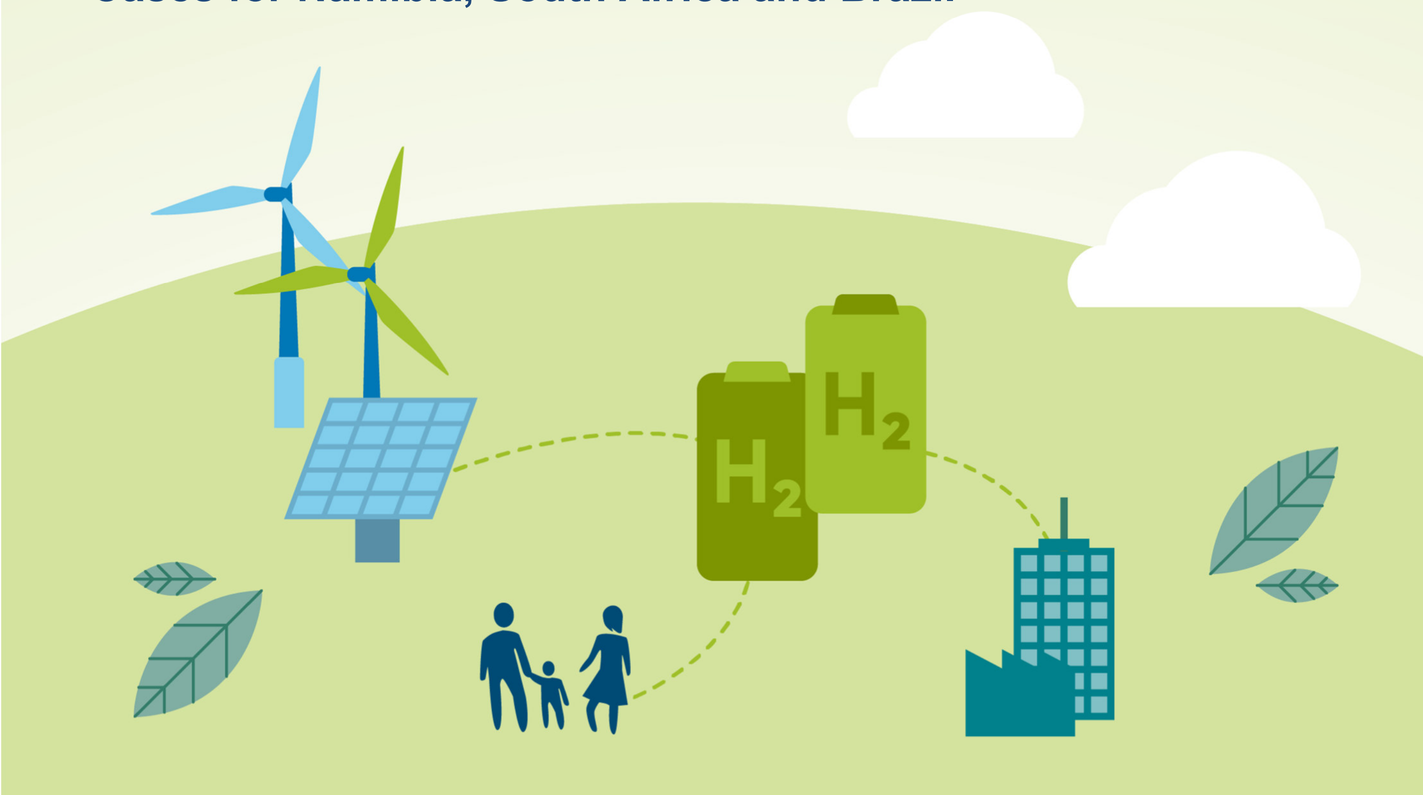
The green hydrogen economy: challenges and opportunities for national development

Cases for Namibia, South Africa and Brazil



Disclaimer

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The Green Hydrogen Business Alliance supports a socio-ecological transformation in chosen partner countries of the BMZ through the promotion of a sustainable market ramp-up of green hydrogen and Power-to-X. The Green Hydrogen Business Alliance is a project implemented by the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ).

Authors

Millennium Institute: Steve Arquitt, Estee Miltz, Igor Oliveira, Vadim Nuñez Pawlowsky

Contact

Green Hydrogen Business Alliance
c/o Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH
Farhanja Wahabzada
wasserstoff@giz.de
www.giz.de

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Abbreviations

BAU	Business-as-usual
BRL	Brazilian real
CO_2	Carbon dioxide
CAPEX	Capital costs
Dmnl	Dimensionless
EU	European Union
FTEs	Full-time equivalents
GH2	Green hydrogen
GDP	Gross domestic product
GHG	Greenhouse gas
iSDG	Integrated Sustainable Development Goal Model
KPI	Key performance indicator
LCOE	Levelised cost of electricity
LCU	Local currency units
LCOH	Levelised cost of hydrogen
MI	Millennium Institute
Mtpa	Million tonnes per annum
NAD	Namibian dollar
OPEX	Operational costs
PtX	Power-to-X
RSA	Republic of South Africa
RLCU	Real local currency units
RMPSE	Root mean squared error
SDG	Sustainable Development Goals
SA	South Africa
TBIAS	Theil statistics mean bias indicator
UN	United Nations
UNAM	University of Namibia
ZAR	South African rand

Executive Summary

Objective

The aim of this study was to assess the role of green hydrogen in the development of partner countries, measured by its contribution to a country's Sustainable Development Goals (SDGs). Three different partner countries were assessed: Brazil, Namibia and South Africa. Simulated scenarios based on enabling market conditions and levels of technological advancement were used to measure proposed green hydrogen ramp-up across the countries. Country-specific conditions, such as electricity generation capacity or the effects of water availability on production costs, were also considered. Proposed outcomes from the analysis include providing contextual insights on the benefits of green hydrogen for national development and hence supporting partner countries in their green hydrogen development endeavours.

