	200 013	4 204 541
		Total	130 289 332	81 491 850	61 147 898	20 343 952

Table 6: Medium GH_2 turnover demand and supply estimates.

Supply location:		**Distributed**	**GH_2 turnover:**	**low**	**Unit:**	**MWh/a (LHV)**
Node	**Name**		**Supply**	**Demand**		
			Total		**of which NH_3**	**of which GH_2**
n_01	Mosselbay		33 217	33 217	24 912	8 304
n_02	Prieska		30 966 185	308 685	-	308 685
n_03	Mahikeng		1 727 779	1 727 779	-	1 727 779
n_04	Polokwane		378 489	378 489	-	378 489
n_05	Secunda		25 839 096	23 721 421	3 200 213	20 521 207
n_06	OR Tambo		-	3 510 348	-	3 510 348
n_07	Bloemfontein		520 856	520 856	-	520 856
n_08	Newcastle		149 567	149 567	-	149 567
n_09	Saldanha Bay		15 668 276	6 097 123	1 145 974	4 951 149
n_10	Boegoebaai		30 474 316	-	-	-
n_11	Gqeberha		14 147 840	2 536 578	1 420 011	1 116 567
n_12	Namibian Exports		-	108 234 689	108 234 689	-
n_13	SA Exports		-	29 397 060	29 397 060	-
n_14	Durban		-	4 334 560	1 743 873	2 590 687
n_15	Richards Bay		5 308 140	2 408 298	1 694 048	714 250
n_16	East London		5 138 591	190 991	74 737	116 254
n_17	Cape Town		-	3 178 993	1 220 711	1 958 282
n_18	Lüderitz		79 792 020	-	-	-
n_19	Walvis Bay		34 196 580	5 753 911	-	5 753 911
n_53	Sasolburg		9 463 905	9 463 905	800 053	8 663 851
		Total		253 804 856	148 956 283	52 990 187

Table 7: High GH_2 turnover demand and supply estimates.

Supply location:		Distributed	GH_2 turnover:	low	Unit:	MWh/a (LHV)
Node	**Name**		**Supply**	**Demand**		
			Total		**of which NH_3**	**of which GH_2**
n_01	Mosselbay		99 288	99 288	74 466	24 822
n_02	Prieska		35 671 543	458 803	-	458 803
n_03	Mahikeng		2 543 601	2 543 601	-	2 543 601
n_04	Polokwane		538 023	538 023	-	538 023
n_05	Secunda		38 409 067	33 114 880	4 517 948	28 596 932
n_06	OR Tambo		-	5 294 187	-	5 294 187
n_07	Bloemfontein		800 413	800 413	-	800 413
n_08	Newcastle		224 351	224 351	-	224 351
n_09	Saldanha Bay		18 453 839	11 338 727	3 313 748	8 024 979
n_10	Boegoebaai		35 104 934	-	-	-
n_11	Gqeberha		16 297 626	6 456 388	4 095 643	2 360 745
n_12	Namibian Exports		-	246 220 889	246 220 889	-
n_13	SA Exports		-	35 029 830	35 029 830	-
n_14	Durban		-	9 795 281	5 063 704	4 731 577
n_15	Richards Bay		16 572 661	6 777 380	4 914 772	1 862 608
n_16	East London		5 919 408	434 877	223 399	211 479
n_17	Cape Town		-	7 115 112	3 537 146	3 577 966
n_18	Lüderitz		151 984 800	-	-	-
n_19	Walvis Bay		99 990 000	5 753 911	-	5 753 911
n_53	Sasolburg		13 298 860	13 298 860	1 129 487	12 169 373
		Total		435 908 413	308 121 032	77 173 768

3.3 Hydrogen production costs

GH_2 production costs are subject to the quality of the renewable energy potentials at the site of production. For solar photovoltaic (PV) plants, the local solar radiation is important, while for wind energy facilities, it is wind speed that is relevant. However, not only the total annual radiation or average annual wind speed are of importance, but also the timely distribution over the year, defining the power generation profile of the renewables. In fact, for GH_2 production, complementing power generation profiles of different renewable sources such as PV and wind power are advantageous to achieve a high utilisation of the electrolyser. To minimise GH_2 production costs, an optimal combination of the available renewable sources needs to be determined. This optimisation also needs to consider the capacity of the electrolyser in relation to the total installed renewable capacity. For achieving low GH_2 production costs, it can be advantageous to oversize renewable capacities compared to the electrolyser capacity and occasionally have unused surplus electricity.

The optimal configuration of renewables and electrolysis is not only site-specific based on the quality of the local renewable potentials but also depends on the techno-economic parameters of the renewables and the electrolysis. This necessitates that an optimal GH_2 production plant configuration is determined for each site and for each considered time horizon, individually.

The following sub-chapters provide insights to the methodology, data and techno-economic assumptions applied to investigate GH_2 production costs, that will be used in the delivery optimisation model.

3.3.1 Methodology and techno-economic assumptions

The cost optimal configuration of renewables and electrolysis is determined for the various GH_2 production sites respectively. For this, representative renewable power generation profiles are based on whether data for a 5-year period (2019 to 2023) are used (Pfenninger & Staffel, 2024). PV (single-axis tracking) and wind power are considered. To identify the plant configuration of PV, wind power and electrolysis that enables the lowest GH_2 production costs, costs for various plant configurations are calculated. The specific GH_2 production costs are calculated by dividing the total annual costs for PV, wind power and electrolysis by the annual GH_2 production. Annual costs for equipment are calculated by using the Microsoft Excel's PMT formula [13] by applying a constant interest rate, depreciation period and investment costs. For the electrolyser, a mixture of alkaline (AEL) and proton exchange membrane (PEM) technology is assumed. Further, an installation factor of two is applied for the electrolyser as well as 10% additional electricity demand for the plant operation (AC to DC losses, cooling, purification, compression, pumps, etc.). The techno-economic data applied is listed in Table 8. Fixed exchange rates of 1 EUR = 1.1 USD = 20 ZAR are applied.

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[13] https://support.microsoft.com/en-us/office/pmt-function-0214da64-9a63-4996-bc20-214433fa6441

Table 8: Techno-economic data for solar PV, wind power and electrolysis.

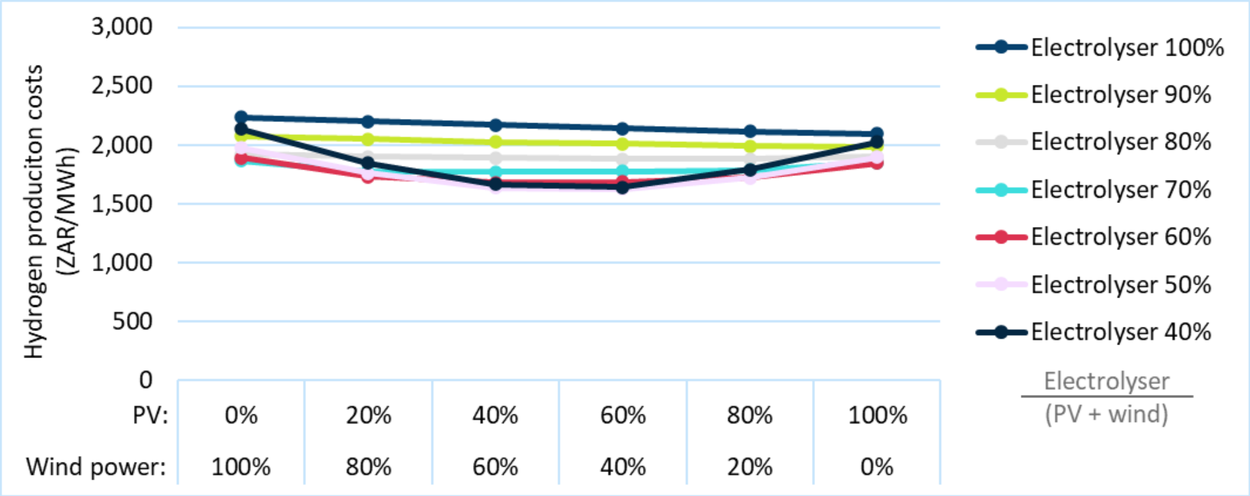
Parameter	Unit	2030	2040	2050
WACC	%		8.2	
Depreciation	years		25	
PV investment	USD/kWp	485	363	306
PV O&M	USD/kW/a		23.47	
PV degradation	%/a		0.4	
Wind investment	USD/kW	800	713	625
Wind O&M	USD/kW/a		50.19	
Wind degradation	%/a		0.1	
Investment	USD/kW	720	570	420
O&M	%/a		2	
Stack lifetime	Hours	95 000	110 000	125 000
Stack cost fraction	% of investment		45	
Electricity demand	kWh/kgH_2	47	44	42
Investment	USD/kW	810	680	550
O&M	%/a		2	
Stack lifetime	Hours	75 000	100 000	125 000
Stack cost fraction	% of investment		30	
Electricity demand	kWh/kgH_2	49	47	45

Source: CSIR, 2025

3.3.2 Resulting hydrogen production costs

For each GH_2 production location, GH_2 production costs for various plant configurations are calculated. An example visualisation of those results for one location is shown in Figure 7. Each line represents a certain ratio of installed electrolyser capacity over installed renewable capacity (PV + wind) and covers multiple combinations of PV and wind power capacities. The figure shows that the optimum plant configuration is little pronounced. A variation of the share of PV capacity at least between 40% and 60% as well as a variation of installed electrolyser capacity between 40% and 60% has little impact on the resulting GH_2 production costs.

Figure 7: Scatterplot of GH_2 production costs for various different plant configurations for an exemplary location.



Source: LSBT, 2025

The little pronounced optimum of the GH_2 production plant configuration applies to all GH_2 production nodes assessed. This makes the calculated Levelised Cost of Hydrogen (LCOH) robust regarding deviating configurations that might be required in the practical implementation e.g. due to limited available land, local conditions, limited potentials of PV or wind. The resulting LCOH for all supply nodes and for all considered time horizons are listed in Table 9.

Table 9: GH_2 production costs for each supply node in 2030, 2040, 2050.

H_2 supply node	2030	2040	2050	Unit
Saldanha Bay	2 111	1 670	1 315	ZAR/MWh
Boegoebaai	2 299	1 791	1 376	ZAR/MWh
Coega	2 218	1 758	1 385	ZAR/MWh
Mossel Bay	2 539	1 979	1 542	ZAR/MWh
Richards Bay	2 037	1 612	1 270	ZAR/MWh
Northern Cape inland (~Prieska)	2 054	1 627	1 277	ZAR/MWh
Vaal Driehoek (~ Sekunda/ vd Bijl/ Jhb)	2 325	1 840	1 434	ZAR/MWh
Limpopo (~Polokwane)	2 464	1 937	1 477	ZAR/MWh
North West (~Mahikeng)	2 196	1 745	1 360	ZAR/MWh

KZN inland (~Newcastle)	2 272	1 801	1 404	ZAR/MWh
Free State (~Bloem)	2 283	1 791	1 396	ZAR/MWh
Lüderitz	1 998	1 568	1 222	ZAR/MWh
Walvis Bay	2 397	1 829	1 361	ZAR/MWh
For reference: 2 000 ZAR/MWh = ~3.3 €/kg, 1 500 ZAR/MWh = ~2.5 €/kg; 1 000 ZAR/MWh =~ 1.7 €/kg				

The calculated LCOH are all within a range of ±15% of the unweighted average costs. In fact, most locations are within a range of ±10%.

To estimate the LCOH for each supply node, a single location was chosen based on renewable potential quality. Although this location represents the area's renewable potential, surrounding areas may have higher or lower quality. A location that is representative of the average was selected, avoiding over- or underestimation. Therefore, the costs provided here are an approximation, with associated uncertainties considered when interpreting the overall delivery model results.

3.4 Hydrogen delivery options and costs

Today, H_2 (regardless of energy source as input, fossil or renewable) is usually produced near the point of its use. Large-scale H_2 consumers are typically supplied "over the fence" from onsite fossil-based GH_2 production plants. Their fossil feedstock can be transported more efficiently than the H_2 product. However, H_2 delivery is required e.g. if additional small consumers are supplied from the same production facility. Then, H_2 delivery is realised either by trucking pressurised or liquid hydrogen. The transported volumes are rather small. The transport distance can be up to a few hundred kilometres long. Some large-scale regional transport of CGH_2 happens via pipeline e.g. in Germany, the US and even across borders between France, Belgium and the Netherlands. Here, chemical plants with the surplus by-product H_2 are connected to sites with H_2 deficit.

The relevance of GH_2 delivery on regional, national and international level will increase in the future. The shift to renewable energies and the decarbonisation of the mobility and industry sector will create new and additional GH_2 consumers as well as renewable based GH_2 production e.g. via electrolysis. GH_2 production and consumption might be located away from each other in different regions or even countries. Consequently, GH_2 delivery is expected to become more relevant than today. The two main drivers for not co-locating GH_2 production and consumption and thus requiring delivery are:

- Local or regional GH_2 demand outnumbers the available GH_2 production potential based on renewable energies due to insufficient space available.
- Limited solar radiation and/or wind speeds in the region of GH_2 demand resulting in (significantly [14]) increased GH_2 production costs compared to other regions.

Further aspects include e.g. strategic business or political considerations (existing business relationships, reliability, resilience, etc.).

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[14] Moving hydrogen is associated with relevant costs, a lot higher than e.g. for fossil energy carriers. Thus, differences in production costs must be rather significant to compensate transport efforts.

Understanding the increased need for GH_2 delivery, various GH_2 delivery options are being proposed and developed by the industry, each having different advantages and disadvantages, technology readiness levels, minimum and maximum transport capacities, enable different transport distances, show different techno-economic characteristics and are thus, relevant for different applications and boundary conditions.

Independent of the technology applied, cost for delivering GH_2 is more relevant for the final GH_2 price than delivery costs are for fossil energies today. The following sub-chapters address selected GH_2 delivery technologies and their main properties and cost parameters as input to the optimisation model of this study.

3.4.1 Delivery options

The delivery of GH_2 as CGH_2, LH_2, LOHC, as well as synthetised to NH_3 are considered. Each of those carriers can be moved using different modes such as road, rail, pipeline or shipping. Most relevant advantages and challenges are listed below.

Table 10: Advantages and challenges of GH_2 carrier and delivery options

Carrier	Advantages	Challenges	Delivery mode
Compressed gaseous hydrogen (CGH_2)	Low technological complexity	Low volumetric density, which represents a challenge when delivering large amounts of H_2	**Road (and rail):** Multiple Element Gas Containers (MEGCs) **Pipelines**: new or repurposed natural gas pipelines (if proven compatible)
Liquefied hydrogen (LH_2)	Higher density than compressed H_2, more suitable for large amounts of H_2	Techno-economic challenges of cryogenic temperatures Boil-off losses	**Road (and rail):** insulated tanks **Multi/inter-modal:** containerised
Ammonia (NH_3) (l)	High H_2 capacity Globally traded chemical commodity	High energy input to crack NH_3 to release H_2 Hazardous substance	**Ship, rail, road:** Well-established **Pipelines:** Pressurised liquid
Liquid Organic Hydrogen Carriers (LOHC)	Liquid at room temp. and atmospheric pressure, easy to handle Commodify waste heat	Discharge requires high energy (heat) Cycling degradation High cost Toxicity	Similar physical properties to fossil fuels, similar transport options **Multi/inter-modal** → containerised

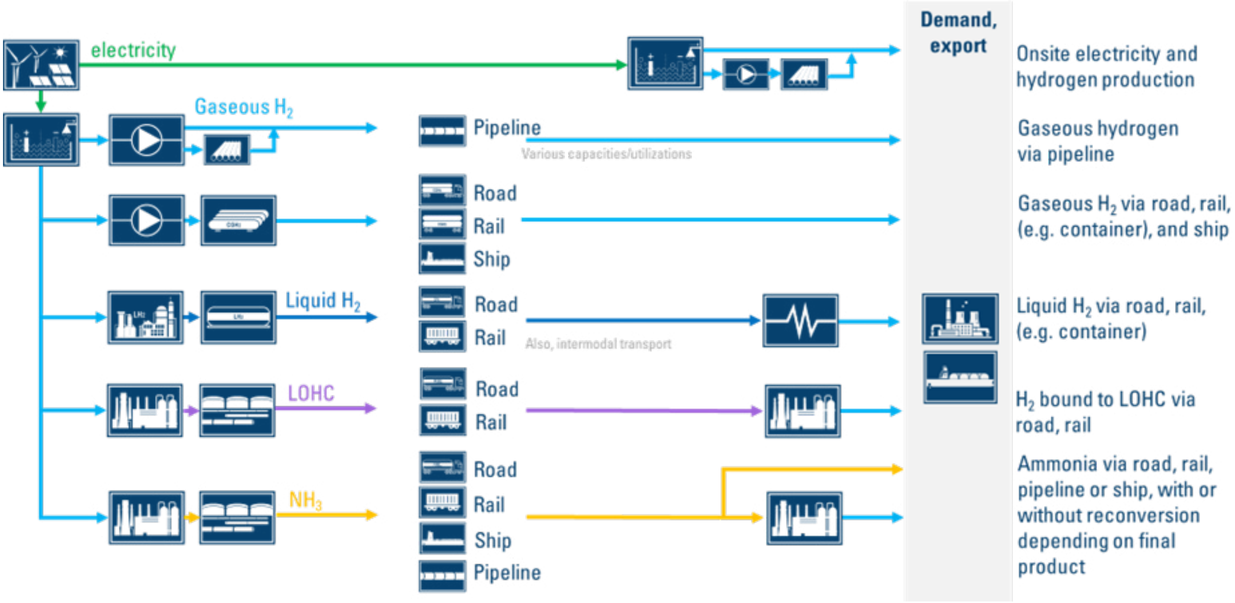
Source: CSIR 2025 (based on Ortiz et al., 2022).

The combinations of GH_2 carrier and delivery mode considered here are:

- **CGH_2 delivery via pipeline:** Highly cost-efficient option for large volumes. Sufficient pipeline utilisation is key for achieving low GH_2 delivery costs. Different pipeline diameters enable different transport volumes. Repurposing existing infrastructure is generally more cost-effective but requires consideration of material and component integrity and compatibility for carrying CGH_2 (Oritz et al., 2022). Pipelines can also be used as a temporary H_2 storage mechanism. Transport pipelines are usually operated at pressures of about 40 to 100 bar. Therefore, a feed-in station is required to compress GH_2 from the source pressure (e.g. 30 bar from pressurised electrolysis) into the pipeline. Depending on flow rates and transport distance, further compression along the pipeline can be required.
- **CGH_2 delivery via road and rail:** CGH_2 can be moved by road or rail using Multiple Element Gas Container (MEGC) systems – bundles of gas cylinders e.g. integrated into ISO container sized frames suited for intermodal transport. Different pressure levels and pressure vessel technologies can be applied, enabling different transport capacities. High-capacity options e.g. utilising carbon fiber pressure vessels are subject to high investment costs. To be cost-effective, this high investment equipment needs to be well utilised and thus requires short turnaround times. If intermodal transport is not required, pressure vessels can permanently be integrated with a trailer chassis for road transport. Due to the larger feasible dimension, e.g. compared to a 40-foot ISO container, additional capacity can be realised. Overall, transport capacities per trailer or MEGC range from about 300 to above 1 200 kg of GH_2.
- **CGH_2 delivery via coastal shipping:** A new transport concept currently under development is the transport of pressurised GH_2 in a dedicated ship. It is investigated for both short distance (KONGSTEIN, 2023) and long-distance transport of GH_2 (Peacock 2021, Ryze Hydrogen 2022). An onshore compressor facility is required to build up pressure within the ship's tanks at e.g. 250 bar during loading. Single ship transport capacities are in the range of 430 to 2 000 t. (Provaris, 2023)
- **LH_2 delivery via road and rail:** H_2 reaches a liquid state at -253 °C at atmospheric pressure. In this state, LH_2 is much denser than CGH_2 and allows greater volumes of H_2 to be transported and stored in cryogenic tanks. Liquefaction plants require a significant amount of energy input to achieve cryogenic temperatures, but despite technological and economic challenges, LH_2 is considered an advantageous H_2 carrier for certain applications (Oritz et al., 2022). A key challenge with LH_2 is evaporation or 'boil-off' of H_2 resulting from heat transfer from the storage tanks' surroundings to the H_2 stored within. The evaporated H_2 increases the pressures within the tank. Pressure increase must be limited to the tank's specifications e.g. by limiting round-trip times, pressure relief strategies or by applying an appropriate ratio of net to gross transport capacity. The latter means to not fill the complete inner tank volume with LH_2 but to keep sufficient volume for the gas phase pressure build up. LH_2 can be transported e.g. in special insulated ISO tank containers. Container transport by truck and/or rail is not routine business, as it is for other goods, but is technically feasible. In fact, a first LH_2 container was internationally shipped over a distance of about 20 000 km, in 2024 (FCW, 2024). The capacity per container tank is more than double compared to gaseous container (MEGC) transport, at about 2 500 kg (net). The net transport capacity depends on product and process specifications such as insulation quality, allowable pressure level and transport round-trip time.
- **Delivery using LOHC:** To enable easy handling and transport, GH_2 is bound to a LOHC using a hydrogenation plant. Different LOHC substances exist, for this study Dibenzyltoluol (DBT) is considered. DBT can be stored, transported and handled just like any other oil product, using standard oil pumps, tanks, tankers, etc. To retrieve pure GH_2 from the LOHC, it needs to be dehydrogenated in an endothermic process. The high energy consumption for this process as well as the costly DBT liquid are the main challenges for this transport mode.
- **Transport of NH_3**: NH_3 will likely become relevant as a GH_2 export carrier for South Africa as well as for bunkering. Further, pure GH_2 can be retrieved by NH_3 cracking. Potential inland transport options for NH_3 include road or rail tankers and bulk ships along coastlines and pipelines. The advantage of NH_3 is the (partly) existing and well-proven technology for synthesis, storage and transport as well as an existing global trade and market, at least for fossil-based NH_3. The main disadvantages are the high hazard potential for NH_3 e.g. to the environment and health, as well as the high energy consumption and missing operational experience for large-scale NH_3 crackers.

The delivery options focused on here are depicted in Figure 8 below.

Figure 8: GH_2 delivery modes under investigation in this study.



Source: LBST, 2025

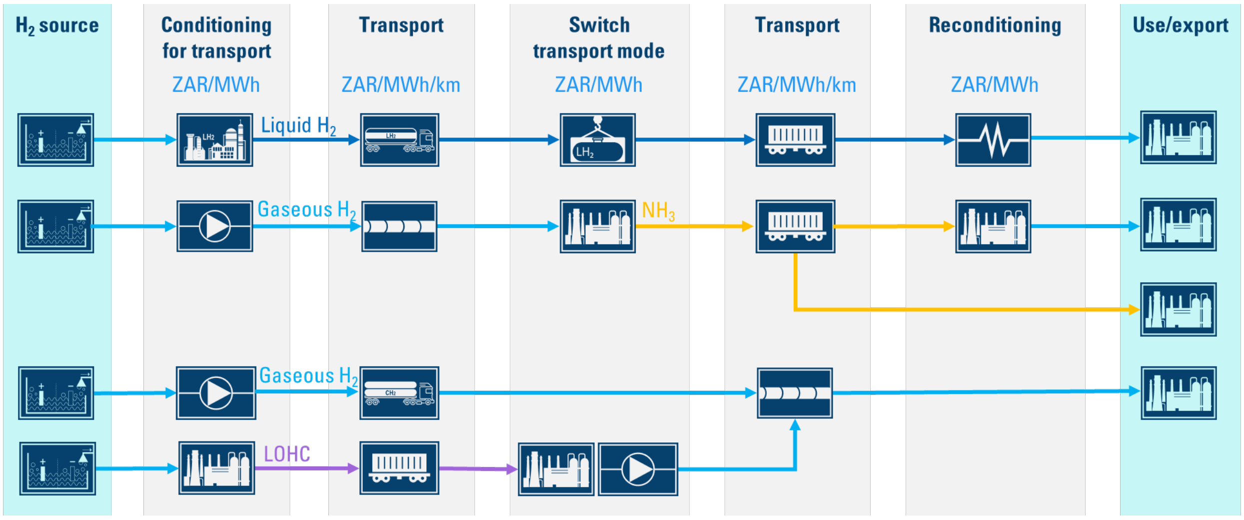
The delivery modes offer different cost structures (e.g. variable vs. fixed costs), feasible transport capacities, scalability potential, future improvement potential, and sensitivity to parameters such as transport distance. The cost optimal choice will be determined by the optimisation model, mainly depending on transport distance and transport volume. However, another relevant boundary condition is the transport capacity that can be realised by each transport technology. This is also considered by the model. Feasible transport capacities per technology are discussed in sub-chapter 4.4.4.

3.4.2 Delivery cost parameters

For the analysis in the model, total GH_2 transport costs are separated into different cost parameters. Those include (see Figure):

- Costs for GH_2 **conditioning** (make GH_2 transportable)
- Costs for GH_2 **transport**
- Costs for **switching transport mode**
- Costs for **reconditioning** of GH_2 (if required)

Figure 9: Cost parameters of selected fictional GH_2 transport chains.



Source: LBST, 2025

The addition of all cost parameters, whereby individual parameters may have to be considered several times, results in the total transport costs of a defined quantity of GH_2 from a GH_2 source to the consumer or export port.

Costs for GH_2 conditioning cover capital expenditure (CAPEX) and operational expenses (OPEX) of all equipment that is required to make GH_2 transportable. This can e.g. be the feed-in station of a pipeline, the compressor and trailer filling facility to transport pressurised GH_2 by truck or rail, or the liquefier to enable the transport of liquefied GH_2. This cost component is specific to the amount of GH_2 throughput and can e.g. be expressed in South African Rand (ZAR) per MWh. It is independent of the transport distance.

Costs for the GH_2 transport itself includes costs for the GH_2 containing vessel (e.g. pressure vessel, liquid GH_2 tank, pipeline) as well as costs for moving the GH_2 (e.g. costs for trucking a GH_2-filled container). This cost element depends on the quantity and distance of GH_2 transport and can e.g. be expressed as ZAR per MWh per kilometre. All costs associated with the GH_2 transport can be converted to this logic. For example, the investment costs for a 40-foot ISO container for liquid GH_2 transport is depreciated over a defined use period. This results in a certain cost share per year. To convert this to the anticipated cost expression (ZAR/MWh/km), a utilisation pattern is assumed for this container (e.g. achievable transport distance and volume per year).

To enable the combination of different transport modes, **costs for switching transport modes** are defined. This allows to e.g. first use trucking to transport a 40-foot ISO container filled with liquid GH_2 which is then handed over to rail transport. These costs are expressed e.g. in ZAR per MWh.

Some GH_2 transport options such as liquid GH_2, NH_3 or LOHC require a **reconditioning of the GH_2** before its use. This cost element is also considered. These costs are expressed in ZAR per MWh.

The main technologies and equipment considered by the cost parameters for each transport mode are listed in the table below.

Table 11: Main technologies/equipment considered for each GH_2 delivery mode.

Delivery mode	**H_2 carrier**	**Cost parameter**			
		Conditioning	**Transport**	**Mode switch**	**Reconditioning**
		Costs covered in the respective cost parameters:			
Road transport	**CGH_2**	Compression, vessel filling facility	Trucking, CGH_2 ISO container	See comment in table footer	Not required
	LH_2	Liquefaction with storage, vessel filling facility	Trucking, LH_2 ISO container		LH_2 evaporiser
	LOHC	Hydrogenation plant, vessel filling facility	Trucking, transport vessel, organic carrier liquid		Dehydrogenation plant
	NH_3	NH_3 synthesis with storage, vessel filling facility	Trucking, NH_3 ISO container		NH_3 cracker if not used as NH_3 directly
Rail transport	**CGH_2**	Compression, vessel filling facility	Rail transport, CGH_2 ISO container		Not required
	LH_2	Liquefaction with storage, vessel filling facility	Rail transport, LH_2 ISO container		LH_2 evaporiser
	LOHC	Hydrogenation plant, vessel filling facility	Rail transport, transport vessel, organic carrier liquid		Dehydrogenation plant
	NH_3	NH_3 synthesis with storage, vessel filling facility	Rail transport, NH_3 ISO container		NH_3 cracker if not used as NH_3 directly
Pipeline	**CGH_2**	Feed-in station	Pipeline and compressors		Not required
	NH_3	NH_3 synthesis	Pipeline and pumps		NH_3 cracker if not used as NH_3 directly
Coastal shipping	**CGH_2**	Loading infrastructure (compression)	CGH_2 bulk carrier		(Unloading infrastructure)
	NH_3	NH_3 synthesis with storage	NH_3 bulk carrier		NH_3 cracker if not used as NH_3 directly
CGH_2: compressed gaseous hydrogen; LH_2: liquefied hydrogen; NH_3: Ammonia; LOHC: Liquid Organic Hydrogen Carrier					
Mode switch: The required equipment for switching transport mode and thus costs heavily depend on the combination of transport modes. Due to the high number of possible combinations, those are not detailed here.					

Some technologies such as e.g. GH_2 liquefiers or certain transport vessels will see relevant cost reductions and technological improvements in the coming years. Those are driven by technology R&D activities, technology upscaling and/or mass production as a result of the global expansion of the GH_2 market. To account for this development, different cost parameter datasets for 2030, 2040 and 2050 are considered.

3.4.3 Green hydrogen transport costs

Specific GH_2 transport cost parameters are calculated based on literature values. The costs are provided as inputs to the optimisation model. Most relevant assumptions and resulting input values are discussed in the following sub-chapters.

General assumptions

The transport related cost parameters are calculated based on available literature and industry data, as well as own assumptions. There is only limited country-specific cost data for GH_2 technology available. Thus, it is assumed that GH_2 technology cost figures from sources referring to Europe or the US are also applicable to the South African context. Fixed exchange rates of 1 EUR = 20 ZAR and 1.1 USD = 1 EUR are applied to literature values. Costs parameters are calculated using a spreadsheet model. The annuity of investments is calculated using Microsoft Excel's PMT function, applying an interest rate of 8% and a depreciation period of 20 years (Staiß, F. et al., 2022) for plants and other stationary equipment and a depreciation period of 12 years for mobile equipment such as transport vessels (unless stated differently). Cost for operation and maintenance are calculated based on typical values, usually expressed as percent of investment per year. This does usually not include costs for energy, which are added based on the energy prices assumed below.

Table 12: Energy cost assumptions.

Parameter	Unit	Value	Comment/source
Electricity costs	ZAR/kWh	2.24	Based on medium voltage, large user (City of Cape Town, 2024)
Heat costs	ZAR/kWh	2.5 (2030) 2.0 (2040) 1.5 (2050)	Indicative estimation based on LCOH, assuming GH_2 (or PtX) is used for heat production

Conditioning assumptions

The main techno-economic assumptions for GH_2 conditioning are listed in Table 13. For the trailer filling compressor and pipeline feed-in station, an average utilisation of 50% was assumed. For the liquefaction, NH_3 synthesis and LOHC plants, a product storage and an utilisation of 80% was assumed. Future cost reductions and efficiency improvement due to expected technology development are assumed for GH_2 liquefaction plants.

Table 13: Main techno-economic parameters for GH_2 conditioning.

Technology	Specific investment ZAR/(kg/h) (installed)	Specific energy consumption (kWh/kg)	O&M (% of invest. p.a.)	Comment/source
Filling compressor for low-pressure	136 000	2.0	5	Investment: Scaled based on CH JU, 2024
Filling compressor for med.-pressure	157 000	2.4	5	Electricity: Own calculation
Filling compressor for high-pressure	188 000	3.1	5	
H_2 liquefaction	2 100 000 (2030) 1 200 000 (past 2030)*	9.0 (2030) 7.5 (past 2030)*	5	Industry data (undisclosed)
Hydrogenation plant	182 000	0.4	3	Based on Staiß, F. et al., 2022
Ammonia synthesis	530 000	9.7	5	(DECHEMA, 2022) (DECHEMA, 2017) (Incl. air separation unit, N2/H_2 compression, liquefaction)
Pipeline feed-in station (large to small)	40 000 to 60 000	0.9	5	Investment: Scaled based on Neuman Esser, 2023 Electricity: Own estimation
CGH_2 shipping export facilities	155 000	1.5	5	Provaris Energy, 2024
NH_3 export terminal storage	16 000	0.005	4	Based on storage costs of 36 ZAR/kgNH_3 IEA, 2020

**A way forward to achieve relevant cost reduction and efficiency improvement for GH_2 liquefaction has been sketched by the industry. For other technologies, cost reductions are less pronounced and/or technology is already more sophisticated.*

Trucking and rail transport assumptions

The costs for moving a GH_2 transport vessel e.g. in the format of a 40-foot ISO container by truck or rail is one of the key parameters for the overall GH_2 transport costs. The costs for one kilometre of transport for one container is listed below. It includes all relevant cost such as fuel, driver, vehicle, infrastructure, insurance and overhead. Not included are the costs for the GH_2 containing vessel itself.

Table 14: Trucking and rail transport costs.

Parameter	Unit	Value	Comment/source
Trucking (40” ISO)	ZAR/km/container	17	Based on Braun, 2019
Rail transport (40” ISO)	ZAR/km/container	10	Based on DAL, 2021

The investment costs for the GH_2 containing vessels considered in this study are listed in Table 15. It also includes the achievable net transport capacity per vessel. An additional one percent of the investment per year is considered in the cost calculation to cover for operational and maintenance costs of the vessels.

Table 15: Main techno-economic parameters for trucking and rail transport vessels.

Transport vessel	Investment (ZAR)	Capacity (kgH_2, net)	Comment/source
CGH_2 low-pressure 1	2.1 million	300	Estimation based on various industry and literature data
CGH_2 low-pressure 2	5.1 million	500	
CGH_2 med-pressure	12 million (2030)*	890	
CGH_2 high-pressure	16 million (2030)*	1 200	
LH_2	16 million (2030)*	2 500	
LOHC	2.6 million	1 300	Incl. LOHC liquid
NH_3	4 million	4 800	Rough estimate
**10% cost reduction is assumed for post-2030 due to tech. improvements, mass production, etc.*			

An annual milage of about 160,000 km for trucking and rail transport are assumed to be achievable per container (based on (Braun, 2019), (ARIA, 2008)).

Pipeline assumptions

Costs for gaseous GH_2 transport via pipeline are estimated based on recent cost figures for new pipelines within the European Hydrogen Backbone. The most relevant data is listed in Table 16. Transport costs via pipeline strongly depend on the pipeline utilisation. Thus, for each pipeline size, three different utilisation rates are considered, representing low, medium and high utilisation rates.

Table 16: Main techno-economic parameters for pipeline transport.

Pipeline size	Investment (ZAR/km)	Capacity (GWH_2)	Investment pipeline compressor (ZAR/km)	Comment/source
Small	36 million	1.2	520 000	Depreciation: 25, 40 years O&M: 5%, 1% (compressor, pipeline) (EHB, 2024)
Medium	64 million	4.7	1 860 000	
Large	88 million	13	3 660 000	

The costs for a NH_3 pipeline are estimated based on specific investment costs of 12 ZAR/(km/kWNH_3) with 3% OPEX and a depreciation period of 40 years (Galimova, et al., 2023).

Shipping assumptions

The main techno-economic assumptions for coastal GH_2 shipping are listed in Table 17. For the CGH_2 carrier, data for the Provaris H_2Neo ship was used. For the NH_3 carrier, a “Handy Gas Carriers” sized ship with a capacity of about 9 000 tonnes of NH_3 was assumed. Costs are scaled down from a large capacity ship based on (Agora & TU Hamburg, 2023).

Table 17: Main techno-economic parameters for GH_2 coastal shipping

Ship type	Investment (ZAR)	Capacity (t)	Source	Further assumptions
CGH_2 carrier	2.3 billion	430	(Provaris, 2023a)	Shipping speed: 30 km/h; Fuel costs: 1 ZAR/kWh; Fuel use: 1 000 kWh/km
NH_3 carrier	0.5 billion	1.600	Scaled based on (Agora & TU Hamburg, 2023)	

Reconditioning assumptions

The main techno-economic assumptions for GH_2 reconditioning are listed in Table 18. For the LH_2 evaporation, NH_3 cracking and LOHC plants, an utilisation of 80% was assumed.

Table 18: Main techno-economic parameters for GH_2 reconditioning.

Technology	**Specific investment ZAR/(kgH_2out/h) (installed)**	**Specific energy consumption (kWh/kg)**	**O&M (% of invest. p.a.)**	**Comment/source**
NH_3 cracker	290 000	2.0 (el.) 10 (heat)	4	Based on (Jackson, et al., 2019), adapted heat input based on current industry data, plus feedstock storage.
LH_2 evaporation	14 000	0.3 (el.)	5	Inflated, scaled and adapted based on literature and own assumptions.
LOHC dehydrogenation	334 000	1.0 (el.) 11.2 (heat)	3	Based on (Staiß, F. et al., 2022)
CGH_2 shipping import facilities	80 000	0.2 (el.)	5	Based on (Provaris Energy, 2024)
NH_3 export terminal storage	16 000	0.005	4	Based on storage costs of 36 ZAR/kgNH_3 (IEA, 2020)

Resulting transport cost parameters

Table 19: Trucking cost parameters.