Method

The analysis conducted was performed using a formal computer model, the Integrated Sustainable Development Goals model (iSDG©), developed by the Millennium Institute. It is an assessment model that integrates environmental, social and economic factors and is used as a policy simulation tool. The model was designed to help policy-makers and stakeholders make sense of the complex web of interconnections between the SDGs. Unlike databases and indexes that provide a measure of where a country stands, iSDG focuses on the dynamic interactions within the SDG system to reveal the best paths and progression towards achieving the SDGs. This makes it well suited to measure the impact of a process that may unfold over several decades and that has the potential to have different impacts throughout the economy, society and the environment.

The iSDG model was calibrated to reproduce each country's historical behaviour over the last 20 years. In parallel, a green hydrogen (GH2) sub-model (or module) was developed. The GH2 module simulates the dynamics driving potential supply, production, infrastructure development, production costs, investments and labour requirements for the green hydrogen sector. Furthermore, it captures current and expected trends in GH2 production, transformation, storage and transportation technologies. In the model it is assumed that increased investment into research and technological development will decrease the costs of these technologies over time. The associated cost reductions involved in GH2 production have been set to meet expected forecasts. There is obviously a degree of uncertainty involved, as some of these technologies are at a very early stage of development. Once the GH2 module had captured expected trends, it was coupled to each country's iSDG model. Coupling, in this context, refers to the exchange of data required for computing elements concerning GH2 production (e.g., levelized cost of electricity (LCOE) or land availability) from the core model (i.e., the iSDG model), where these variables are consistently estimated. At the same time, variables in the core model that are influenced by the evolution of the GH2 market incorporate the output data in the model formulation.

Once the GH2 module had been coupled with the core iSDG model, a series of scenarios were performed, under varying parameter values representing different market conditions in order to assess knock-on effects on the SDGs and related causes. The scenarios varied as follows:

- SDG performance without ramp-up of the green hydrogen market
- SDG performance with an organic ramp-up of the green hydrogen market – one where future investment will continue at the current levels
- SDG performance with a strong ramp-up of the green hydrogen market – one where investments are boosted
- Lastly, SDG performance under a strong ramp-up of the green hydrogen market coupled with a steep increase in fossil fuel prices together with carbon pricing implementation.

Despite the underlying uncertainties in the model, such as those associated with the rate of technological development, the model provides supporting information on the evolution of green hydrogen production under varying market conditions. Moreover, the model accurately captures the rate of change of the green hydrogen ramp-up under exploratory investment and policy scenarios with the aim of measuring the knock-on effects on a country's SDGs.

Key findings

- The model results suggest that the rate of the green hydrogen ramp-up is dependent on a range of factors and that obtaining the highest performance in sustainable development outcomes will require a combination of interventions, ranging from the size of investments, investment time frames, and additional policies such as carbon taxation on fossil fuel alternatives or tax breaks for carbon-neutral fuel consumption.
- The rate of the green hydrogen ramp-up is dependent on external factors. This means that local and foreign market forces, as well as changes in fuel prices, need to be carefully monitored to plan for future GH2 investments.
- Green hydrogen and associated derivatives form only one suite of decarbonisation tools. A range of others need to be implemented at the same time in order to achieve net-zero emission goals and a just energy transition.
- Partnerships between energy stakeholders, government, environmental authorities, regulatory bodies, private investors, and scientific knowledge-holders are key to achieving green hydrogen objectives in line with national SDGs.

Brazil

Green hydrogen

- In total, the green hydrogen sector's contribution to GDP, in terms of its value added, may in real terms be as much as BRL 70 billion in 2050 (referred to in the graphs as RLCU – real local currency units). This corresponds to 1.6% of the projected GDP for the same year in the strong ramp-up with the fossil fuel price increase scenario.
- The sector's contribution in terms of direct job creation is projected to be relevant, potentially surpassing 100,000 full-time equivalents (FTEs) by 2050 in both ramp-up scenarios.
- Of the five green hydrogen products tested in the model, ammonia is key for Brazil, achieving up to BRL 22 billion in value added. It is also very sensitive to fossil fuel prices due to the more direct substitution process. The consumption of green ammonia, projected at 5 million tonnes by 2043 in the two scenarios with strong ramp-up, would be sufficient to completely replace the imports of nitrogen fertilisers by that year.
- Most of the jobs created by this emerging economic sector are projected to be created in green ammonia-related activities, from electrolysis operations and downstream activities. In the strong ramp-up scenarios, installed green ammonia capacity would not peak in the simulation period, while in the organic ramp-up scenario a peak could be expected in the early 2040s.
- According to our model, the necessary conditions for exports occur only for green ammonia and only in the strong ramp-up fossil scenario. A key limitation of this study is that we consider domestic consumption as the key purpose of green hydrogen production. A model to analyse the competitive strength of each country against its peers in the global markets would have to follow a different approach.

SDG performance

- The results show no significant indication of major SDG trade-offs in the four scenarios. In other words, the model indicates that green hydrogen has no relevant negative impact on any of the SDGs.
- The positive impacts seem more relevant in the case of SDGs 7 (Affordable and clean energy), 13 (Climate action), 12 (Responsible consumption and production) and 8 (Decent work and economic growth), ordered by magnitude of the projected impact. For a single sub-sector, a 2% overall increase in SDG performance is considered a very positive contribution.
- Marginal gains (1–2%) were also observed for SDG 15 (Life on land).

- Brazil is a country that has near-universal access to water and electricity, which is an advantage compared to other low- and middle-income countries that compete for investments in the green hydrogen sector. None of the simulated scenarios modify these conditions.
- The simulations performed do not support the hypotheses that a GH2 economy might increase inequality, poverty, water or energy scarcity.

Findings

- By integrating a green hydrogen module into the iSDG model calibrated for Brazil, we found support for increased projected overall SDG performance in the country by 2050, in the magnitude of 2% for all targets to be achieved.
- Moreover, a cut in overall GHG emissions, in the magnitude of 10% of total emissions, can be achieved if a prosperous green hydrogen sector develops.
- The green hydrogen sector could contribute significantly to minimising unemployment, which could fall as low as 6% by 2050.
- The analysis points to a need for increased investment in education, not only to fulfil the needs of the emerging green hydrogen sector, but also to mitigate the risk of trade-off with SDGs 3, 4 and 10 in the context of the chronic underinvestment dynamics in the country.
- Investments in climate adaptation, upgrading unpaved roads, reforestation and hydropower capacity (including modernisation of current capacity) seems to be very synergic with investments in green hydrogen, according to our model analysis.
- Slowly declining subsidies for green hydrogen itself and for fertiliser production in the country might help smooth the transition when the first cycle of investment in green hydrogen ends.