Transport mode number (TM):		TM1	TM2	TM3	TM4	TM5	TM6	TM7
		CGH_2 (LP 1)	CGH_2 (LP2)	CGH_2 (MP)	CGH_2 (HP)	LH_2	LOHC	NH_3
Conditioning costs (ZAR/MWh)	**2030**	418	456	545	624	2 208	210	1 055
	2040	418	456	529	608	1 475	210	1 055
	2050	418	456	529	608	1 475	210	1 055
Transport costs (ZAR/MWh/km)	**2030**	3.8	2.6	1.9	1.6	0.7	0.9	0.3
	2040	3.8	2.6	1.8	1.5	0.7	0.9	0.3
	2050	3.8	2.6	1.8	1.5	0.7	0.9	0.3
Reconditioning costs (ZAR/MWh)	**2030**	-	-	-	-	29	1 108	1 075
	2040	-	-	-	-	29	940	925
	2050	-	-	-	-	29	772	775

Table 20: Rail cost parameters.

Transport mode number (TM):		TM8	TM9	TM10	TM11	TM12	TM13	TM14
		CGH_2 (LP 1)	CGH_2 (LP2)	CGH_2 (MP)	CGH_2 (HP)	LH_2	LOHC	NH_3
Conditioning costs (ZAR/MWh)	**2030**	418	456	545	624	2 208	210	1 055
	2040	418	456	529	608	1 475	210	1 055
	2050	418	456	529	608	1 475	210	1 055
Transport costs (ZAR/MWh/km)	**2030**	2.5	1.8	1.4	1.2	0.6	0.4	0.2
	2040	2.5	1.8	1.3	1.1	0.6	0.4	0.2
	2050	2.5	1.8	1.3	1.1	0.6	0.4	0.2
Reconditioning costs (ZAR/MWh)	**2030**	-	-	-	-	29	1 108	1 075
	2040	-	-	-	-	29	940	925
	2050	-	-	-	-	29	772	775

Table 21: CGH_2 pipeline cost parameters.

Transport mode (TM):		TM15	TM16	TM17	TM18	TM19	TM20	TM21	TM22	TM23
Pipeline capacity:	**Small**	**Small**			**Medium**			**Large**		
Pipeline utilisation:		**Low**	**Med.**	**High**	**Low**	**Med.**	**High**	**Low**	**Med.**	**High**
Conditioning costs (ZAR/MWh)	**2030**	119	119	119	107	107	107	98	98	98
	2040	119	119	119	107	107	107	98	98	98
	2050	119	119	119	107	107	107	98	98	98
Transport costs (ZAR/MWh/km)	**2030**	1.3	0.7	0.5	0.6	0.3	0.2	0.3	0.2	0.1
	2040	1.3	0.7	0.5	0.6	0.3	0.2	0.3	0.2	0.1
	2050	1.3	0.7	0.5	0.6	0.3	0.2	0.3	0.2	0.1
Reconditioning costs (ZAR/MWh)	**2030**	-	-	-	-	-	-	-	-	-
	2040	-	-	-	-	-	-	-	-	-
	2050	-	-	-	-	-	-	-	-	-

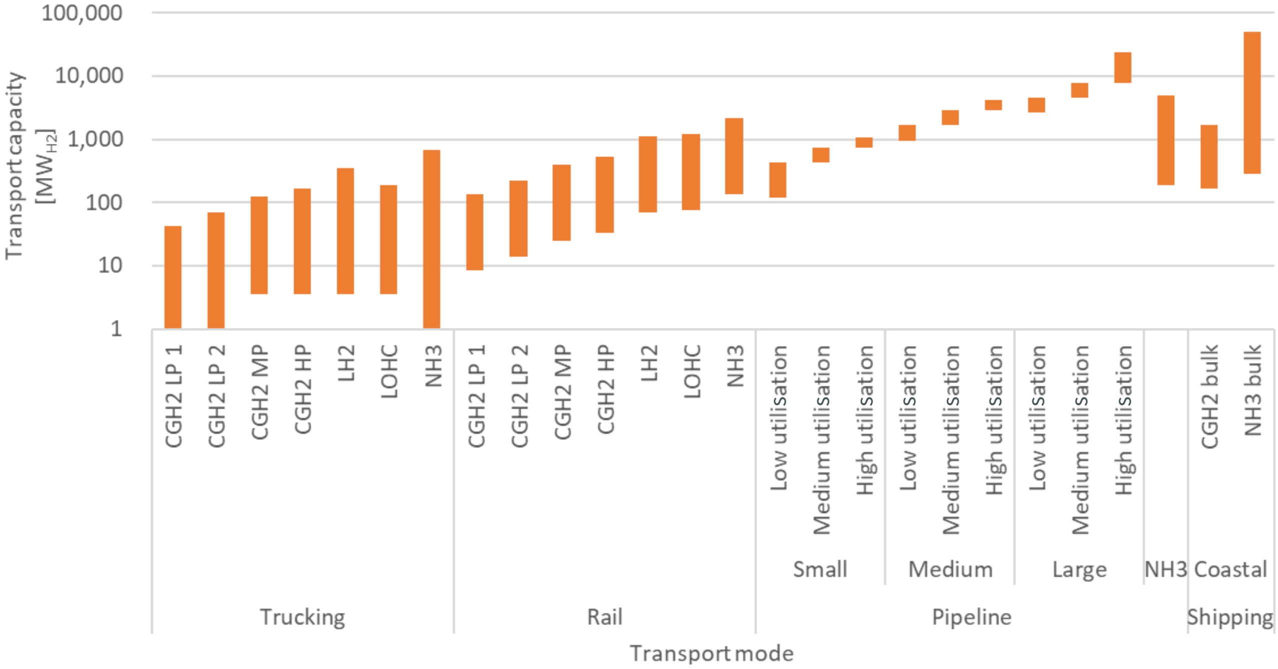
Table 22: NH_3 pipeline and coastal shipping cost parameters.

Transport mode (TM):		TM24	TM25	TM26
		NH_3 pipeline	**CGH_2 shipping**	**NH_3 shipping**
Conditioning costs (ZAR/MWh)	**2030**	995	237	1 011
	2040	995	237	1 011
	2050	995	237	1 011
Transport costs (ZAR/MWh/km)	**2030**	0.3	0.5	0.1
	2040	0.3	0.5	0.1
	2050	0.3	0.5	0.1
Reconditioning costs (ZAR/MWh)	**2030**	1 075	-	1 075
	2040	925	-	925
	2050	775	-	775

3.4.4 Feasible transport capacities

The capacity of a GH_2 transport technology cannot always be scaled up or down without limits. Minimum and maximum limits might apply due to technical, logistical, financial, or other reasons. To account for this, the logistics model also takes into account a minimum and a maximum feasible capacity for each transport mode. The capacity limits that are applied and their rationale are listed below.

Figure 10: GH_2 transport capacity range per transport mode.



Source: LBST, 2025

It needs to be noted that for some technologies the GH_2 volumes that are being transported have a direct impact on the specific transportation costs. This effect comes e.g. from the utilisation rate of equipment. High transport volumes allow for high utilisation and thus low costs, while for the same technology a low transport volume results in low equipment utilisation and thus high specific costs. Thus, transport capacity and costs need to be aligned to remain reasonable. The dataset provided to the optimisation model considers this correlation.

Table 23: Rationale and GH_2 transport capacity range per technology.

Technology			Minimum capacity [MWH_2]	Maximum capacity [MWH_2]	Rationale
Trucking	**CGH_2 (LP1)**		0**	42	**Minimum:** defined by small-scale trailer filling facility, minimum plant liquefaction plant capacity, single trailer per day for NH_3; *for past 2030 liquefiers to achieve low costs and high efficiency; **no effective minimum set for model to ensure solvability **Maximum**: assuming up to 100 truck deliveries per day
	CGH_2 (LP2)		0**	69	
	CGH_2 (MP)		3	124	
	CGH_2 (HP)		3	167	
	LH_2		3 (70*)	347	
	LOHC		3	185	
	NH_3		0**	667	
Rail	**CGH_2 (LP1)**		8	133	**Minimum**: assuming single train with 20 containers (ISO 40” container or equivalent) per day **Maximum**: assuming eight trains with each 40 containers (ISO 40” container or equivalent) per day
	CGH_2 (LP2)		14	222	
	CGH_2 (MP)		25	396	
	CGH_2 (HP)		33	533	
	LH_2		70	1111	
	LOHC		74	1182	
	NH_3		133	2136	
CGH_2 pipeline	**Small**	**Low**	120	420	Utilisation rates for all CGH_2 pipeline capacities: • Low: 20% to 35% • Medium: 35% to 60% • High: 60% to 90% Exceptions: • Low utilisation for small pipeline: 10% • High utilisation for large pipeline: 200% (2 parallel pipelines)
		Med.	420	720	
		High	720	1 080	
	Medium	**Low**	940	1 645	
		Med.	1 645	2 820	
		High	2 820	4 230	
	Large	**Low**	2 600	4 550	
		Med.	4 550	7 800	
		High	7 800	23 400	
NH_3 pipeline			187	5 000	**Minimum**: assuming 20% utilisation **Maximum**: based on 7 Mt/a NH_3 (ISPT, 2025)
CGH_2 coastal shipping			166	1 655	Capacity estimated based on literature case study (Provaris, 2023) (Provaris Energy, 2024) **Minimum**: 50% case study small ship **Maximum**: 5x case study; multiple ships or larger ship
NH_3 (coastal) shipping			280	6 000+*	**Minimum**: Single NH_3 ship (Handy Gas Carrier or Coaster) **Maximum**: Multiple Large or Very large Gas Carriers **There is no effective limit set for the model to allow for large-scale export.*

3.5 Scenarios: Green hydrogen turnover and delivery infrastructure

Three scenarios [15] were defined and assessed to explore possible optimal delivery networks for GH_2 within a South Africa-Namibian GH_2 economy, considering distributed GH_2 production. Scenarios differ in GH_2 supply and demand volumes ("GH_2 turnover": low, medium and high) (see section 4.2.6), as well as exploratory delivery infrastructure development options. The results in a total of nine sub-scenarios that were modelled (Table 24).

Distributed production of GH_2 is assumed. Thus, the assumption is that it is always cheaper to produce GH_2 where it is consumed, even if renewable potential is sub-optimal. Furthermore, additional production capacity was added directly at high-demand nodes, and Cape Town, Durban, and OR Tambo were excluded from new production due to spatial constraints and competing land uses.

3.5.1 Scenario 0: Existing infrastructure

Scenario 0 (Sc0) represents the baseline at current and seeks to answer the question: **"How would GH_2 be delivered only using infrastructure that currently exists (road, rail, pipeline, coastal shipping routes)?"**

The base case considers only transport modes and infrastructure where they currently exist. This means that only existing road and railway infrastructure can be used for transport and pipelines are only feasible in areas where pipelines already exist today (refer to Figure 4 in section 3).

3.5.2 Scenario 1: Unconstrained infrastructure expansion, excluding Boegoebaai

Scenario 1 (Sc1) assumes that delivery infrastructure (road, rail, pipeline) is an available option wherever a delivery pathway exists, and seeks to explore **"How would GH_2 be delivered if any infrastructure theoretically existed along every delivery pathway, but the Port of Boegoebaai did not yet exist?"**

For Sc1, and Sc2 below, delivery pathways are not limited to existing infrastructure, but assume that the required infrastructure to facilitate the selected cost-optimal GH_2 transport network is in place. The results from this scenario may provide clues as to where certain types of infrastructure development could be prioritised.

3.5.3 Scenario 2: Unconstrained infrastructure expansion, including Boegoebaai

Finally, Scenario 2 (Sc2) assumes that delivery infrastructure (road, rail, pipeline) is an available option wherever a delivery pathway exists, and explores a future where the proposed Port of Boegoebaai has been realised. It thus seeks to answer: **"How would GH_2 be transported if any infrastructure theoretically existed along every delivery pathway and the Port of Boegoebaai was operational?"**

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[15] Where the word "scenario" is abbreviated to Sc0/Sc1/Sc2, it refers to the infrastructure development and GH_2 turnover scenarios developed and considered in this study.

3.6 Green hydrogen delivery model

3.6.1 Selection of modelling approach

Two modelling approaches were considered, namely simulation modelling and optimisation modelling. In short, simulation modelling refers to the creation of a digital twin of an actual system that allows the user to compute the performance of various "what-if" scenarios without disrupting the real-world process. Some simulation modelling software, such as Anylogic, allow visualisation and analysis of the simulated process. This is advantageous as it simplifies model verification, allows the user to inspect and interact with the model, and makes it easier to communicate and understand the results. Although initially thought to be the ideal approach, this modelling technique was not chosen as it requires pre-defined scenarios of delivery options that will need to be simulated individually and compared manually afterwards to identify the most efficient scenario. The requirement for pre-defined scenarios could lead to potential bias and limits the possibility of finding the optimal solution, thereby explaining why simulation modelling is not an optimisation technique.

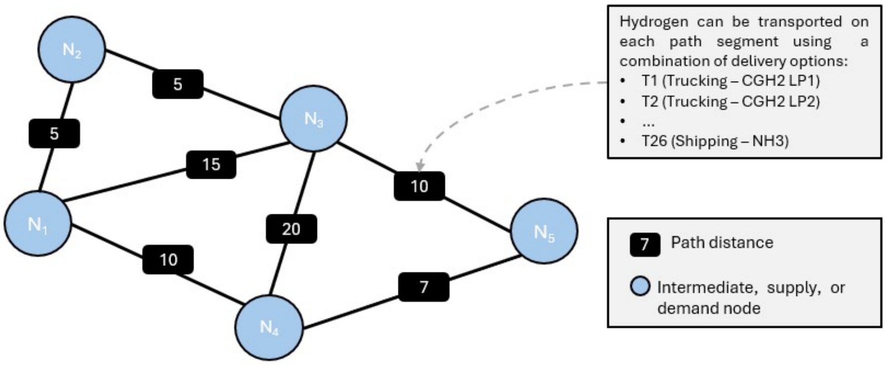
Given the objective of identifying the optimal network configuration for a given scenario for bulk GH_2 delivery in South Africa with links to Namibia, an optimisation model was deemed the most suitable approach. An optimisation model is a mathematical representation of a problem and, when solved, can find the true or near optimal solution by considering all possible delivery options and related constraints. Accordingly, it avoids the need for the user to pre-empt the delivery options as it will inherently consider all possible GH_2 delivery options for the entire network in order to identify the optimal network configuration. The model developed will be programmed in and solved using Wolfram Mathematica.

3.6.2 Model overview

The objective of the model is to determine the most cost-effective network for GH_2 delivery throughout South Africa with links to Namibia. This entails determining the node-to-node flows of GH_2, as well as the most appropriate delivery options (i.e., the transport mode and GH_2 carrier pairs) to use when considering various factors (e.g., the distance between the origin and destination points, delivery cost, etc.) and constraints (e.g., the minimum and maximum volume capacity of the delivery option, the available delivery options, etc.).

The network optimisation model consists of a set of nodes (92 in total) and various path segments, all of which are strategically selected to represent all the major GH_2 production and demand points, as well as all the major transportation networks (e.g., the national road, rail and pipeline network) of importance. Each node in the network is connected to selected neighboring nodes via path segments with fixed distances. A node could represent a GH_2 supply point, a demand point, and/or an intersection between different pathways that are not necessarily associated with GH_2 supply or demand. An example for a simplified network consisting of five nodes is shown in Figure 10.

Figure 11: Illustration of a network consisting of roads and path segments.



Hydrogen can be transported on each path segment using a combination of delivery options:

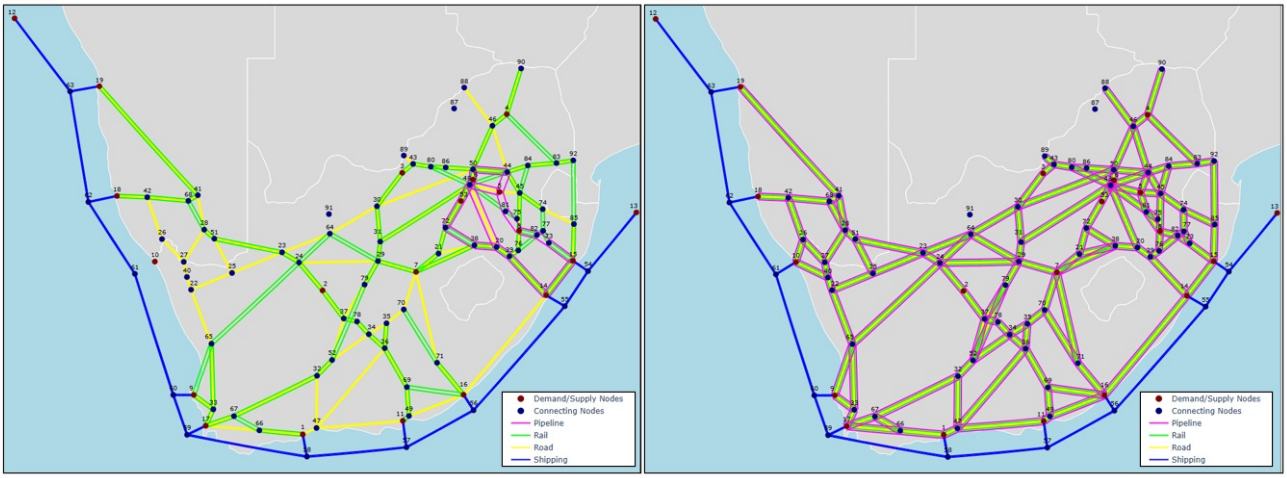
- T1 (Trucking – CGH2 LP1)
- T2 (Trucking – CGH2 LP2)
- ...
- T26 (Shipping – NH3)

Source: CSIR, 2025

The model focuses on the flow of GH_2 through each node to find the ideal GH_2 delivery network. More specifically, it tries to balance each node's GH_2 "inventory". Simply put, the model attempts to source GH_2 from elsewhere if the node's demand exceeds its internal supply, which will result in inflows of GH_2 from neighboring nodes. If the node's supply potential is greater than its internal demand, its excess inventory might be transported to neighboring nodes to satisfy demand elsewhere in the network. Depending on the overall network's total supply and demand, some nodes might remain with a GH_2 shortage or surplus (see notes a and b at the end of this section 4.6.2).

Outflows or inflows of GH_2 occur through the transportation of GH_2 to or from neighboring nodes (i.e., when there is a path segment connecting the two nodes). GH_2 can be transported on a path segment using at least one type of transport mode, such as road, rail, pipeline, or maritime. The model will account for the fact that not all transport modes are feasible (meaning available) between each neighboring node pair. This is important because of pre-existing rail and pipeline infrastructure networks, or due to geographical limitations (i.e., maritime is not possible inland). Figure 11 shows how the transport mode feasibility differ between the scenarios Sc0 and Sc2 considered (see section 4.6 for a full description of the scenarios developed and considered in this study).

Figure 12: Applicability of transport modes for Sc0 – currently existing infrastructure (left) and Sc2 (right).



Source: CSIR, 2025

Different carriers can be used to transport GH_2 (see section 4.4). Accordingly, a distinction is made between transport modes (road, rail, pipeline, and maritime) and delivery options. The latter refers to a transport mode and carrier type pair that can be selected by the model to deliver GH_2 on a path segment. Table 25 lists the 26 delivery options available.

Table 24: Delivery options considered by the model.