Finally, we recommend a multi-country modelling effort be conducted to consider competitiveness aspects that are not captured by single-country modelling.

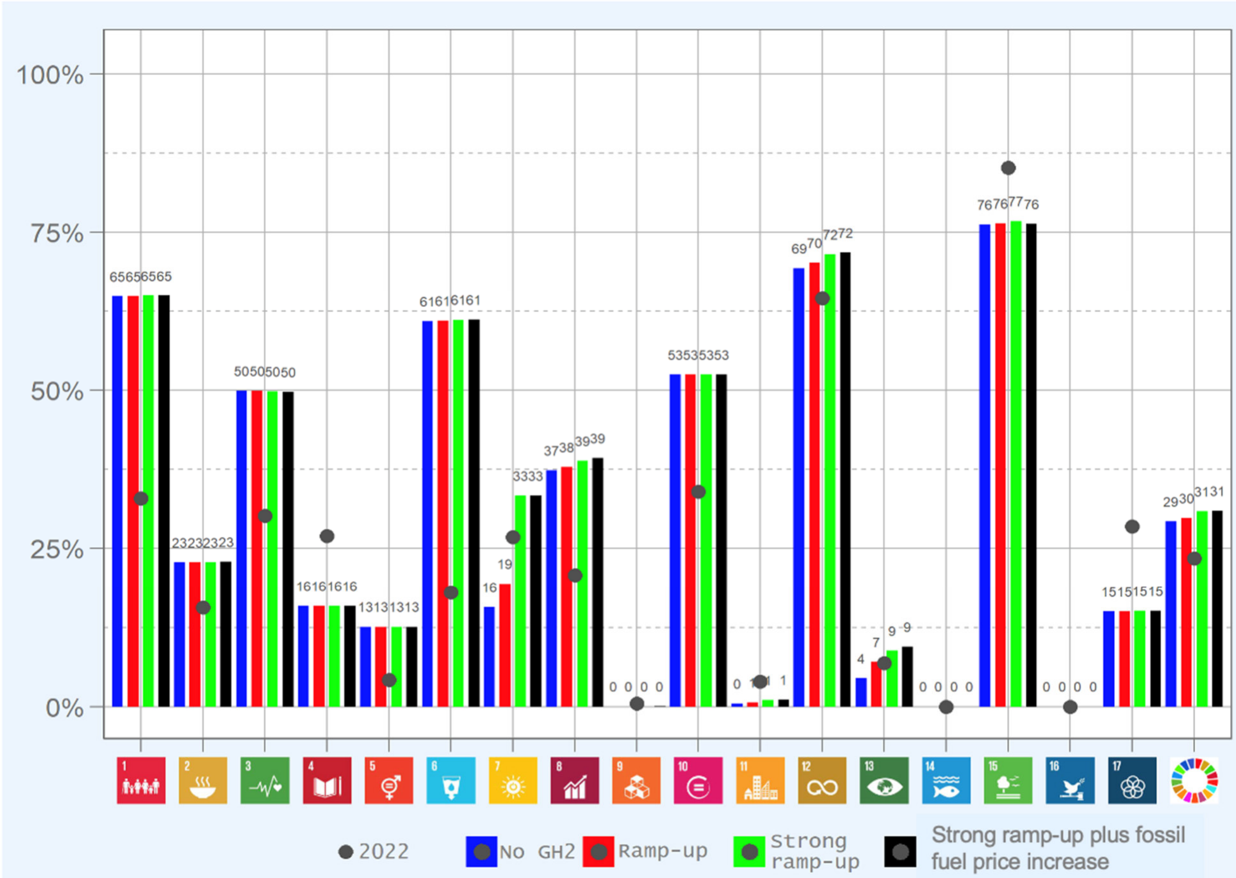

Figure 1 Brazil: SDG attainment in 2050 (the black dots represent the levels of SDG attainment in 2022)

South Africa

Green hydrogen

- In total, the consumption of green hydrogen in South Africa, including the consumption of hydrogen derivatives (i.e. pure GH2, pure GH2 in the fuel cell sector, ammonia, synthetic methane and synthetic diesel), is projected to range between 1.1–6.4 million tonnes/year by 2050, with a total sector value between ZAR 77 billion/year (USD 4.5 billion/year) and ZAR 370 billion/year (USD 22 billion/year), which corresponds to between 1–5% of current GDP.
- In terms of total job creation, the sector could create between 200,000 and 556,000 jobs by 2050 across different stages of construction and operation.
- Across model scenarios, it is projected that green hydrogen consumption in the form of pure hydrogen gas could range between 1 million to 4 million tonnes/year by 2050, with

revenue generation varying between ZAR 14 to 45 billion/year (USD 820 million–2.6 billion/year).

- Job creation is shown to vary depending on the stage of implementation. For green hydrogen consumption alone, job creation is projected to range from 12,000–50,000 jobs during the peak construction period (~2032), and between 2,500–8,000 jobs during operation.
- Under enabling conditions, including higher investment, lower transportation costs and higher costs for traditional fossil fuels, an export supply of 700,000 tonnes/year of ammonia, valued at approximately ZAR 22 billion/year (USD 1.28 billion/year), is projected for 2050.