Delivery Mode ID	Transport Mode	Carrier	Delivery Mode ID	Transport Mode	Carrier
T1	Trucking	LP 1	T15	Small pipeline – low utilisation	CGH_2
T2	Trucking	LP 2	T16	Small pipeline – medium utilisation	CGH_2
T3	Trucking	MP	T17	Small pipeline – high utilisation	CGH_2
T4	Trucking	HP	T18	Medium pipeline – low utilisation	CGH_2
T5	Trucking	LH_2	T19	Medium pipeline – medium utilisation	CGH_2
T6	Trucking	LOHC	T20	Medium pipeline – high utilisation	CGH_2
T7	Trucking	NH_3	T21	Large pipeline – low utilisation	CGH_2
T8	Rail	LP 1	T22	Large pipeline – medium utilisation	CGH_2
T9	Rail	LP 2	T23	Large pipeline – high utilisation	CGH_2
T10	Rail	MP	T24	Pipeline	NH_3
T11	Rail	HP	T25	Shipping	CGH_2
T12	Rail	LH_2	T26	Shipping	NH_3
T13	Rail	LOHC	*(LP: low pressure; MP: medium pressure; HP: high pressure; LH_2: liquefied hydrogen; LOHC: liquid organic hydrogen carrier; NH_3: ammonia: CGH_2: compressed gaseous hydrogen).*		
T14	Rail	NH_3			

When needed and feasible, the model will be able to switch between the different delivery options at each node, but this will incur a switching cost. Note that some delivery options (e.g., pipelines) require a minimum quantity of GH_2 to function properly, while others (e.g., rail) have a maximum limit per annum. These capacity constraints will also be considered by the model.

Allowing the model to choose the carrier type to utilise (through the appropriate selection of the delivery option with the desired carrier) enables the model to account for the fact that some nodes will have a demand for NH_3

specifically. If this is the case, then the model must ensure that this demand is fulfilled using NH_3-carrying delivery options, namely T7, T14, T24, and/or T26. Alternatively, the model must incur switching costs to switch other delivery options to a NH_3-carrying option at the respective node. Future expansions of the model could include demand (or even production) requirements specific to other carrier types.

Ultimately, the model strategically selects each node's GH_2 inflow and outflow quantities and the accompanying delivery option to use in order to minimise the overall cost of the network. Various cost components are accounted for, as discussed previously:

- **Transportation/delivery cos**t – this measure is dependent on the quantity of GH_2 delivered, the distance over which it is transported, and the cost of the delivery option used.
- **GH_2 production/supply cost** – the cost to produce or supply GH_2 could differ between nodes. For example, domestic production might be less expensive compared to imports, or vice versa. Accordingly, in some cases, it might be less cost efficient to source GH_2 from the closest suppling node. The model must, therefore, consider the trade-off between delivery and production cost.
- **Make transportable cost** – In addition to production costs, another cost is incurred after production to ensure that the GH_2 can be transported using the respective delivery option. Intuitively, this cost depends on the delivery option utilised.
- **Reconditioning cost** – After the GH_2 has been delivered to its final destination, a cost is incurred to convert it to a usable state. This cost depends on the delivery option utilised.
- **Switching cost** – Since the model will consider all possible scenarios, it will encounter multi-modal solutions where the GH_2 is delivered using more than one delivery option. While this is feasible, there could be costs involved in switching the GH_2 to the appropriate state required for the subsequent delivery option. Thus, this cost component depends on the existing and subsequent delivery option.

Other supporting decisions that the model needs to make at each node include the following:

- For each delivery option, the quantity of GH_2 that should be produced.
- For each delivery option, the portion of the total demand that needs to be delivered (fulfilled) by the respective delivery option.
- The quantity switched between each delivery option pair.

Additional notes:

a. A surplus occurs when more GH_2 is transported to a node than what is required. This will happen when the model increases the quantity transported to the respective node to ensure that the delivery option's minimum capacity constraint is adhered to. A surplus will most likely not occur due to additional production of GH_2 at the node under consideration. This is because the model does not have to utilise the node's full production potential. The only requirement is that the quantity produced exceeds the assigned delivery option's minimum capacity requirement.

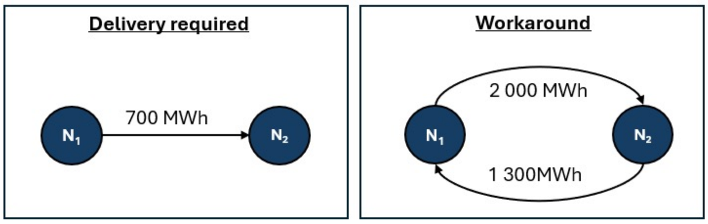
b. An instance has been observed where the model identified solutions where it is more cost-effective to fulfill demand from GH_2 sourced elsewhere, than to use GH_2 produced on-site. The root cause behind this observation was since some nodes have a specific demand for NH_3 that can only be fulfilled by NH_3-carrying delivery options. Although these delivery options have high 'make transportable' and reconditioning costs associated with them, their transport cost rates are mostly cheaper than their non-NH_3-carrying alternatives. Thus, since the former costs will need to be incurred to satisfy the NH_3-specific demand, the model found a solution that took advantage of the NH_3-carrying delivery options' reduced transportation costs to reduce the overall network costs, which involved not using on-site production to satisfy a specific node's demand.

3.6.3 Notable limitations of the model

The cost rates (e.g., for delivery, conversion to a transportable form, production, etc.) associated with each delivery option assume that a minimum quantity of GH_2 is met. This threshold is required for the costs to be realistic and to reflect economies of scale. The model applies the same minimum quantity assumption across all cost components. For example, if Delivery Option T7 (i.e., Trucking – NH_3) requires a minimum of 876 MWh of NH_3, the model cannot produce, deliver, or recondition any amount below this threshold when using this delivery option. Future modifications of the model should consider adding cost-specific minimum quantity requirements to improve realism and better reflect practical delivery and production constraints.

It was noted in a few isolated cases that the model found a workaround regarding the minimum capacity requirement. This entailed delivering an additional amount of GH_2 to ensure that the total delivery exceeded the delivery option's minimum capacity requirement; however, to cancel out the additional amount delivered, the model would add a reverse delivery. This is demonstrated in Figure 12 where the model delivers a net quantity of 700 MWh from Node 1 to Node 2 via a forward flow of 2 000 MWh and a reverse flow of 1 300 MWh, if the minimum delivery quantity required was 1 300 MWh.

Figure 13: Illustration of model workaround to overcome minimum capacity requirement of 1 300 MWh.



Source: CSIR, 2025

The forward and reverse delivery of the additional GH_2 increases the overall delivery cost of the entire network. However, despite being wasteful and potentially redundant, it is the most-cost effective solution. The practical implication of the workaround is dependent on the chosen delivery option. For example, if the required delivery quantity falls below a truck's minimum threshold, the delivery could still proceed with the smaller amount – only the associated economies of scale would not be realised. However, if the delivery is intended to occur via pipeline, the delivery option may not function correctly unless the minimum threshold is met, which may require the additional forward and reverse GH_2 flows to compensate.

Lastly, as mentioned, the model identifies the most cost-effective network for the bulk delivery of green GH_2 by identifying the solution with the lowest objective function value (see Appendix A for more details). However, it is important to note that multiple "optimal" solutions may exists (i.e., different network configurations resulting in the same minimum objective function value). Unfortunately, the model only returns one of these potential solutions. The likelihood of this occurrence can be reduced in future work by incorporating additional decision criteria and/or objectives to help differentiate between otherwise equivalent solutions.

4 Model results and discussion

The discussion of the model results is twofold. First, the most relevant aspects from the direct model results are presented. However, taking current model shortcomings (Section 5.1), cost data uncertainties and methodological constraints into account, in a second step, the results will be interpreted accordingly.

4.1 Assumptions and limitations regarding the model and input data

It is important to recognise that the results presented in this chapter are subject to the underlying optimisation methodology and the input data used. To make the model computationally feasible, real-world conditions and relationships have been simplified. Moreover, data on current and future real-world conditions, especially those that are country-specific or cost-related, are not perfectly available.

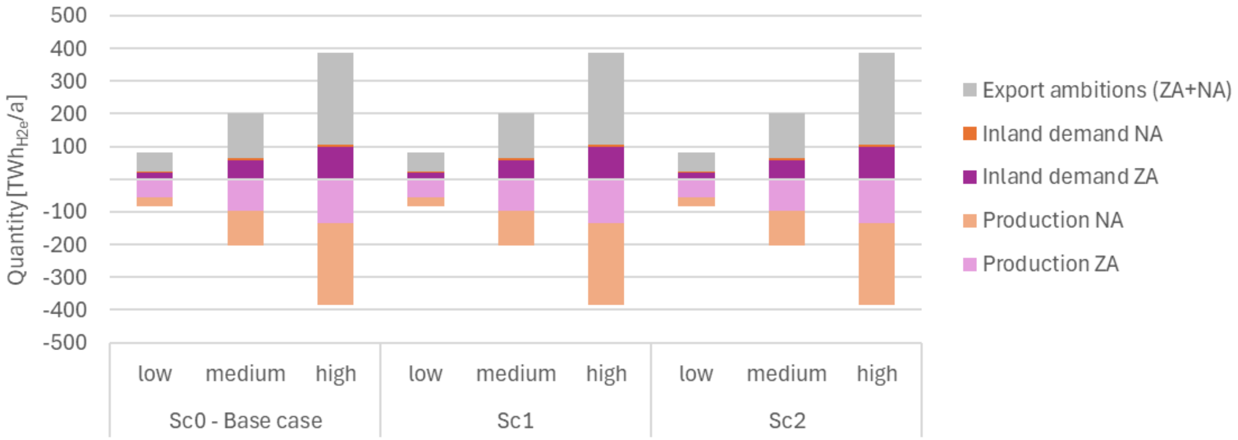
As such, the results should be understood as approximations that support stakeholder discussion rather than precise forecasts. Key simplifications made during model and data preparation are outlined below, along with their potential impacts to the results. For a comprehensive overview of model assumptions and input data, please refer section 4.

- **Static input assumptions:** Demand, supply, costs, or infrastructure are assumed to be fixed for each scenario, not accounting e.g. for site-specific transport capacities, site-specific costs, utilisation rates impacting specific costs, or seasonal fluctuations of supply and demand.
- **Technology or mode availability:** A limited set of logistics options are considered (e.g., certain transport modes or technologies are excluded due to scope or data availability).
- **Simplified infrastructure modelling:** Existing capacities (e.g., terminals, pipelines, roads) are treated with general assumptions, not exact capacities, feasibility or operational constraints.
- **Exclusion of regulatory or political factors:** Policy, permitting, and other aspects are not modelled, though they may influence feasibility.
- **Perfect foresight assumption:** The model assumes complete knowledge of inputs across the planning horizon (without conflicting interests of individual stakeholders), which may not align with real-world decision-making under uncertainty.

4.2 Scenario overview

The GH_2 (incl. NH_3) turnover and balance are identical for all scenarios. It is mainly determined by input assumptions regarding national demands and export ambitions. Despite some theoretical flexibility in terms of production location (South Africa or Namibia), the scenarios result in the same split. The supply and demand balance are shown in Figure 13.

Figure 14: GH_2 supply and demand balance for the analysed scenarios.

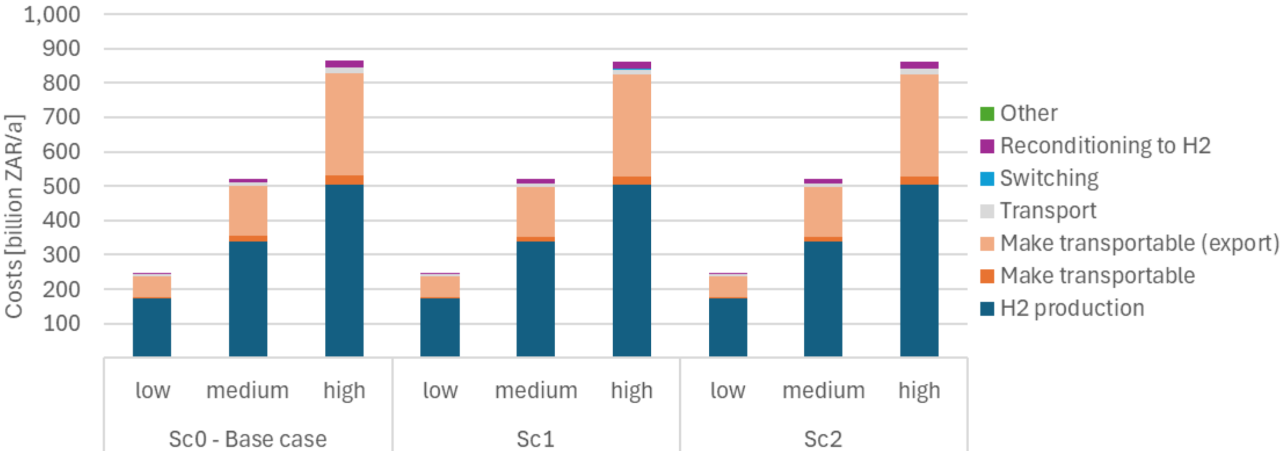


Source: Model result

It is clearly visible that the nations' export ambitions dominate the GH_2 market accounting for 70% of total GH_2 (incl. NH_3) turnover. As a result of the specified GH_2 supply potentials and GH_2 production costs, a somewhat higher share of Nambian-based production is evident. However, a detailed look at the intermediate model data suggests that the difference in production costs (Namibia vs. South Africa) are within data uncertainty. Thus, the split of production volumes is highly uncertain.

Like the supply and demand balance, there are also only minor differences in total costs [16] for national GH_2 (incl. NH_3) supply and export (Figure 14). Depending on the turnover, costs amount to about 250 to 850 billion ZAR per year. The vast majority of the costs are associated with GH_2 production (mainly renewables and electrolysis). Another large cost share applies to GH_2 quantities that are converted to NH_3 for delivery reasons (mainly export). Transport costs, costs for switching transport mode, and costs to recondition NH_3 to GH_2 for national demand are minor.

Figure 15: Total costs for national (ZA + NA) GH_2 supply and export.



Source: Model result

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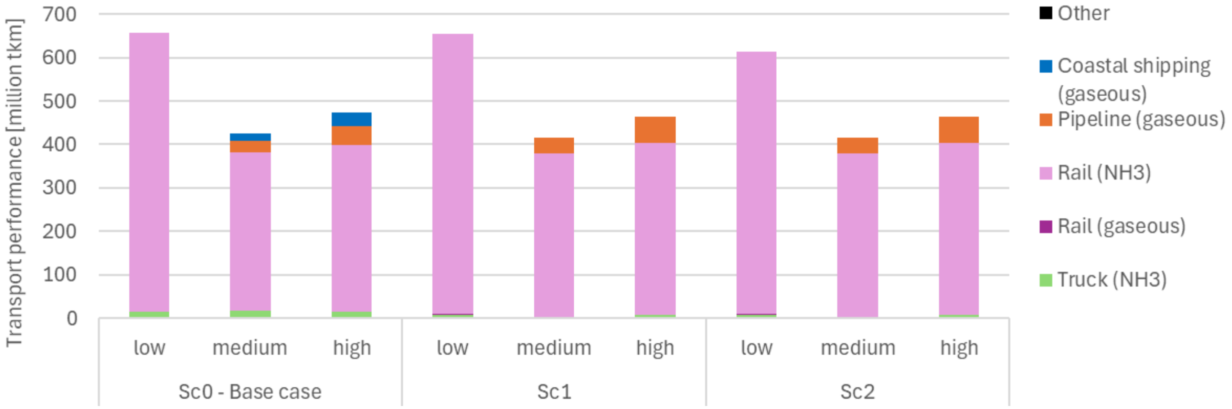
[16] Total costs according to the scope of the analysis, e.g. not including delivery to final consumer but covering inter-regional transport only.

The importance of exporting GH_2 using NH_3 as a carrier is also reflected its transport performance. Figure 15 shows the transport performance per transport mode (without NH_3 shipping [17]). NH_3 transport via rail is the most relevant option. It is used to supply inland GH_2 production already synthesised to NH_3 to be exported (to be discussed in more detail in the following sub-chapter). Only a minor share is used to supply inland NH_3 or GH_2 demand.

In all scenarios, there is a drop in the transport performance of NH_3 via rail, going from low to medium turnover. In the low turnover case, more inland supply potential needs to be accessed to satisfy the defined export ambition. In the medium and high case, more supply potential in coastal regions becomes available to feed the growing export market. In the real-world it is likely that there would rather be less export in the low case or an earlier access of coastal supply options instead of excessive transport for a limited time.

Figure 16: GH_2 transport performance (without NH_3 shipping).



Source: Model result

Out of the roughly 400 to 650 million tonnes per km (tkm) [18] of transport performance, pipelines account for up to 60 million tkm, especially if infrastructure build out is unconstrained (Sc1 & Sc2). If the use of pipelines is limited to regions with existing pipelines (Sc0), coastal shipping of gaseous GH_2 could account for about 30 million tkm. Other transport modes play a minor role for inter-regional transport, could however be more relevant for inner-regional delivery, which is not considered in this assessment.

Each scenario is discussed in more detail in sections 5.3 to 5.5.

4.3 Scenario 0: Existing infrastructure

The cost optimisation results for the base case scenario are visualised in Figure 16. Results are discussed below for each region (A-E) indicated in the figure.