SDG performance

- In terms of SDG performance, overall SDG attainment ranges from 0 to 2%, with the greatest increase being observed for the model scenarios with higher investment in green hydrogen infrastructure and an increase in fossil fuel prices.
- In terms of attainment of the individual goals, the largest gains are observed for SDG 7 (Affordable and clean energy: 2–12%), SDG 8 (Decent work and economic growth: 3–4%), SDG 12 (Responsible consumption and production: 1–8%) and SDG 13 (Climate action: 3–6%) across the GH2 model scenarios.
- Marginal gains (1–2%) were also observed for SDG 2 (Zero hunger), SDG 3 (Good health and well-being), SDG 9 (Industry, innovation and infrastructure), SDG 14 (Life below water) and SDG 16 (Peace, justice and strong institutions).
- In contrast, SDG 10 (Reduced inequalities) showed a 2% reduction in final performance, with SDG 5 (Gender equality) and SDG 6 (Clean water and sanitation) also decreasing by approximately 1%.
- Based on an evaluation of key environmental indicators, it appears that natural resources, specifically water and land, do not constrain development under current model projections.
- Lastly, minor improvements are observed on levels of inequality, poverty and unemployment, possibly owing to the small scale of the green hydrogen economy in relation to the broader national context.

Findings

- South Africa largely remains off track to achieving the 2030 SDGs, being less than half-way towards achievement (i.e. 42%) by 2050, although the implementation of a green hydrogen policy alone is shown to produce an improvement of 2%.

- Green hydrogen may be used to substitute various fossil fuel energy sources, although the magnitude of substitution and type of energy source that is being replaced could largely affect national development outcomes. In the case of South Africa, a larger portion of coal-based sectors would need to use alternative energy sources, such as GH2, to accelerate decarbonisation.
- Although green hydrogen can provide an alternative to fossil-fuel sources and increase the energy resilience of certain sectors of the economy, finding long-term solutions to address energy disruptions and electricity shortages remains imperative.
- SDG performance could be further improved by the implementation of synergistic policies directed at decarbonisation and national development.

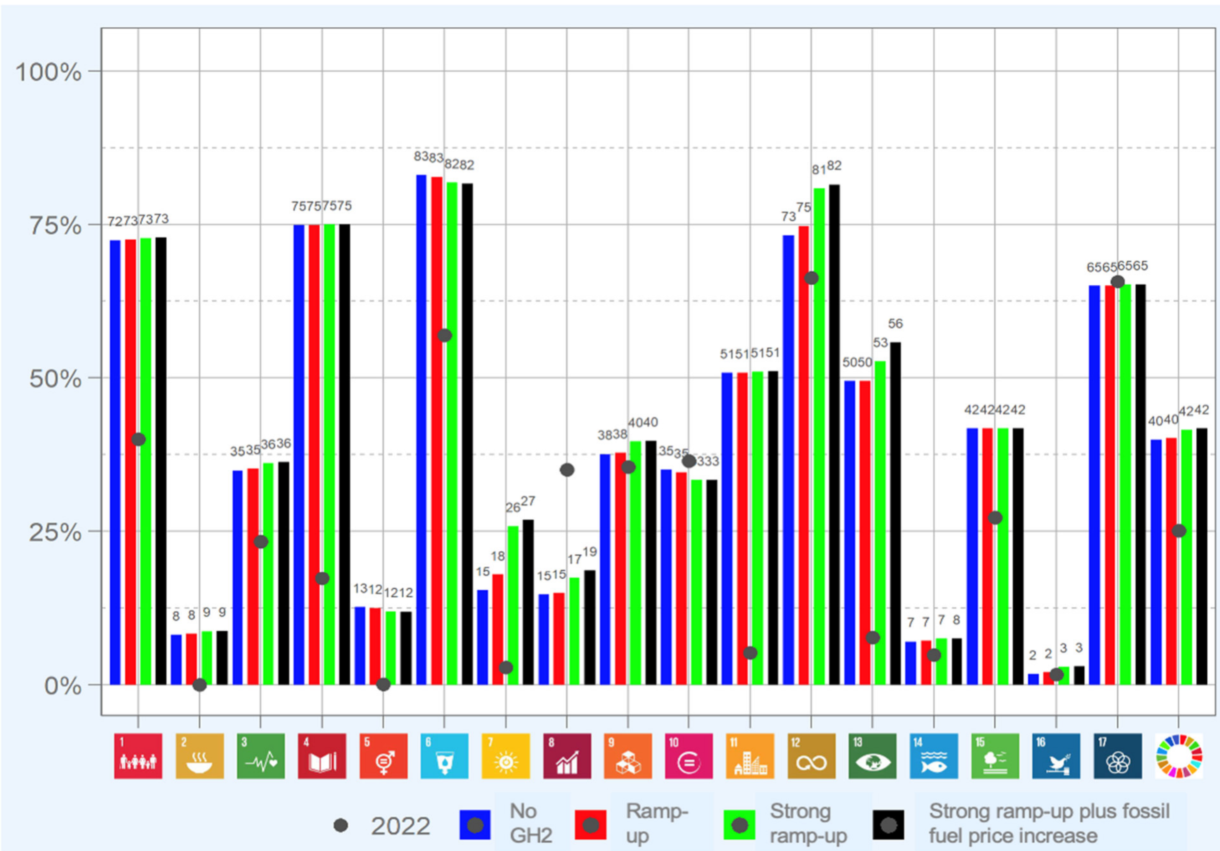

Figure 2 South Africa: SDG attainment in 2050 across different green hydrogen ramp-up scenarios

Namibia

Green hydrogen

- Simulations indicated that a green hydrogen industry in Namibia could yield value-added of close to NAD 60 billion (USD_{2010} 6.06 billion) by 2050. This assumes a strong ramp-up investment of twice the current level, carbon pricing in place, and increases in international fossil fuel prices. A green hydrogen ramp-up with currently indicated initial investment and carbon pricing or assumptions of increasing fossil fuel prices yields value-added closer to NAD 22.5 billion (USD_{2010} 2.27 billion).
- Only the scenario with strong ramp-up, carbon pricing, and assumed fossil fuel price increases incentivised exports of green ammonia. Exports of green hydrogen products are essential to achieve the Namibian Government's goals for the green hydrogen sector. The simulations suggest that demand from the Namibian market alone would be inadequate to promote the desired levels of long-term growth in the green hydrogen sector.
- Green hydrogen ramp-up at current levels without implementation of carbon pricing, and without strongly increasing fossil fuel prices would lead to a pattern of boom and decline in green hydrogen operating capacity as domestic demand alone would not be able to sustain the industry. Simulations show that policies to subsidise shipping costs and set a carbon price may be necessary to generate international demand.
- The employment patterns associated with green hydrogen are coupled with those for capacity in operation and construction. In the strong ramp-up scenarios, employment for operations staff and construction staff peak at approximately 32,000 in 2030. Construction employment falls rather abruptly after the peak; however, some construction employment persists as capacity is retired and renewed. Growth in the sector led by exports would moderate the boom-decline pattern shown in the simulations. Employment in the model does not include ancillary employment and services employment from related developments associated with the green hydrogen sector.