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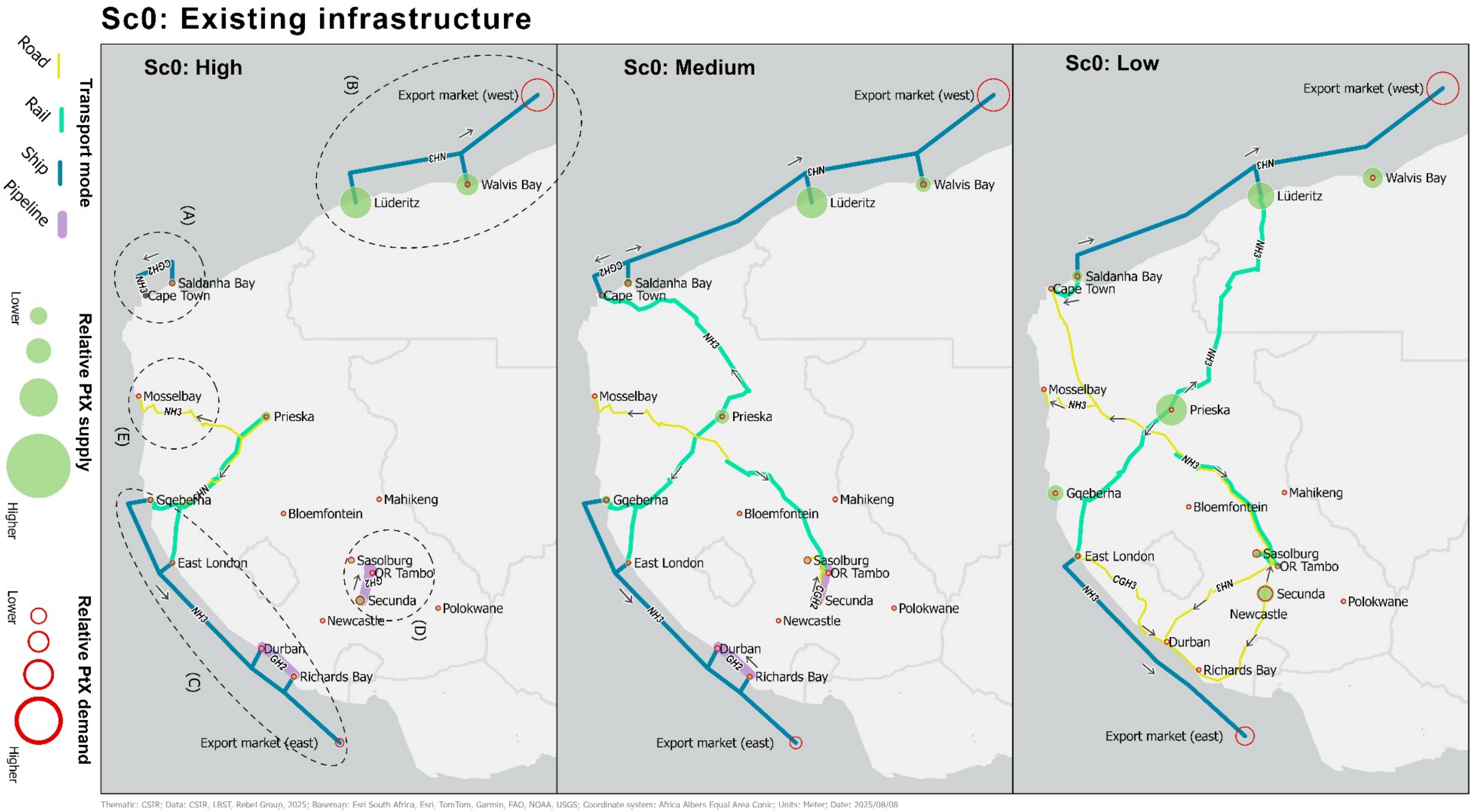
[17] NH_3 shipping is not included as it is dominated by export shipping, which has a significantly larger transport performance than the other transport modes.

[18] Tonne kilometre (tkm) is a measurement of quantity used in freight transport and represents the transport of one tonne of goods over a distance of one kilometre.

Figure 17: Visualisation of modelling results: cost-optimised GH_2 delivery network using currently existing infrastructure (Sc0). Key results labelled A-E are discussed in the text below. Main PtX products being transported and flow direction indicated. For finer and complete details refer to Appendix B.



Source: Model result

(A) Saldanha Bay (node #9) and Cape Town (node # 17)

Saldanha Bay has surplus GH_2 supply potential and some demand (GH_2, NH_3) while Cape Town has no local GH_2 supply potential but also some demand (GH_2, NH_3), e.g. for shipping fuel.

Model results: At low and medium volumes, Cape Town's NH_3 demand is supplied via road and rail from inland locations. Saldanha Bay's surplus NH_3 production is used for export. GH_2 is supplied by rail from Saldanha Bay to Cape Town at low volumes. For both NH_3 and GH_2, the transport switches to coastal shipping from Saldanha Bay to Cape Town for high volumes.

Result interpretation: Saldanha Bay seems to be the logic supplier for GH_2 and NH_3 demand that materialised in Cape Town (for maritime fuels). Depending on the volumes, truck, rail or coastal shipping are the relevant transport modes.

(B) West coast export (node #12)

Large-scale GH_2 production potentials are defined for Lüderitz (node #18) and Walvis Bay (#19). Export from Boegoebaai is deactivated in this scenario.

Model results: Lüderitz is the first and major export location on the west coast for all assessed GH_2 turnovers. Walvis Bay only becomes relevant if Lüderitz supply potential is insufficient to meet export ambitions. For the low case, NH_3 exports are supplemented by deliveries from Prieska (#2) via rail and from Saldanha Bay (#9) via coastal shipping.

Result interpretation: The differences in NH_3 production and export costs fall within the uncertainty range of the techno-economic input data used in the model[19]. Therefore, the model's emphasis on NH_3 exports from Lüderitz should not be overinterpreted. Instead, the results suggest potential complementary export options, such as transporting NH_3 by rail from inland production sites or using coastal shipping from other coastal areas that may not be suitable for large-scale international exports.

(C) East coast export (node #13)

Model nodes with surplus GH_2 potential on the east coast are East London (#16), Richards Bay (#15) and Gqeberha (#11). Durban (#14) has a supply deficit.

Model results: NH_3 exports are mainly fed from East London, and, at higher export volumes, supplemented from Richards Bay and Gqeberha. The quantities exported from East London are mainly supplied from Prieska as NH_3 is using rail transport (plus some local surplus production). Some quantities are also delivered via rail from Prieska to Gqeberha for export.

The local supply deficit (NH_3, H_2) in Durban is first met by using truck and rail transport from different surrounding supply nodes. With increasing GH_2 and NH_3 demand, transport switches to pipeline supply from Richards Bay for GH_2 and to coastal shipping-based supply for NH_3.

Result interpretation: GH_2 export quantities on the south-east coast could be accumulated from various ports (Richards Bay, Gqeberha, East London). The question arises whether each of the ports will enable direct international export (handling large NH_3 ships) or whether coastal NH_3 shipping to one or two international export facilities will be the best solution. In this discussion, the additional supply and export via rail from inland locations such as Prieska might also play a relevant role.

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[19] The model selects hydrogen export locations based on costs covering renewable electricity generation, hydrogen production, NH_3 synthesis and export. While technology costs are identical for all locations, the main cost difference comes from renewable generation. Those costs are highly sensitive to the exact location that is chosen from the renewable plants. The gradients of the quality of the renewable potential are high, e.g. wind speeds in Lüderitz. Thus, slightly varying the location of the renewables has a relevant impact on the costs.

The mode of supply of any NH_3 and/or GH_2 deficit in Durban will depend on the volume and the local surplus of adjacent regions. There is a potential for a GH_2 pipeline from Richards Bay to Durban if demand develops accordingly.

(D) Sasolburg (#53), OR Tambo (#6), Secunda (#5)

OR Tambo has GH_2 supply deficit (no NH_3 demand), Sasolburg and Secunda have supply surplus potential.

Model results: At low volumes, OR Tambo is supplied with GH_2 via truck from Secunda and via rail from Sasolburg. At medium and high volumes, a supply via pipeline from Secunda is used.

For low NH_3 demand volumes, Sasolburg and Secunda are supplied via intermodal transport, combining rail and road, from Prieska. Some of the imported quantities are also forwarded to some east-cost NH_3 demand centers. At medium volumes NH_3 supply is still met by imports from Prieska, only changing to local NH_3 production at high volumes.

Result interpretation: The OR Tambo–Secunda–Sasolburg cluster is expected to be largely self-sufficient. Initial GH_2 supply to OR Tambo is provided via rail and road transport, with a later transition to pipeline supply from Secunda. The production and supply of NH_3 within the cluster should be assessed based on local conditions.

(E) Mossel Bay (#1)

Mossel Bay has surplus GH_2 potential.

Model results: NH_3 is supplied via truck from Prieska (or from supply nodes further north-east).

Result interpretation: Despite Mossel Bay's overall GH_2 surplus, the result shows NH_3 imports to cover local NH_3 demand. Why is NH_3 not produced locally from the surplus GH_2 production potential that is available? This is due to the minimum capacity that was set for NH_3 synthesis plants in the analysis (see section 4.4.4). Local NH_3 demand is below this minimum capacity. Small-scale NH_3 production is technically feasible. However, small plants have a relevant cost premium. This option is not implemented in the model. Thus, once NH_3 demand materialises, the option of using local small-scale NH_3 synthesis instead of imports should be assessed.

4.4 Scenario 1: Unconstrained infrastructure expansion, excluding Boegoebaai

The cost optimisation results for scenario 1 are visualised in Figure 17.

In Sc1, compared to Sc0, the model is not limited to existing infrastructure, but assumes that the required infrastructure to facilitate the selected cost-optimal GH_2 transport network is in place. Below, only the differences between Sc0 and Sc1 are discussed.

Differences in model results: Some of the road and rail transport now use different routes. Sometimes, different modes of transport are used as well, mainly switching between road and rail transport.

An additional pipeline is built between Saldanha Bay (#9) and Cape Town (#17).

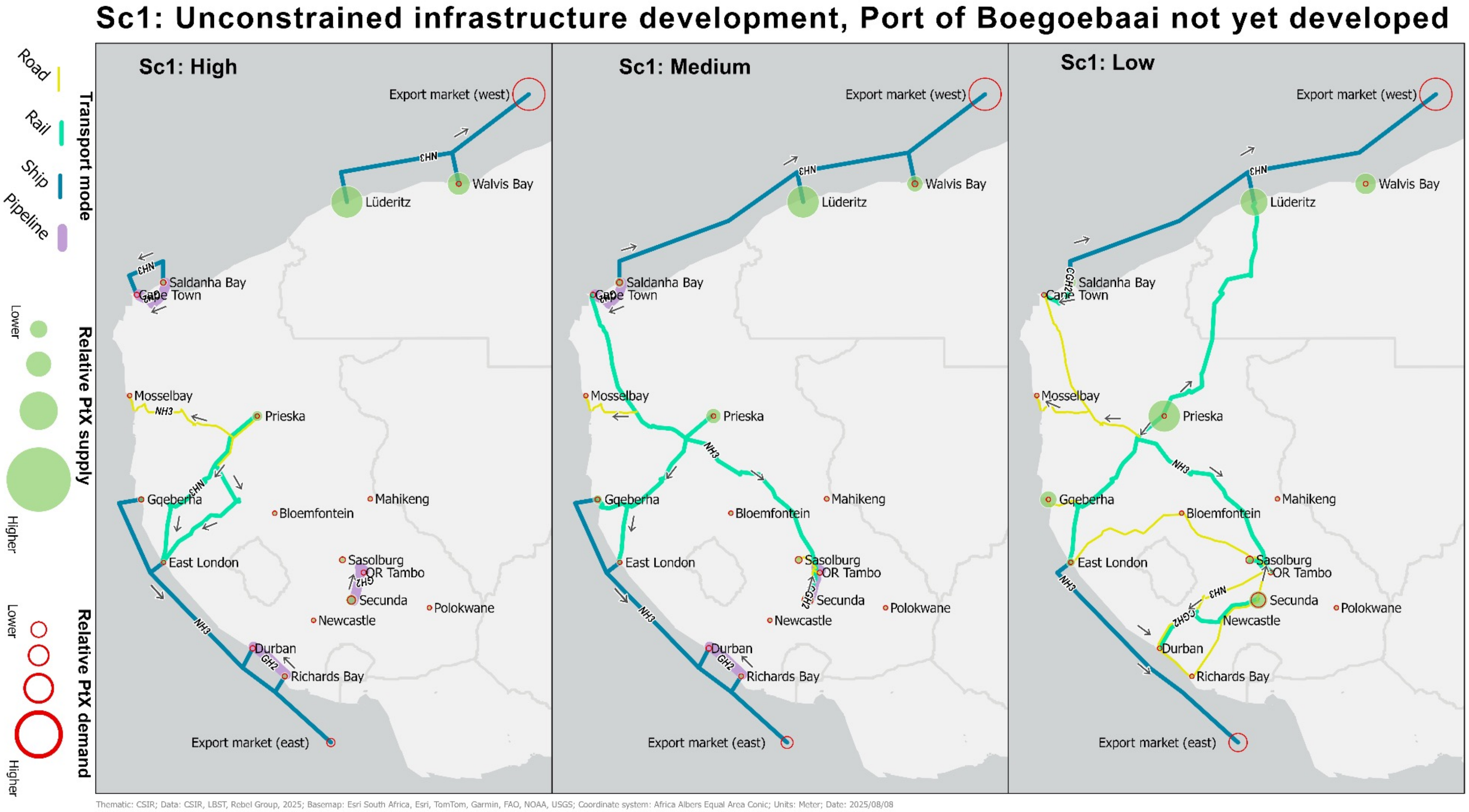
Result interpretation: The new transport routes are chosen by the model to avoid any detour and to work around some of the transport capacity constraints that are set in the model. For example: to make additional NH_3 quantities from Prieska (#2) available for export, the model now uses two parallel rail lines to East London (#16). In the base case (Sc 0), the model detoured some NH_3 to Gqeberha (#11) to overcome this issue. If large quantities from Prieska are to be exported from East London in the future, first the real capacity of the rail track must be assessed against the set limit in the model. The avoidance of detours is a logical choice of the model based on the input data, however, in real world implementation this might not be that relevant.

Further, the model indicates that it might be economically advantageous if GH_2 transport from Saldanha Bay to Cape Town is realised with a GH_2 pipeline instead of using coastal shipping. Both options need to be benchmarked against each other in more detail to get a better understanding of the advantages and disadvantages of the options.

Further comment: One could expect to see more additional pipelines for GH_2 transport in a scenario that allows unconstrained infrastructure expansion (incl. pipelines). The reasons why this does not materialise in Sc1 are as follows:

- GH_2 supply and demand are already quite balanced in each node in Sc1. Thus, the imbalance that causes GH_2 transport is minor. However, pipelines require large-scale transport to be economically advantageous.
- Most of the inland transport is required to meet the defined export ambitions. As exports are assumed to be NH_3 based, the most cost advantageous option is to already use NH_3 via road or rail for inland transport.

Figure 18: Visualisation of modelling results: cost-optimised GH_2 delivery network when infrastructure development is unconstrained, but the proposed Port of Boegoebaai is not yet developed (Sc1). Main PtX products being transported and flow direction indicated. For finer and complete details refer to Appendix B.


Sc1: Unconstrained infrastructure development, Port of Boegoebaai not yet developed

Sc1: High

Sc1: Medium

Sc1: Low

Thematic: CSIR; Data: CSIR, LBST, Rebel Group, 2025; Basemap: Esri South Africa, Esri, TomTom, Garmin, FAO, NOAA, USGS; Coordinate system: Africa Albers Equal Area Conic; Units: Meter; Date: 2025/08/08

Source: Model result

4.5 Scenario 2: Unconstrained infrastructure expansion, including Boegoebaai

The cost optimisation results for Sc2 are visualised in Figure 18.

Scenario 2 assumes that the port of Boegoebaai is existing and available for NH_3 (as a GH_2 carrier) export. As in Sc1, unconstrained infrastructure expansion is allowed. In the following, only the differences compared to Sc1 (without the availability of Boegoebaai) are assessed.

Differences in model results: For low GH_2 turnover, exports from Prieska (#2) are now being exported via Boegoebaai instead of Lüderitz. This is to reduce inland transport distance and thus to reduce costs. However, as observed in Sc0 and Sc1, exports from Prieska via west-coast harbors are not relevant anymore in the medium and high GH_2 turnover case.

No additional changes in the results. No exports of locally produced GH_2/NH_3 from Boegoebaai shown in the model result.

Result interpretation: Exports from Prieska e.g. via Boegoebaai but also via Lüderitz (in Sc1) are driven by the high export ambitions that can't be met by the GH_2 production potential defined for the harbor regions. It is not caused by cost advantages. **In fact, the costs of all western NH_3 export options (that are relevant in the scenarios) only differ by below 10%. This level of cost difference is well below the level of uncertainty that can be achieved in this kind of modelling exercise.** Thus, the fact that the model results e.g. do not show any exports of locally produced NH_3 for Boegoebaai does not indicate that this option is uncompetitive or should not be considered further.

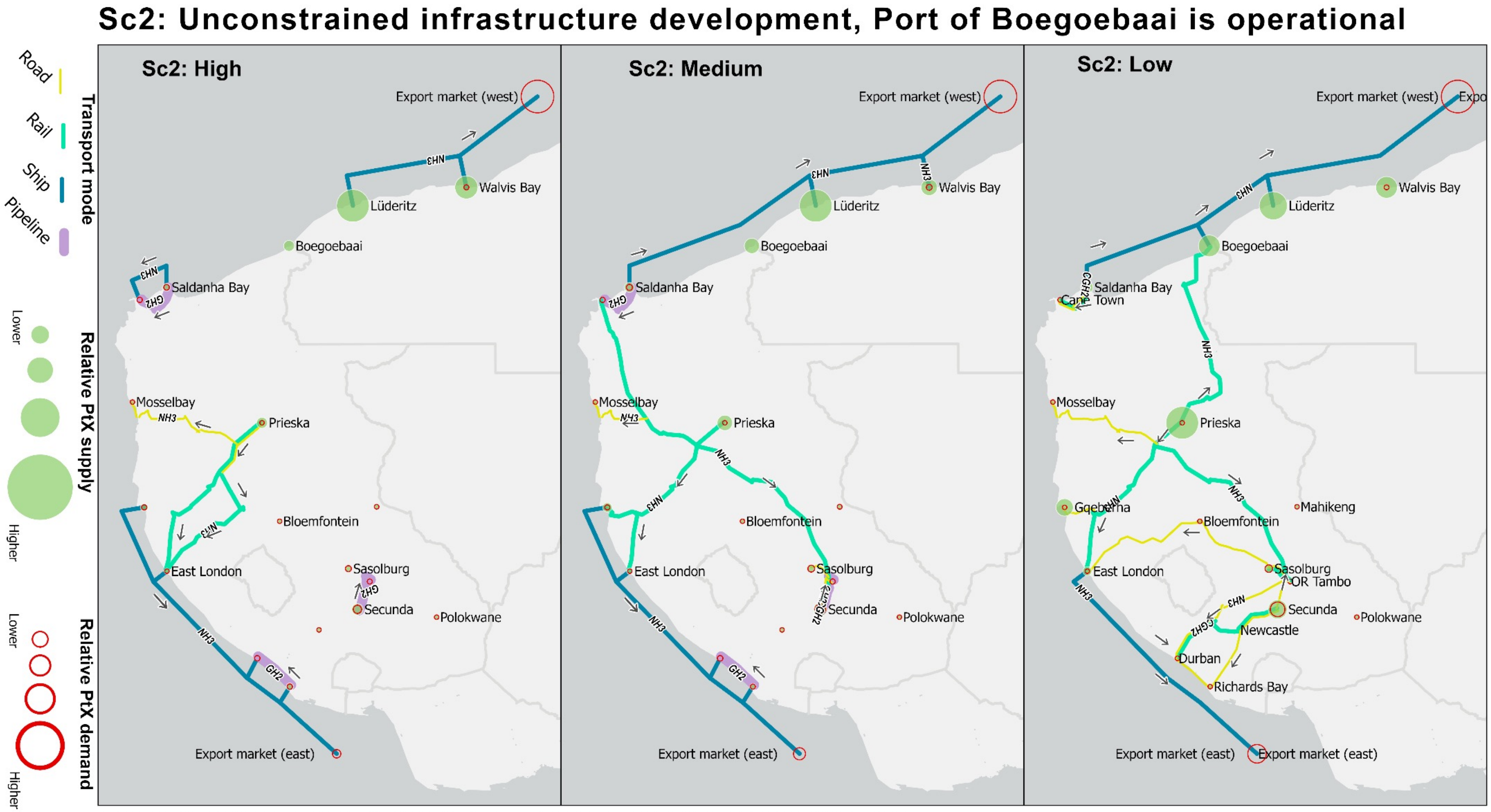
4.6 Overall results

GH_2 and PtX transport is associated with relevant costs. It contributes to a significant share to the total cost of GH_2 supply. Consequently, GH_2 transport is usually avoided or minimised as much as possible. In general, there are two aspects that can trigger GH_2 transport:

1. Significant differences in GH_2 production costs (LCOH) in different regions that compensate for GH_2 transport costs.
2. GH_2 demand that can only be met using GH_2 surplus from other regions, thus, requiring GH_2 imports.

In this assessment, GH_2 production costs are rather similar for all considered locations. Especially in respect to the costs associated with GH_2 transport. The delta in LCOH is not sufficient to pay for transport. Consequently, GH_2 transport is not triggered due to above aspect 1.

Figure 19: Visualisation of modelling results: cost-optimised GH_2 delivery network when infrastructure development is unconstrained, and the proposed Port of Boegoebaai is operational (Sc2). Main PtX products being transported and flow direction indicated. For finer and complete details refer to Appendix B.



Thematic: CSIR; Data: CSIR, LBST, Rebel Group, 2025; Basemap: Esri South Africa, Esri, TomTom, Garmin, FAO, NOAA, USGS; Coordinate system: Africa Albers Equal Area Conic; Units: Meter; Date: 2025/08/08

Source: Model result

Looking at regional supply and demand balance, **most regions in Namibia and South Africa can meet their own demand by local production of GH_2 based on renewables.** This is directly related to the assumption of distributed supply in the scenario definitions (see section 4.5). **Thus, inter-regional transport of GH_2 is limited to supplying metropolitan areas such as Cape Town being supplied from Saldanha Bay, Durban being supplied from other coastal regions or OR Tambo being supplied from Secunda**. However, large international GH_2 export ambitions are included in the scenarios. Those export ambitions are based on the understanding that certain regions in Europe and Asia will rely on GH_2 imports in the future. **Due to the long distance between southern Africa and the export markets, NH_3 was selected as most suitable transport vector**. This has a direct impact on the inland transport in South Africa to support GH_2 exports. **If synthesis of NH_3 is required for export, the least cost option is to already produce NH_3 at the site of GH_2 production and to already use NH_3 as inland transport vector e.g. via rail**. In fact, NH_3 transport using rail is the dominating transport mode in all considered cases.

Various coastal regions in the west and east can contribute to the GH_2 export ambitions using NH_3 as export vector. On the west coast, large export potentials are available in the region and hinterland of Lüderitz, Walvis Bay and Northern Cape (Boegoebaai). While the optimisation model favours Lüderitz as main export location, intermediate model processing data suggests that the cost difference of NH_3 exports for all three regions are very similar. In fact, all costs differ by less than 10% from the mean value. This is clearly within the uncertainty of the economic input data and model output. Thus, Lüderitz, Walvis Bay and Northern Cape (Boegoebaai) can all be considered for exports. Their export quantities could be supplemented by NH_3 volumes supplied from central Northern Cape (e.g. Prieska) transported to Boegoebaai (if available in the future) or Lüderitz using rail transport. Cost data indicates no relevant disadvantage for this hinterland option. Alternatively, or supplementary, Prieska's NH_3 could also be transported via rail to an east coast harbour for export e.g. East London or Mossel Bay. Both harbours as well as Richards Bay might be used to accumulate exports on the east coast.

What remains unclear from the modelling is the question whether international exports would be facilitated from all or multiple harbours in parallel or whether single harbours would take the role as international export gateway, e.g. also receiving NH_3 quantities via (smaller) coastal shipping for other national harbours (and by rail from inland locations).

5

Conclusions and recommendations

This study aimed to develop a modelling approach to investigate **possible cost-effective networks for the bulk delivery/transport of GH_2 in South Africa and Namibia** under different possible infrastructure development and GH_2 utilisation Scenarios.

In interpreting the results, it is important to recognise the assumptions underlaying the data and scenarios, and to be aware of the limitations of the model and data.

Four key messages are derived from the results:

1. **The market will dictate PtX product (GH_2 carrier) and volumes, in turn the product and volume will dictate delivery infrastructure.** The result of this study shows that delivery of NH_3 via rail is a relevant option for PtX delivery in and from South Africa and Namibia. However, this assumes that the off taker wants to buy NH_3. Ultimately the market (what the off taker wants) will be a determining factor in the transport infrastructure requirements.
2. **It is worth aligning GH_2 ecosystem activities between South Africa and Namibia, especially to strengthen the Northern Cape province of South Africa's GH_2 proposition before the proposed Port of Boegoebaai is developed.**
3. **GH_2 delivery by rail may play an important role, especially as a central north-south corridor.** Whilst both South Africa and Namibia have ambitions to export GH_2 and may be considered competitors, an integrated GH_2 ecosystem can benefit both countries. This does not necessarily have to focus strictly on pipelines, but can also include rail to leverage early anchor GH_2 projects such as those proposed in Prieska, South Africa.
4. **The GH_2 economy of South Africa's highveld interior (Sasolburg, OR Tambo, Secunda) may operate relatively independently.** Based on the results, the production and transport of PtX product in South Africa's interior could occur in relatively independent system. However, these areas generally have more limited land and renewable energy resources, implying that renewable energy would be produced elsewhere and thus requires capable electricity grid infrastructure. Alternatively, GH_2 could be produced in resource-rich areas and transported inland, which may prove more feasible or cost-effective depending on infrastructure readiness, transport economics and demand volumes.

Whilst the results from the Scenarios analysed in this study are interesting and thought provoking, **the development of the model to achieve the results is the main value-added output from this project**. It provides a framework as a point of departure for future investigation of GH_2 delivery networks as the global market establishes and grows.

The following recommendations to research, industry and policymaker stakeholders are made (Table 26). The recommendations aim to:

- Strengthen the capability of the model to explore additional questions and yield more robust results;
- Better understand the infrastructural and policy realities and interventions required towards functional and efficient GH_2 delivery networks in South Africa and Namibia.

Table 25: Recommendations to research, industry and policymakers

Recommendations for research
1) Investigate a “GH_2 Hubs” scenario The current scenarios assume distributed production of GH_2 largely localised in the regions of demand. By definition, this limits the need for transport. An alternative not yet assessed is the development of several large-scale national GH_2 supply hubs. In this case, GH_2 production is centralised in few locations, requiring more extensive delivery networks to service distributed demand.
2) Integrate GH_2 delivery and energy system modelling The approach of modelling GH_2 transport with a detailed logistic model rather than an overall energy system model is new. Making both types of models with their unique strengths and weaknesses work together or coordinated might generate new insights and learnings. Thus, the option of combining or integrating both types of models should be checked.
3) Expand the analysis to consider performance beyond economic cost Economics are key for GH_2 production, transport and export. However, further relevant aspects such as local or regional value creation, job creation, security of supply, safety and further socio-economic and environmental aspects can be relevant. Those should be included in an overall assessment when selecting inland GH_2 transport options. Post facto Life Cycle Assessment (LCA) comparison modes may also reveal comparative sustainability performance of different transport modes.
4) Improve input data and further test the model This analysis was based on best available information but is underpinned by extensive assumptions ranging on supply and demand locations and volumes, and the costs of GH_2 production and transport. As better, additional or actual data becomes available the modeling should be revisited. Particularly with regards to: • More detailed spatio-temporal supply and demand data and scenarios. • Cost-specific minimum quantity requirements to improve realism and better reflect practical delivery and production constraints. • Consideration of infrastructure constrained (e.g. which ports may or may not be suitable to handle and export certain PtX products). • Inclusion of additional GH_2 carriers (e.g. methanol).

5) Investigate a transitional uptake scenario from most likely GH_2 supply and demand sites

The current investigation assumes that a fully operational supply and demand ecosystem exists between the two countries, with no production variability. To support strategic planning, a recommended study should systematically visualise potential transportation scenarios based on low, medium, and high uptake projections. These scenarios would reflect the most probable production and consumption patterns across the countries, highlighting the infrastructure developments required to enable cost-effective transport of GH_2 and PtX molecules. The analysis should consider the availability of supply at active sites and corresponding demand profiles within each country according to the uptake profiles.

6) Consider the impact of low-carbon road, rail and shipping on transport costs and thus model outcomes

This study considered costs of conventional trucks, trains and ships using carbon-based fuels. Transporting GH_2 with such modes will compromise the “greenness” of the GH_2. In a low-carbon future, electric or low-carbon transport may be used to move GH_2. The impact of the different costs associated with low carbon transport on the model’s selection of cost-effective modes can be explored. This is of particular interest as e.g. EU green fuel imports require to stay below a certain GHG emission threshold along the entire supply chain.

Recommendations for policymakers and industry

1) Assess the suitability of ports for large-scale NH_3 exports

The current modeling approach considers all ports to be equally suitable for NH_3 exports. However, some ports may have certain advantages or disadvantages that make them more or less suitable for exports. This information should be generated and used in the model. Such information can also be used to build capacity and guide ports towards NH_3 export readiness.

2) Check infrastructure and legislative readiness regarding the large-scale transport of NH_3 via rail (and road) in South Africa

The model assumes that GH_2 exports from South Africa will primarily occur in the form of NH_3, which is currently the most viable large-scale GH_2 carrier for long-distance international shipping. This assumption is embedded in the model input data, and as a result, the optimisation frequently selected inland NH_3 transport – particularly via rail – as a cost-effective delivery option to coastal export hubs. Given this outcome, it is important to assess whether appropriate safety standards, regulations, and permitting frameworks are in place for the large-scale transport of NH_3 within South Africa. In particular, the readiness of the freight rail system – including the capability and willingness of the national rail operator to handle hazardous cargo such as NH_3 at industrial scale – should be urgently investigated to ensure it can support GH_2 export ambitions.

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Appendix

Appendix A

Model formulation

The model formulation consisting of (a) the sets and variable definitions, (b) constraints, (c) and its objective function, along with an (d) overview of the verification and validation process followed are given and discussed below.

Notation

The sets, parameters, decision-variables, and utility variables used within the model are given below. Sets refer to a collection of grouped elements, such as all the nodes within the model. Unlike variables, parameters are known values (e.g., input data) that are not allowed to be manipulated. Decision variables are the elements within the model that can be changed in order for the model to find the best solution. Utility variables can also be manipulated by the model, but the final values thereof are considered unimportant.

Sets:

Let:

- **N** be the set of all nodes such that **N** = $\{N_1, N_2, \ldots, N_{92}\}$.
- **T** be the set of all delivery options such that **T** = $\{T_1, T_2, T_{3, \ldots,} T_{26}\}$, where T_1 = Trucking – LP1, T_2 = Trucking – LP 2, etc., as shown in Table 24.
- **A** represent the set of delivery options that carry hydrogen in the form of ammonia (NH_3), such that **A** = $\{T_7, T_{14}, T_{24}, T_{26}\}$. Note that **A** is a subset of **T**.

Parameters:

$H_a^{MaxProduce}$ ≜ The given maximum quantity of hydrogen (in MWh) that can be produced and/or be supplied by Node a ∈ **N** per annum.

$C_a^{Produce}$ ≜ The given cost (ZAR/ MWh) to produce or purchase 1 MWh of hydrogen at Node a ∈ **N**.

$H_a^{DemandTotal}$ ≜ The given total quantity of hydrogen (in MWh) that will be demanded/consumed at Node a ∈ **N** during the year.

$H_a^{DemandAmmonia}$ ≜ The given quantity of hydrogen (in MWh) in the form of ammonia that will be demanded/consumed at Node a ∈ **N** for the specific year (note that the following should hold: $H_a^{DemandTotal} \geq H_a^{DemandAmmonia}\ \forall a \in \boldsymbol{N}$, else there is an error with the input data and the model will not function as intended).

D_{ab} ≜ The given average travel distance (in km) between Node a ∈ $\mathbf{N}$ and Node b ∈ $\mathbf{N}$ *if* there is a path connecting the two locations.

$$L_{ab} \triangleq \begin{cases} 1 \text{ If Node a} \in \mathbf{N} \text{ has a path segement directly linked with Node b} \in \mathbf{N} \\ 1 \text{ If Node a} \in \mathbf{N} = \text{Node b} \in \mathbf{N} \\ 0 \text{ Otherwise} \end{cases}$$

$C_t^{transport}$ ≜ the given cost (ZAR/ km) to transport 1 MWh of hydrogen using Delivery Option t∈ $\mathbf{T}$ over a distance of 1 km.

$C_t^{MakeTrans}$ ≜ the given cost (ZAR/ MWh) to make hydrogen transportable using Delivery Option t∈ $\mathbf{T}$ after production.

$C_t^{Recondition\ cost}$ ≜ the given cost (ZAR/ MWh) to recondition the hydrogen delivered when transported using Delivery Option t∈ $\mathbf{T}$.

$C_{t^1t^2}^{switch}$ ≜ the given cost (ZAR/ MWh) to switch 1MWh from Delivery Option t^1 ∈ $\mathbf{T}$ to t^2 ∈ $\mathbf{T}$.

$$v_{t^1t^2}^{switch} \triangleq \begin{cases} 1 \text{ If it is possible to switch from Delivery Option } t^1 \in \mathbf{T} \text{ to } t^2 \in \mathbf{T} \\ 0 \text{ Otherwise} \end{cases}$$

$$F_{tab} \triangleq \begin{cases} 1 \text{ If it is feasible to use Delivery Option t} \in \mathbf{T} \text{ from Node a to Node b} \in \mathbf{N} \\ 0 \text{ Otherwise} \end{cases}$$

r_t^{max} ≜ the given maximum quantity (in MWh) of hydrogen that can be delivered using Delivery Option t∈ $\mathbf{T}$ on a specific pathway (i.e., the maximum capacity restriction).

r_t^{min} ≜ the given minimum quantity (in MWh) required to use Delivery Option t∈ $\mathbf{T}$ on a specific pathway (i.e., the minimum capacity requirement).

shortagePenaltyConstant ≜ the given penalty applied (ZAR/ MWh) for any hydrogen shortage within the model.

bigM ≜ a very big constant value (i.e., 2 000 000 000) used to model logical conditions (i.e., to force constraints to become active under certain conditions).

Decision variables:

The most important decisions that the mode needs to make are:

1. The quantity of hydrogen that should be transported between two nodes that are connected by a path segment.
2. The delivery option that will be used to transport the quantity between the two nodes (note that multiple modes can be chosen simultaneously).

$X_{tab} \triangleq$ the quantity of hydrogen (in MWh) delivered from Node a ∈ $\mathbf{N}$ to Node b ∈ $\mathbf{N}$ using Delivery Option t ∈ $\mathbf{T}$.

$Y_{at^1t^2} \triangleq$ The quantity of hydrogen (in MWh) switched from being delivered by Delivery Option $t^1 \in \mathbf{T}$ to Delivery Option $t^2 \in \mathbf{T}$ at Node a ∈ $\mathbf{N}$.

Utility variables:

Depending on the scenario, the network's hydrogen supply might exceed the demand, or vice versa. The following variables are included to account for this.

$H_{at}^{surplus} \triangleq$ surplus hydrogen (in Mwh) in stock at Node a ∈ $\mathbf{N}$ and prepared to be delivered using Delivery Option t∈ $\mathbf{T}$.

$H_{at}^{shortage} \triangleq$ the quantity of hydrogen (in MWh) demanded by Node a ∈ $\mathbf{N}$ that could not be delivered by Delivery Option t∈ $\mathbf{T}$.

$h_{at}^{Demand} \triangleq$ the quantity of hydrogen (in MWh) demanded at Node a ∈ $\mathbf{P}$ and to be delivered by Delivery Option t∈ $\mathbf{T}$ if sufficient supply is available.

$h_{at}^{Produce} \triangleq$ The actual quantity of hydrogen (in MWh) that will be produced/purchased at Node a ∈ $\mathbf{N}$ and delivered using Delivery Option t∈ $\mathbf{T}$.

$$b_{tab}^{quantity} \triangleq \begin{cases} 1 & \text{If } \mathrm{X_{tab}} > 0 \\ 0 & \text{Otherwise} \end{cases}$$

$$b_{ab}^{production} \triangleq \begin{cases} 1 & \text{If } h_{at}^{Produce} > 0 \\ 0 & \text{Otherwise} \end{cases}$$

$$b_{at}^{short} \triangleq \begin{cases} 1 & \text{If } H_{at}^{shortages} \geq 0 \\ 0 & \text{Otherwise} \end{cases}$$

$$b_{at}^{recondition} \triangleq \begin{cases} 1 & \text{If } (h_{at}^{Demand} - H_{at}^{shortages}) \geq 0 \\ 0 & \text{Otherwise} \end{cases}$$

The following variables are also declared in the model, and are used to represent the cost of the solution and to calculate the objective function:

- cost_transport;
- objectiveFunction;
- cost_shortagePenalty;
- cost_switching;
- cost_production;

- cost_makeTransportable;
- cost_reconditioning;

Constraints

The model is subjected to the constraints discussed below.

The model attempts to find the most cost-effective delivery network to fulfil the hydrogen demand of each node within the network. Parameter $H_a^{DemandTotal}$ represents the total hydrogen demand of Node $a \in \boldsymbol{N}$**.** The model needs to allocate this demand to one or more Delivery Option using (1), where h_{at}^{Demand} represents the quantity of hydrogen demanded by Node a that needs to be delivered by Delivery Option t ∈ $\mathbf{T}$ specifically.

$$H_a^{DemandTotal} = \sum_{t \in \boldsymbol{T}} h_{at}^{Demand}, \ \forall\, a \in \boldsymbol{N} \qquad (1)$$

Allocating portions of the demand (and production) to specific delivery options enables the model to determine the mix of delivery options to use and, subsequently, the most cost-effective network.

For some nodes, a portion or all of the hydrogen demand will be demanded in the form of ammonia. Accordingly, this demand needs to be allocated to the delivery options that carry ammonia specifically, defined as set $\boldsymbol{A} = \{T7, T14, T24, T26\}$**.** Constraint (2) ensures that the demand collectively allocated to ammonia-carrying delivery options is equal to the minimum requirement for Node a, represented with $H_a^{DemandAmmonia}$, or greater.

$$\sum_{t \in \boldsymbol{A}} h_{at}^{demand} \geq H_a^{DemandAmmonia}, \forall a \in \boldsymbol{N} \qquad (2)$$

Similar to (4), $H_a^{MaxProduce}$ represents the maximum production capacity of Node $a \in \boldsymbol{N}$, which is allocated to individual delivery options with (3). Accordingly, $h_{at}^{produce}$ represent the quantity of hydrogen that will be produced at Node a with the intention that it will be delivered using Delivery Option t ∈ $\mathbf{T}$.

$$H_a^{MaxProduce} \geq \sum_{t \in \boldsymbol{T}} h_{at}^{produce}, \ \forall\, a \in \boldsymbol{N} \qquad (3)$$

Note that the inequality sign in (3) allows the model to decide if only a portion of the production capacity should be utilised to prevent unnecessary hydrogen surpluses at Node a.