SDG performance

- Green hydrogen investment favourably impacts SDG performance by 2050 for all SDGs except SDGs 10 (Reduced inequalities), 11 (Sustainable cities and communities), and 13 (Climate action). The average SDG performance of the ramp-up scenarios exceeded that of the no-GH2 scenario by 5, 6, and 7 per cent for the ramp-up, strong ramp-up, and strong ramp-up with fossil fuel price increase respectively. With the exception of SDGs 10, 11, and 13, the pattern was consistent with the strong ramp-up with fossil fuel price increase having the greatest effect, followed by the strong ramp-up.
- GH2 investment shows little to no effect on SDGs 11 and 13. SDGs 11 and 13 both emphasise the impacts of disaster events caused by climate warming and their effects on

the national economy and well-being of the population. Disaster events caused by climate warming call for strategies and investments in climate change adaptation. Adaptation to disasters caused by climate warming is outside the scope of GH2 investment in the current model.

- In the case of SDG 10, the no-GH2 scenario out-performs the ramp-up scenarios due to an assumption in the iSDG that influences the performance of SDG Indicator 10.4.1. – the share in GDP accounted for by labour. The ramp-up scenarios result in a greater labour share in GDP than in the no-GH2 scenario. No GH2 out-performs the other scenarios in the simulation because it is closest to the iSDG default setting of 0.5 for the desired labour share. To assess the influence of GH2 on SDG 10, a better understanding of the Namibian Government's desired level of labour share in GDP is necessary. The results shown in the current model for SDG 10 should therefore be considered as inconclusive.
- Strong effects of green hydrogen investment are seen for SDG 1 (No poverty: 18–25% above no-GH2 investment), SDG 3 (Good health and well-being: 13–18%), and SDG 7 (Affordable and clean energy: 15–20%).
- Indirect effects of green hydrogen investment are important drivers of SDG performance. For instance, industry production is increased by the growth of the green hydrogen sector; this in turn increases GDP and the resources available for government investment in sectors relevant to the SDGs, such as health, education, agriculture development etc. Development in these sectors then increases productivity and GDP, setting in motion a reinforcing feedback loop that leads to yet more resources for development.

Findings

- The simulations shown in Figure 3 make a strong case for favourable impacts on the SDGs from a green hydrogen sector. For 14 out of 17 SDGs the stronger the ramp-up investment, the greater the SDG attainment compared to the case with no green hydrogen investment.
- Except for the strongest ramp-up scenario, with accompanying fossil fuel price increases, the green hydrogen model does not generate exports of green hydrogen derivative products (in particular green ammonia), despite the fact that the production costs of green ammonia fall to a competitive level over time. This is due to shipping costs, which drive the cost of Namibian green ammonia well above that of grey ammonia.
- Subsidies in the order of 50% of shipping cost and carbon prices close to USD 200 per tonne per year enabled export of green ammonia in the model simulations.
- The model assumes exports to potential European markets; including regional African markets would benefit the demand for Namibian green hydrogen products.
- Explicitly modelling policies that force demand for green hydrogen products through blending requirements in cases of fungible products could lead to valuable insights.

- Certification systems to desegregate supply chains could conceivably cut the cost of accessing international markets and could be examined through further modelling work.
- Coordinated policies on the sides of both supply and demand are needed if Namibia is to meet its green hydrogen goals.

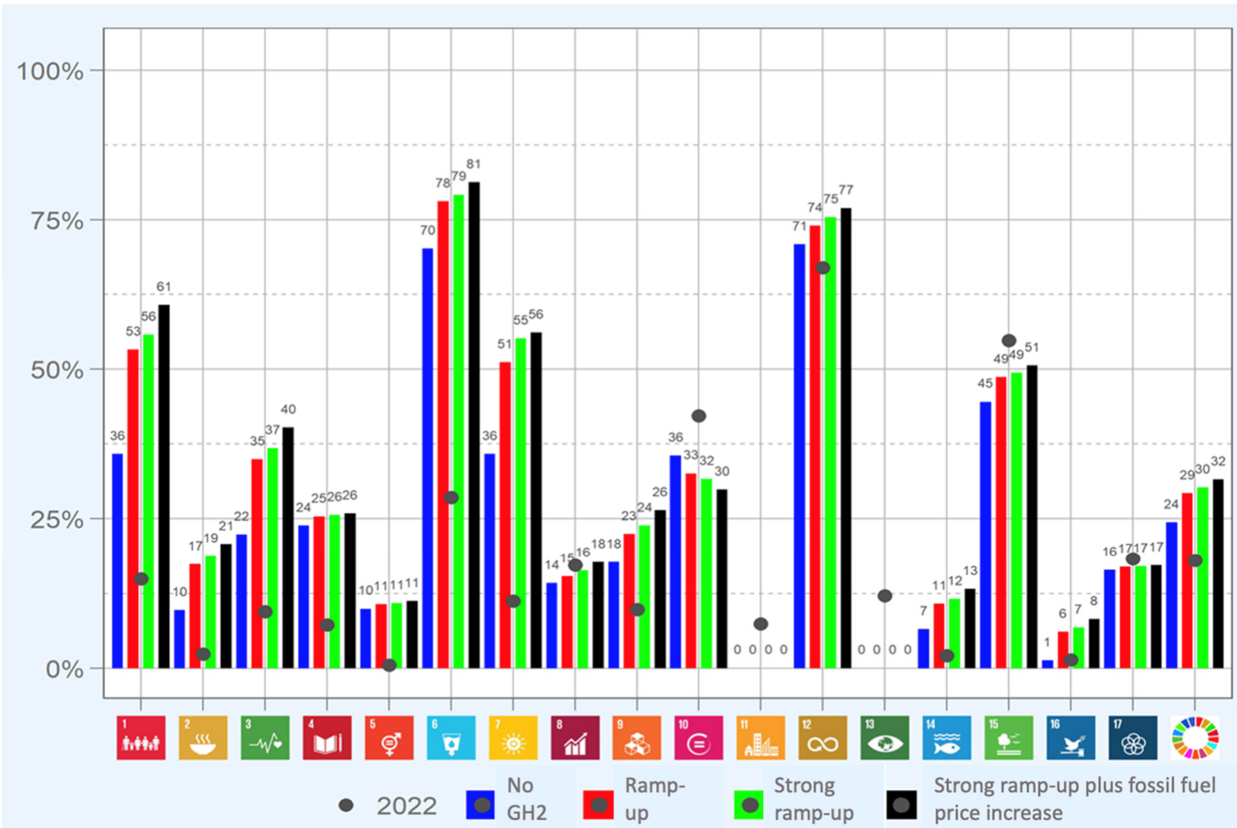

Figure 3 Namibia: SDG attainment in 2050 across different green hydrogen ramp-up scenarios

1. Introduction

1.1 The global need for green hydrogen

Increasing energy demands from the growing world economy continue to contribute to the climate crisis, with increasing impacts being observed globally. Since the 2015 Paris Climate Agreement was adopted, countries have dedicated government policy to decarbonisation and green economy strategies in an attempt to meet the climate goals. Various policies focus on transitioning towards more sustainable, long-term energy solutions that will decrease reliance on fossil fuels as a way of achieving emission targets. However, to ensure a just transition it is important to keep economic and societal goals in mind, to guarantee equity in the energy landscape, and to align energy transition strategies with the Sustainable Development Goals.

Complying with the Paris Agreement requires decarbonisation of energy systems and greener economies. Various countries are proactively testing renewable energy solutions to develop alternative fuels. This includes increases in energy efficiency, electrification, renewable energy and renewable Power-to-X (PtX) applications. Global interest in green hydrogen (GH2) has become of particular interest considering its characteristics and technological developments, which seem to be adequate to power those economic sectors where emissions are hard to abate. Moreover, climate challenges and energy shortages during recent unstable political circumstances emphasise the vulnerabilities of the energy system and highlight the potential of more sustainable alternatives. It has been estimated that global hydrogen demand could reach 510 million tonnes per annum, with ~60% derived from renewable sources (IEA, 2021), replacing conventional fuels, particularly in transportation and the industrial and agriculture sectors. The interest in ramping up green hydrogen economies is growing across the world, with some countries holding the potential to become hydrogen exporters, while others with fewer resources may look to import from partnering countries.

This is particularly true for countries with high energy needs or limited land area or where the potential for renewable power capacity is restricted. These countries are therefore aiming to set up strategic partnerships to co-develop trade routes. This is particularly true for the German Government which, since the publication of its National Hydrogen Strategy (BMWI, 2020), has used funds from the economic stimulus package (EUR 9 billion, of which EUR 2 billion in international components) to develop initial funding instruments to gradually close the existing financing gap for industrial-scale GH2 projects. At the other end of the spectrum, Brazil, South Africa and Namibia have endowed renewable energy sources that will allow lower prices for renewable power, which is the single most important factor in bringing hydrogen production to the required level for widespread adoption.

1.2 What do GH2 and Power-to-X mean?

GH2 is specifically produced through the process of electrolysis powered with renewable energy sources. This process splits water molecules into its constituent elements – oxygen and hydrogen – without emissions.

The type (colour classification) of hydrogen is based on the source of energy that is used to produce it. Today, the most widely used hydrogen is typically produced from natural gas (grey hydrogen) or from coal (black hydrogen). One of the proposed solutions to avoid the associated CO_2 emissions is to produce hydrogen from fossil fuels but with the addition of carbon capture and storage technologies (blue hydrogen). Nevertheless, the need to move from fossil-fuel dependency has stimulated more interest in GH2 which is produced using renewable energy sources with zero emissions. This is the reason that this solution is the one that holds the most significance for decarbonisation.

Power-to-X (also known as PtX or P2X) is a collective term for conversion technologies that turn electricity into carbon-neutral synthetic fuels, such as hydrogen, synthetic natural gas, liquid fuels, or chemicals. In the case of GH2, renewable energy is the power source and hydrogen is the energy carrier. However, despite its energy density, hydrogen presents problems when it comes to handling, storing, and transporting it across long distances. For this reason, combining it with other components to produce hydrogen-based liquid fuels has been identified as the way forward for technological progress. Hydrogen is therefore the core PtX energy carrier, serving as the input for the production of synthetic fuels. Hydrogen can be further synthesised and combined with other feedstocks such as CO_2 (sourced from fossil fuels or renewables) or nitrogen to produce liquid fuels including methanol, synthetic diesel, or industrial chemicals such as ammonia. The resulting products can then be used to enhance decarbonisation in 'hard-to-abate' sectors of the economy.

Today, hydrogen is mainly used in oil refining and in the production of ammonia, but its properties hold potential to further progress energy transformation. It also offers additional advantages: it can be used to store and distribute renewable energy, to increase grid resilience by balancing fluctuations in power generation, and to power various end-uses in industry. The GH2 economy, however, consists of a complex value chain which not only involves production, but also storage, transmission, distribution, and application in a variety of forms and contexts.