In order to satisfy the demand of each node, hydrogen needs to be transported from nodes with surplus supply using the most cost-effective delivery option. Decision variable X_{tab} represents the quantity of hydrogen transported from Node a to Node b using Delivery Option t ∈ $\mathbf{T}$. However, hydrogen can only be transported/ delivered between two nodes if

i. they are neighbouring nodes (i.e., there is a path segment between them), and if
ii. there is a suitable Delivery Option operating on the path segment between the two nodes.

Constraint (4) enforces (i) and (ii) by ensuring that hydrogen can only be delivered from Node a to Node b using Delivery Option t ∈ $\mathbf{T}$ if the nodes are linked (i.e., when $L_{ab} = 1$) and if the relevant delivery option is feasible between the two nodes (i.e., when $F_{tab} = 1$). Note that L_{ab} and F_{tab}, are Boolean parameters that represent, respectively, if Node a and Node b are linked (neighboring) nodes and if Delivery Option t ∈ $\mathbf{T}$ can be used to move hydrogen between these two nodes. If either of these two Boolean parameters are equal to zero, then the quantity transported is forced to be zero ($i.e., X_{tab} = 0$).

$$X_{tab} \leq BigM \cdot L_{ab} \cdot F_{tab} \quad \forall \ a, b \in \boldsymbol{N} \ and \ t \in \boldsymbol{T} \qquad (4)$$

Each delivery option has a minimum capacity requirement, and a maximum capacity constraint associated with it to prevent unrealistic solutions; these are represented with r_t^{Min} and r_t^{Max}, respectively, for Delivery Option $t \in \boldsymbol{T}$ and enforced with (5) and (6) for each potential pathway (i.e., between each Node a∈ $\boldsymbol{N}$ and Node b∈ $\boldsymbol{N}$ pair).

$$X_{tab} \leq r_t^{Max} \cdot B_{tab}^{quantity} \quad \forall \ a, b \in \boldsymbol{N} \ and \ t \in \boldsymbol{T} \qquad (5)$$

$$X_{tab} \geq r_t^{Min} \cdot B_{tab}^{quantity} \quad \forall \ a, b \in \boldsymbol{N} \ and \ t \in \boldsymbol{T} \qquad (6)$$

Note that the minimum capacity requirement should only be activated when hydrogen is actually transported between the two respective nodes (i.e., when $X_{tab} > 0$). Thus, since it is highly unlikely that hydrogen will be moved between each and every node pair and using each delivery option available, the model should determine when to apply the minimum capacity constraint. This is achieved using the Boolean variable $b_{tab}^{quantity}$. Simply put, it ensures that the minimum capacity constraint is only activated if X_{tab} is greater than zero, else the model would be deemed unsolvable. Constraint (6) is used to determine the appropriate value for $B_{tab}^{quantity}$ by forcing it to be equal to 1 if $X_{tab} > 0$ and, accordingly, to ensure that the minimum capacity requirement in (7) is enforced.

The core concept of the model is centred around hydrogen "inventory modelling" of each individual node and delivery option pair. This means that the model balances the inventory of hydrogen at Node a that was allocated to Delivery Option t for each Delivery Option t ∈ $\mathbf{T}$ and Node a ∈ $\mathbf{N}$ combination.

Node a ∈ $\mathbf{N}$'s hydrogen inventory for Delivery Option t ∈ $\mathbf{T}$ is the difference between all of the node's hydrogen inflows and outflows allocated to the delivery option under consideration. Hydrogen inflows consist of the quantity produced/supplied at Node a, the hydrogen received from neighbouring nodes, and the quantity of hydrogen switched from other delivery options. Outflows consist of the portion of Node a's demand allocated to the specific delivery option, the hydrogen transported to neighbouring nodes, and the quantity of hydrogen switched from the delivery option under consideration to other options. If the inflows are greater than the outflows, the node will have a surplus inventory of hydrogen (i.e., $h_{at^1}^{surplus} > 0$). If the reverse is true, the node will experience a hydrogen shortage ($h_{at^1}^{shortage} > 0$). Measuring the hydrogen surplus or shortage of each node enables the modelling of scenarios where demand exceeds supply, or vice versa. It also allows the model to consider whether it is worthwhile to fulfil the demand (depended on the shortage penalty applied, as explained later). This inventory balancing constraint is represented with (7).

$$\left(h_{at^1}^{produce} + \sum_{b \in \boldsymbol{N}} X_{t^1ba} + \sum_{t^2 \in \boldsymbol{T}} Y_{at^2t^1}\right) - \left(h_{at^1}^{demand} + \sum_{b \in \boldsymbol{N}} X_{t^1ab} + \sum_{t^3 \in \boldsymbol{T}} Y_{a_{t^1t^3}}\right) = h_{at^1}^{surplus} - h_{at^1}^{shortage},$$
$$\forall \ a \in \boldsymbol{N} \ and \ t^1 \in \boldsymbol{T} \qquad (7)$$

It should not be possible for a node to have a hydrogen shortages and surplus for a specific delivery option simultaneously. This is enforced with (8) and (9) with the aid of Boolean variable b_{at}^{short}. The Boolean variable is equal to one if there is a shortage associated with Delivery Option t at Node a, and zero otherwise.

$$h_{at}^{shortages} \leq BigM * b_{at}^{short} \ \ \forall \ \ a \in \boldsymbol{N} \text{ and t} \in \mathbf{T} \quad (8)$$

$$h_{at}^{surplus} \leq BigM * (1 - b_{at}^{short}) \ \ \forall \ \ a \in \boldsymbol{N} \text{ and t} \in \mathbf{T} \quad (9)$$

To ensure that the model does not source and transport hydrogen that does not exist, it should not be possible for a node's shortages to exceed its demand, as shown with (10).

$$h_{at}^{shortages} \leq h_{at}^{demand} \ \ \forall \ \ a \in \boldsymbol{N} \text{ and t} \in \mathbf{T} \quad (10)$$

Hydrogen can be switched from one delivery option to another at a node. A switch from Delivery Option t^1 to Delivery Option t^2 occurring at Node a is represented with $Y_{at^1t^2}$, where $a \in \boldsymbol{N}$ and $\mathrm{t}^1, \mathrm{t}^2 \in \mathbf{T}$. Constraint (11) ensures that hydrogen can only be switched between allowed Delivery Option pairs.

$$Y_{at^1t^2} \ \leq BigM * v_{t^1t^2}^{switch} \forall * \textstyle\sum_{b \in \boldsymbol{N}} F_{t^2ab} \ \ a \in \boldsymbol{N} \text{ and } \mathrm{t}^1, \mathrm{t}^2 \in \mathbf{T} \quad (11)$$

Boolean parameter $v_{t^1t^2}^{switch}$ indicates when the switch is allowed to occur (i.e., $v_{t^1t^2}^{switch}$ = 1). If the switch is not allowed (i.e., $v_{t^1t^2}^{switch}$ = 0), $Y_{at^1t^2}$ is set to zero. It further ensures that a switch can only happen if Delivery Option t^2 is feasible at Node a (i.e., when $\sum_{b\in N} F_{t^2ab} \geq 1$). In other words, a switch is only possible if the respective delivery option can be used to deliver hydrogen to at least one neighbouring node. This helps to avoid unnecessary and unfeasible switching. This is achieved using Boolean parameter F_{t^2ab} that indicates (i.e., when equal to one) if Delivery Option t^{2}can be used to transport hydrogen from Node a to Node b.

The production cost rate associated with Delivery Option t ∈ **T** is depended on a minimum production quantity (economies of scale) that needs to be achieved, else it is not feasible. For this project, this minimum quantity is assumed to correspond with the minimum delivery quantity required (r_t^{Min}) for Delivery Option t (further improvements to the model could consider adding a production-specific minimum quantity). Constraint (12) ensures that this minimum production quantity is achieved.

$$h_{at}^{Produce} \geq r_t^{Min} \cdot b_{at}^{production} \; \forall \; a \in \boldsymbol{N} \text{ and t} \in \mathbf{T} \quad (12)$$

Note that the Boolean variable $b_{at}^{production}$ is used in (12) to ensure that the constraint is only applied when applicable. The constraint is only applicable $(\text{i.e.}, \text{when } b_{at}^{production} = 1)$ when the quantity produced at Node a for delivery using Delivery Option t is greater than zero. The value of the $b_{at}^{production}$ is determined using (13). Note that BigM represents a significantly large value and is included to model conditional logic.

$$h_{at}^{Produce} \leq BigM \cdot b_{at}^{production} \; \forall \; a \in \boldsymbol{N} \text{ and t} \in \mathbf{T} \quad (13)$$

Similar to the above, the quantity of hydrogen reconditioned also needs to equal or exceed the minimum delivery quantity required for the respective delivery option to ensure it is economically viable. The quantity reconditioned in (17) is calculated as the node's demand allocated to the delivery option less any shortages ($h_{at}^{demand} - h_{at}^{shortage}$).

$$\left(h_{at}^{demand} - h_{at}^{shortage}\right) \geq r_t^{Min} \cdot b_{at}^{recondition} \in \{0,1\} \; \forall \; a \in \boldsymbol{N} \text{ and t} \in \mathbf{T} \quad (17)$$

The Boolean variable $b_{at}^{recondition}$ ensures that (17) is only applied when applicable, and its value is determined with (18).

$$\left(h_{at}^{demand} - h_{at}^{shortage}\right) \leq BigM \cdot b_{at}^{recondition} \in \{0,1\}\ \forall\ \ a \in \boldsymbol{N} \text{ and t} \in \mathbf{T}\ \ (18)$$

The remining constraints ensure that the variables are non-negative, Booleans, and integer values, where applicable.

$$X_{tab} \geq 0 \quad \forall\ \ a, b \in \boldsymbol{N} \text{ and t} \in \mathbf{T}\ \ (19)$$

$$Y_{at^1t^2} \geq 0 \quad \forall\ \ a \in \boldsymbol{N} \text{ and } \mathrm{t}^1, \mathrm{t}^2 \in \mathbf{T}\ \ (20)$$

$$h_{at}^{surplus}, h_{at}^{shortage}, h_{at}^{demand}\ \&\ h_{at}^{Produce} \geq 0\ \ \forall\ \ a \in \boldsymbol{N} \text{ and t} \in \mathbf{T}\ (21)$$

$$\mathrm{b}_{\mathrm{at}}^{\mathrm{short}}, b_{at}^{production}, b_{at}^{recondition}, b_{at}^{quantity} \in \{0,1\} \text{ and integer } \ \forall\ \ a \in \boldsymbol{N} \text{ and t} \in \mathbf{T}\ (22)$$

Objective function

Overall, the objective function in (23) aims to minimise the total network cost of hydrogen delivery.

$$\begin{aligned}\min Z = & \sum_{\substack{a,b\in N\\ t\in T}} \left(X_{tab} \cdot C_t^{transport} \cdot D_{ab}\right) + \sum_{\substack{a\in N\\ t\in T}} \left(10^6 \cdot h_{at}^{shortage}\right) + \sum_{\substack{a\in N\\ t^1,t^2\in T}} \left(Y_{at^1t^2} \cdot C_{t^1t^2}^{switch}\right) \\ & + \sum_{\substack{a\in N\\ t\in T}} \left(h_{at}^{produced} * \left(c_a^{production} + C_t^{MakeTrans}\right)\right) \\ & + \sum_{\substack{a\in N\\ t\in T}} \left(\left(h_{at}^{demand} - h_{at}^{shortage}\right) * C_t^{Recondition}\right) \qquad (23)\end{aligned}$$

Note the final results of the objective function does not represent the actual cost of the scenario due to the inclusion of penalties for demand shortages, as explained below.

The first term represents the total transportation or delivery cost (i.e., the total cost of delivery the allocated hydrogen quantities using the chosen delivery options over the distances required). The third term accounts for the costs involved in switching between delivery options.

The second term is included to penalise the model (with R1 million per MWh) if any demand is not met (i.e., if $h_a^{shortage} > 0$ for any node a). Without penalising shortages, the model will simply allow shortages at all the nodes where demand exceeds local production as a way to prevent incurring delivery costs. Thus, by adding the penalty, the model is forced to transport hydrogen from nodes with excess supply to those nodes in short supply if the potential penalty costs outweigh the remaining costs. In some cases, the model could decide to allow a shortage and accept the penalty cost if the transport and other relevant costs exceed the penalty cost. Due to the inclusion of this term, the final result of the objective function cannot be used as a cost indication of the solution.

The fourth term accounts for the possibility that it might be more expensive to produce or source hydrogen at certain locations (nodes). For example, there will likely be a cost difference between importing hydrogen or using domestically produced hydrogen to satisfy demand. Thus, by adding this term, the model is forced to consider the trade-off between production cost and delivery cost. The term also incorporates the cost of making the hydrogen transportable for the relevant delivery option.

The fifth term includes the cost to recondition the hydrogen when it reaches its final destination point. This cost is incurred to ensure that they hydrogen delivered will be suitable for use. Note, the cost is only incurred for the portion of the demand satisfied (i.e., $\left(h_{at}^{demand} - h_{at}^{shortage}\right)$.

Model verification and validation

Model verification focuses on ensuring that the model behaves according to its (mathematical) design i.e., it ensures that the model behaves as intended. This process was carried out by testing various simple test cases to confirm that the output aligned with the expected results.

An example of a test case included the following. In both scenarios, it was assumed that Node 10 demanded 1000 000 MWh of hydrogen and that Nodes 14 and 10 could supply 800 000 MWh each. In Scenario A, the production cost for the two supply nodes were the same, while Node 14 was 50 times more expensive than Node 10 in Scenario B. The outputs obtained are visualised in Figure 19, where the line thickness increases with the hydrogen quantity delivered – as expected, the majority of the hydrogen is sourced from the cheapest supply node.

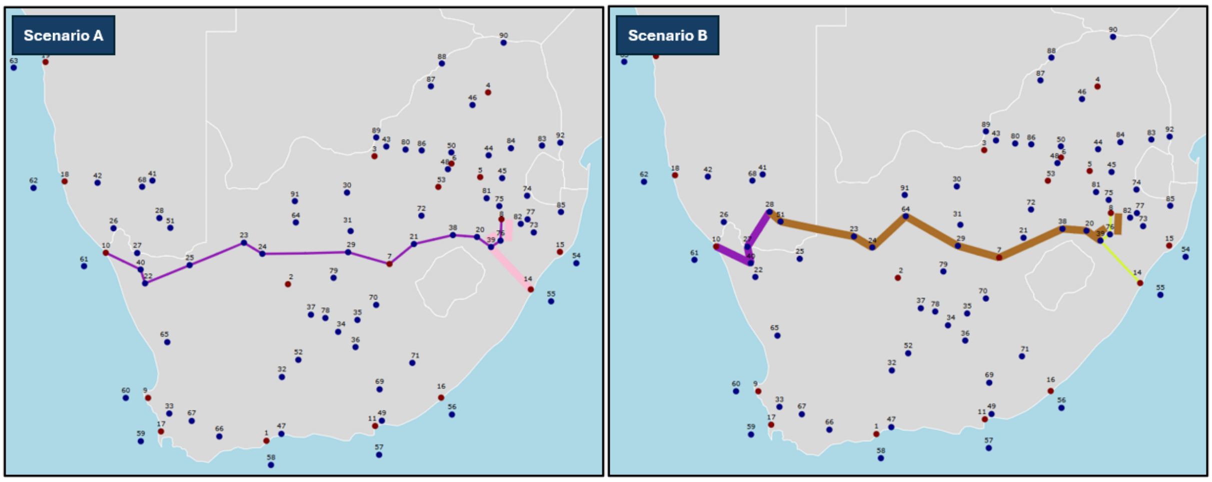


Figure 19: Comparative output of test case for model verification

Further tests were conducted to verify model behaviour. The following are some of the factors that were verified to be functioning as intended by such tests:

- Hydrogen is only sourced from supply nodes, and supply nodes cannot supply more than allowed.
- The shortest route possible between the supply and demand node(s) is selected.
- The flow of hydrogen between the supply and demand node(s) is continuous.

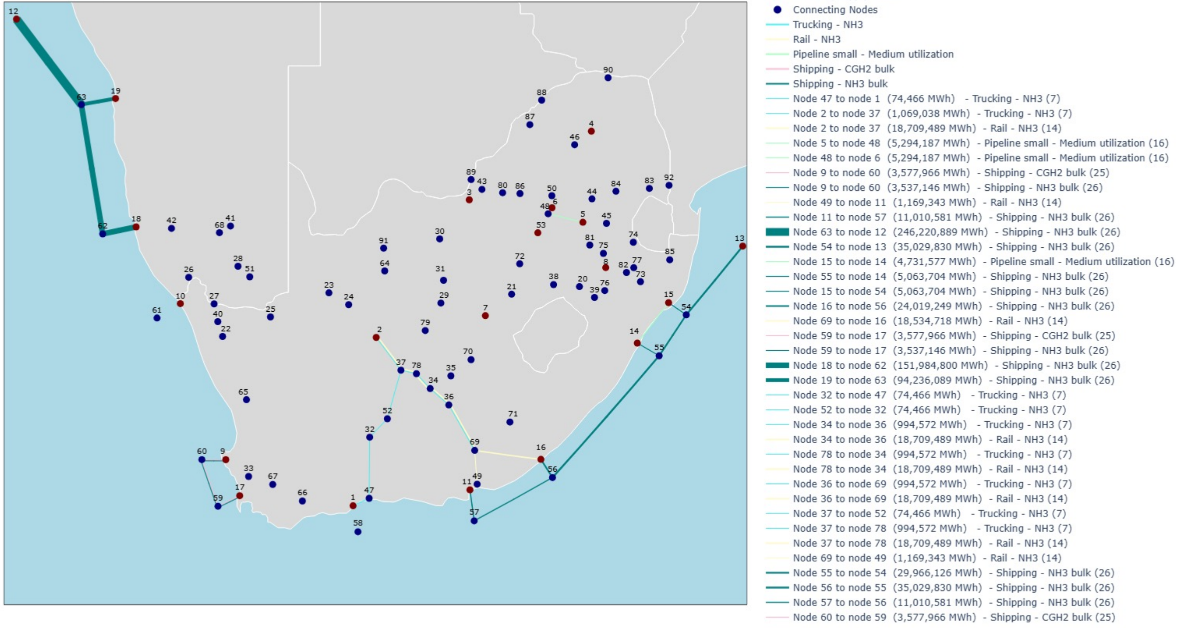
- The most cost-effective and feasible delivery option is selected.
- All costs are correctly calculated.
- The delivery options’ minimum and maximum capacity requirements are taken into account.
- NH3-demand is allocated to, and delivered by, NH3-carrying delivery options.
- Surpluses and shortages are correctly accounted for.
- Multiple delivery options are selected if the hydrogen quantity exceeds the maximum quantity of the most-cost effective transport mode.
- The model correctly switches between delivery options when feasible and appropriate.
- The quantities delivered are correct.
- Relaxing the shortage penalty cost reduces hydrogen delivery (i.e., shortages increase).
- Etc.