1.3 Challenges

Global obstacles for GH2 uptake include the costs, particularly those associated with the supply of renewable electricity and electrolyser manufacturing costs, as well as the technology and regulatory readiness levels for the different GH2 products. To date, the levelised cost of hydrogen remains higher than traditional, fossil-fuel based alternatives, with hydrogen costing USD 5–6/kg as compared with USD 1–2/kg for fossil fuel alternatives. However, we are now seeing significant cost declines as renewable energy supply becomes widely available with costs as low as

USD 0.06/kWh in 2021 for solar PV in the European Union (EU) as stated in IRENA's Renewable Power Generation Costs (IRENA, 2021). Similarly, technological innovation is expected to bring down the costs associated with electrolysis infrastructure. Additional challenges include costs associated with storing and transporting hydrogen, particularly over long-distances for export, not to mention speculation regarding safety standards. Even at lower production costs, measures to increase the cost of emissions will be needed to enable green alternatives to compete against fossil fuels that are readily available for extraction though limited in long-term supply. To facilitate a transition from fossil fuels, policies such as carbon taxation will be necessary to make traditional fuels more costly over time.

This requires an evaluation of the costs in relation to the supply and demand dynamics and of the various elements associated with the sustainability of the hydrogen economy, taking care to maintain and boost economic growth, increase social welfare, and decrease environmental impacts. Therefore, evaluating an effective ramp-up strategy requires an analysis of the various stages in the GH2 value chain to identify potential barriers as well as areas of leverage that can support successful uptake. From a national planning perspective, this requires measuring how different stages of the ramp-up can contribute towards the national Sustainable Development Goals (SDGs).

1.4 Study objectives

The overarching goal is to contribute to the SDGs with a PtX economy in the partner countries (Brazil, South Africa and Namibia), with a special focus on SDG 7 (Affordable and clean energy), SDG 8 (Decent work and economic growth), and SDG 9 (Industry, innovation and infrastructure). The aim is to design activities in such a way that the contribution to the SDGs is increased, synergies are created, and trade-offs are minimised. For this purpose, GIZ commissioned this study by the Millennium Institute (MI), a non-profit research organisation with expertise in employing systems thinking and system dynamics methodology to design strategies that lead to measurable progress in wellbeing and sustainability transitions.

To do this work, MI builds integrated simulation models that make it possible to test different strategies and their impacts on the economy, society and environment. The standard model, the Integrated Sustainable Development model (iSDG), is a policy simulation tool designed to help policy-makers and planners make sense of the complex web of interconnections between the 17 SDGs. Unlike static indicators, databases and indexes that provide a measure of where a country stands, iSDG focuses on the dynamic interactions within the SDG system to reveal the best paths and progression towards achieving their SDG targets. By analysing synergies and trade-offs, the models provide MI with the necessary information to identify and recommend cost-effective policy interventions to improve sustainability performance. A detailed explanation of the iSDG model is provided in the report's Annex.

For this analysis, MI expanded and adapted the iSDG model to include a GH2 sub-model (or module) in the country's production structure and linked it to the other sectors in the model, where potential impacts have been identified. The model can be used to simulate various scenarios and assess the key factors in achieving a sustainable GH2 market and its contribution to the Sustainable Development Goals (SDGs). It can also identify existing barriers to a sustainable hydrogen economy and evaluate what measures are needed to overcome these barriers (in terms of financing, regulations, natural resources, renewable energy capacities, jobs).

The overall analysis draws conclusions on how to harness impact potentials (e.g. on various SDGs) that exist in the different countries, for example how the energy transition can be advanced and how local stakeholders can benefit from the economic development (**Table 1**). The results are illustrated by means of the model's interactive user interface.

Table 1 Key connections between green hydrogen development objectives and the United Nations Sustainable Development Goals (SDGs)

Green hydrogen objectives	SDGs
Reduce inequality, poverty and unemployment	1 NO POVERTY; 2 ZERO HUNGER; 10 REDUCED INEQUALITIES
Increase energy security and provide energy stability	7 AFFORDABLE AND CLEAN ENERGY; 11 SUSTAINABLE CITIES AND COMMUNITIES; 10 REDUCED INEQUALITIES
Reduce greenhouse gas emissions for a cleaner environment	3 GOOD HEALTH AND WELL-BEING; 7 AFFORDABLE AND CLEAN ENERGY; 13 CLIMATE ACTION; 15 LIFE ON LAND
Stimulate foreign and domestic investment	8 DECENT WORK AND ECONOMIC GROWTH; 9 INDUSTRY, INNOVATION AND INFRASTRUCTURE
Boost economic growth	8 DECENT WORK AND ECONOMIC GROWTH
Reduce capital outflows through the export of green hydrogen and derivatives	8 DECENT WORK AND ECONOMIC GROWTH; 12 RESPONSIBLE CONSUMPTION AND PRODUCTION
Enable regulatory frameworks	17 PARTNERSHIPS FOR THE GOALS

2. Methodology summary

2.1 Stakeholder engagement and data collection

During the model conceptualisation phase, workshops with local stakeholders in Brazil, South Africa and Namibia were organised to engage with the different players (public sector, private sector, scientists and engineers) to include their views on the GH2 ecosystem and the key elements for its sustainable market ramp-up. The aim was to understand the government plans, investment strategies, expectations in terms of production costs, and country specificities in terms of resource availability (land, water, skilled workforce, renewable power, ancillary infrastructure) as well as perceived challenges. The different players were encouraged to provide their views on the key constraints to a GH2 market ramp-up, as well as the socio-economic benefits of the GH2 market. Additional information on the stakeholder engagement process is available in a supplementary report available upon request.

In parallel, historical data was collected to calibrate the core iSDG model for each country in the analysis (see Annex). Building a comprehensive database is a compulsory step in building a model capable of reproducing the country's observed behaviour and hence to ensuring confidence in the model results.

2.2 Modelling process

During the modelling process, a specific GH2 module (or sub-model) was built and calibrated to reproduce expected technological progress, driving costs down to around USD 1/kgH_2 by 2050 or earlier. Owing to a lack of GH2 production data, the results remain uncertain, though they are based on expected trends reported in scientific literature and GH2 case studies (International PtX Hub Berlin, 2022).

Nevertheless, this uncertainty does not invalidate the insights provided by this study, as the intention is to evaluate the effects of different GH2 ramp-up scenarios on the performance of the country's SDGs, as opposed to accurately predicting the rate and timing of GH2 production and uptake. In addition, the parameters with a higher degree of uncertainty, such as the rate of technological progress or the global prices for oil and gas, are the same across the three country models, but can be adapted to explore the effects of different parameter values in the model user interface.