Model validation aims to confirm that the model accurately represents the real-world system. This is challenging, given that the global hydrogen economy is still emerging and associated with significant uncertainty. Accordingly, the model developed could not be compared with an existing system. Instead, the results for the various scenarios analysed within this report were compared and investigated by the model developers, as well as other members of the project team. Results that seemed unrealistic were scrutinized to determine the causes thereof. In one instance, a realization was made that some of the input data were incorrectly interpreted by the model developers, thereby emphasizing the importance of including other team members or stakeholders within the validation process. In another instance, the model results were completely unexpected, and a conclusion was reached that the capacity restrictions imposed on the delivery options were too strict. The validation process also included a sensitivity analysis, since the different scenarios were each evaluated with low, medium, and high supply and demand data separately, and the results were compared for consistency across scenarios.

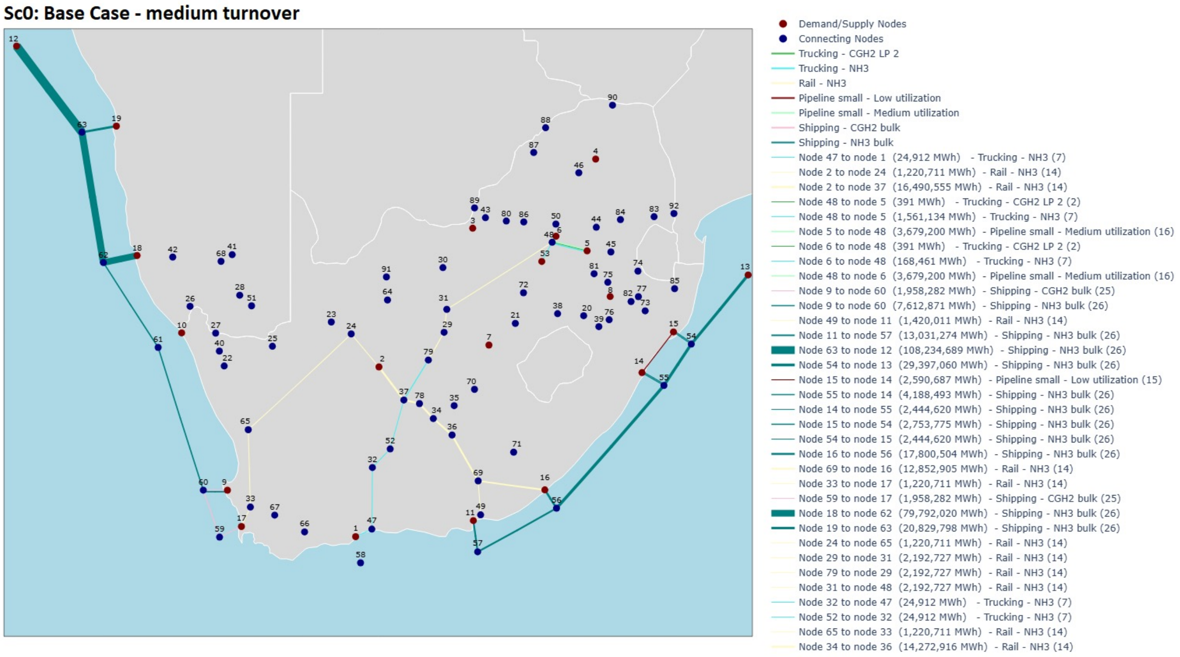
Appendix B

Detailed result visualization

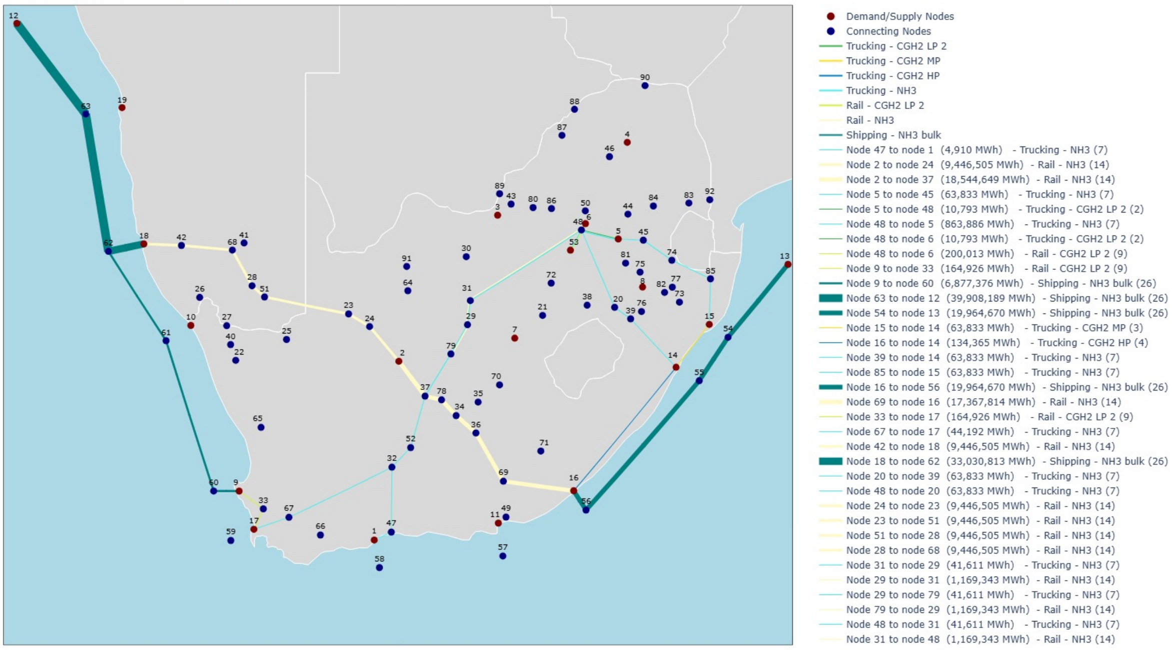
Sc0: Base Case - high turnover



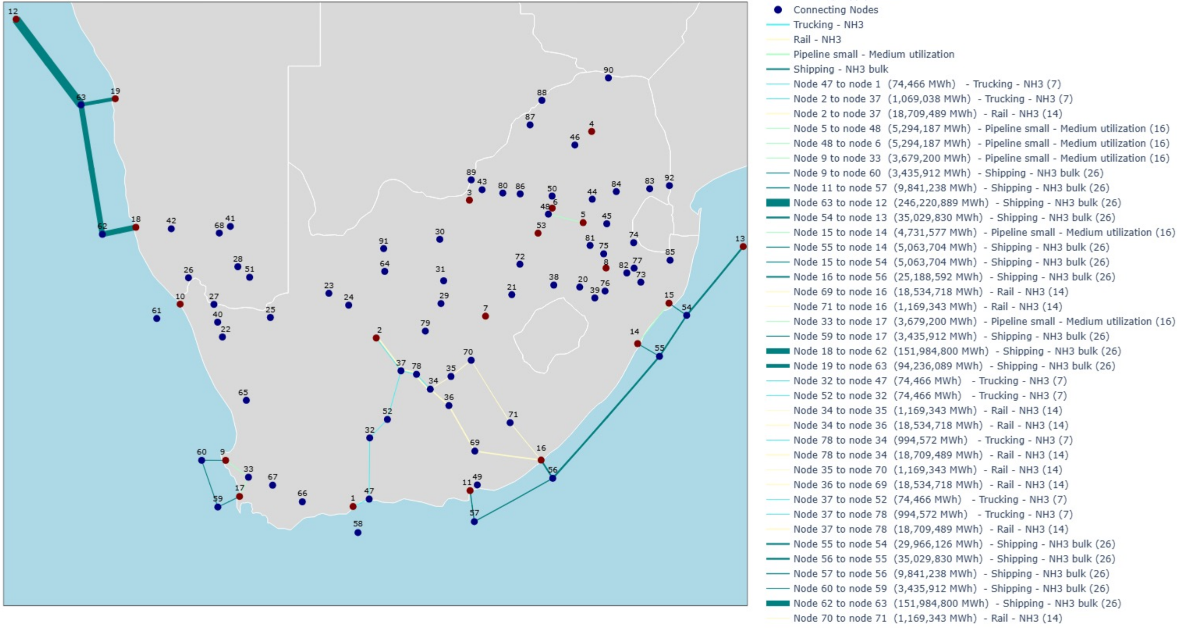
Sc0: Base Case - medium turnover



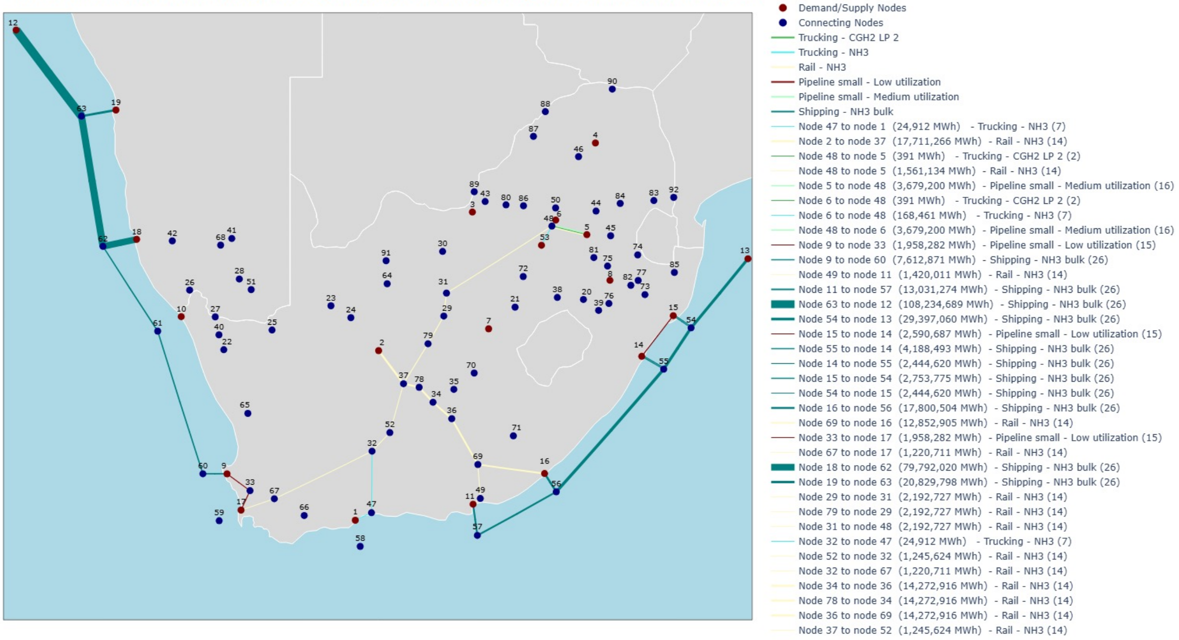
Sc0: Base Case - low turnover



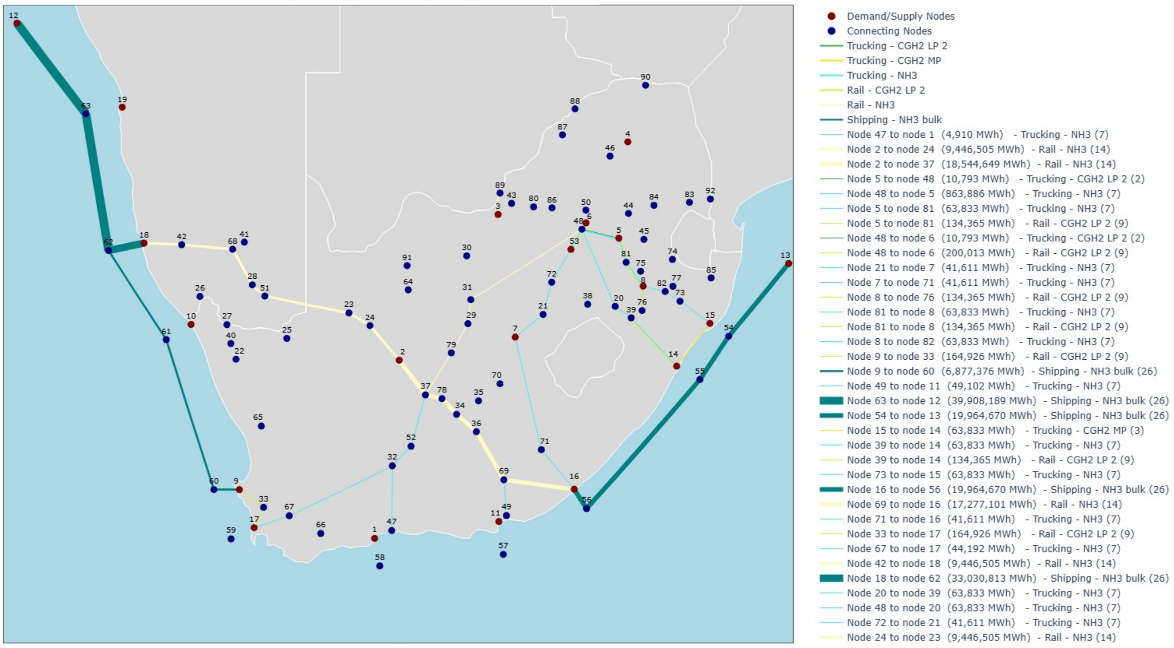
Sc1: Unconstrained infrastructure expansion, excluding Boegoebaai - high turnover



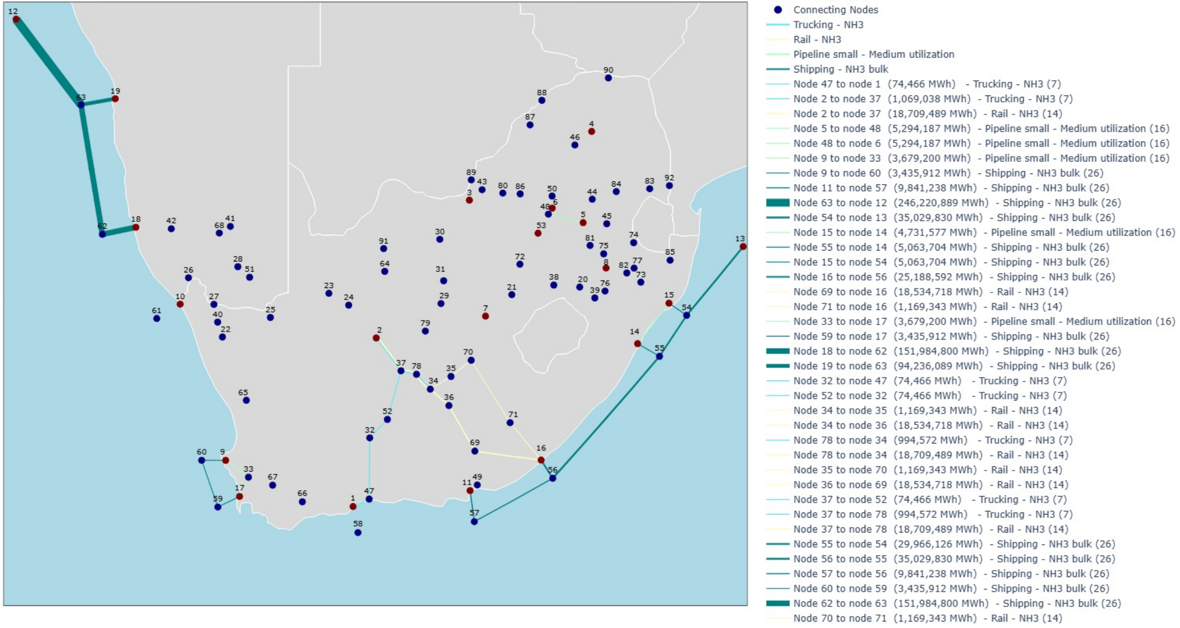
Sc1: Unconstrained infrastructure expansion, exlcuding Boegoebaai - medium turnover



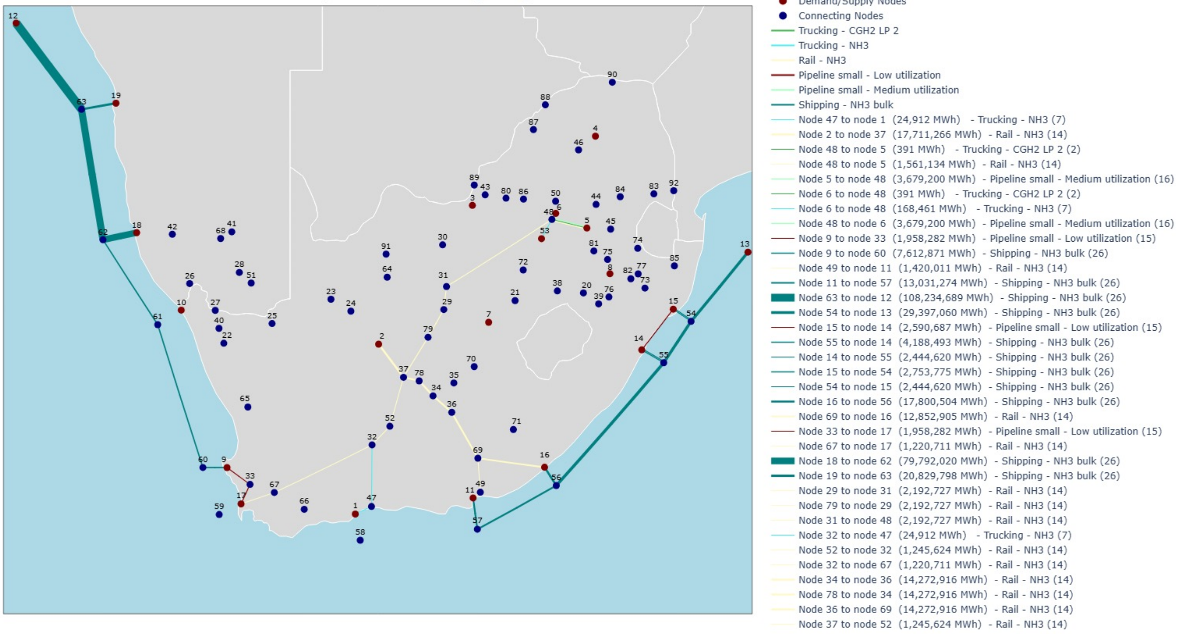
Sc1: Unconstrained infrastructure expansion, excluding Boegoebaai - low turnover



Sc2: Unconstrained infrastructure expansion, including Boegoebaai - high turnover



Sc2: Unconstrained infrastrcuture expansion, including Boegoebaai - medium turnover



Sc2: Unconstrained infrastructure expansion, including Boegoebaai - low turnover