Once the GH2 module had been adjusted to reproduce expected cost reduction curves over time it was coupled to the iSDG model. The model is structured to analyse medium-term and long-term development issues at the national level. The iSDG's sectors cover the key social, economic, and environmental development issues, and these sectors are dynamically linked such that the complex, interconnected relationships that drive sustainable development are represented.

The model's comprehensiveness and level of aggregation make it an appropriate tool to support a detailed analysis of alternative government strategies (UNEP, 2014). The analysis itself is not intended to provide a forecast, rather to improve policy-makers' understanding of the complex inter-sectoral connections that drive attainment of development goals and inform the design of public policies with an integrated perspective. A detailed explanation of the common methodology for model validation and a description of the core model structure is provided in the annex to the report.

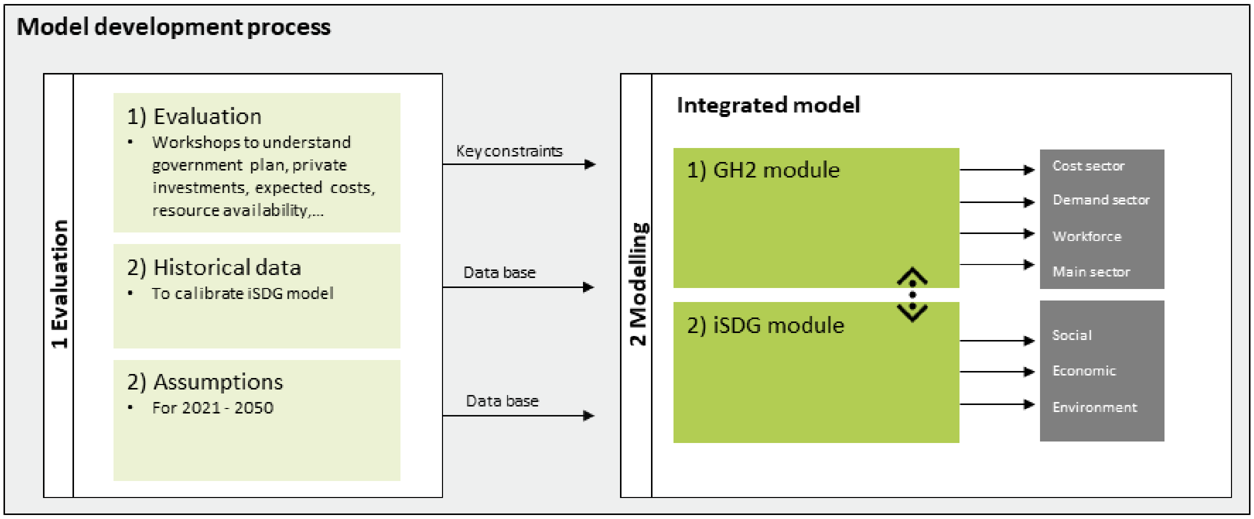

Figure 4 The model development process undertaken to investigate the effects of GH2 on national development goals

2.3 Green hydrogen module

The green hydrogen module is divided into four main sectors: the cost sector, the demand sector, the workforce sector and the main sector, where supply capacity is generated in order to respond to market demand.

The cost sector computes potential green hydrogen production based on the levelised cost of electricity (LCOE) of the country, which has been calibrated to historical values and therefore related future trends. To represent the change over time in capital and operational costs (CAPEX and OPEX), a non-linear asymptotic decay function is used in the model to capture the decline and stabilisation of the costs in time. To further quantify GH2 production costs, additional costs associated with transformation (conversion to PtX applications such as ammonia, synthetic gas or synthetic diesel), short-term and long-term storage and transportation costs are considered, while taking into account the transportation distance from supply countries to Germany. The cost decline rate for all technology-related processes are input values in the model's interface to enable the user to experiment with different decline rates. The behaviour over time of technological development is difficult to forecast in the absence of long-term historical cost data. Nevertheless, it is reasonable to assume that expected reductions depend on investment in research. With this structure, two different costs are obtained: a cost for the domestic market (GH2 production cost + transformation cost + short-term storage) and a cost for the international market (domestic cost + transportation + long-term storage costs).

In the model, GH2 demand is generated using a two-step process. First, the model computes what uses in the domestic economy could be replaced by GH2 or PtX products (potential demand based on technical substitutability); this then affects the price of GH2 and PtX declines. To decide when the price is adequate for a potential use to adopt the GH2-based solution, the model compares costs to the fossil fuel or grey alternatives, with varying levels of intervention in the form of carbon taxes, based on the government's climate ambitions.

While the price is not yet sufficiently low, the rate of adoption by first movers stimulates potential demand. This process captures the dynamics of the companies making early investments because they foresee much higher benefits in the near future. Lastly, a network effect increases the adoption rate, as seen in other technological development processes, where more players adopt a product when they see others doing so. The network effect is further affected by the regulatory strength available in the country, represented by the average adoption time.

A similar structure is defined for international markets but, as it is difficult to project global market shares in the future (since this would require a comparison between international competitors), the model computes an export fraction that increases as prices become more attractive. Once potential demand has been calculated, the model compares it with current supply. If the supply is close to full satisfaction of demand, the cost mark-up to compute the prices declines, since the model assumes there will be more competition. On the other hand, if the prices are much lower than the fossil fuels-based alternatives, the cost mark-up will rise to take advantage of the opportunity. These mechanisms lead to price computation from production and distribution costs and therefore the sector's turnover and revenues. It is then assumed that a share of the profits is reinvested into the sector to increase production infrastructure. The higher the return on capital, the higher the reinvestment fraction. Again, the model considers certain investments linked to pioneering projects or linked to the potential demand.

The production infrastructure equations consider infrastructure investments in production facilities under construction and facilities in operation, with a certain average construction time between the two stages. The model therefore accounts for the total staff needed for each one of the development phases as well as the time needed for a new worker to become an experienced one. The number of workers being hired depends not only on the total staff needed but also on the sector’s attractiveness, calculated from a ratio that measures how the sector’s initial wage level compares to the average wage level of the industrial sector, as well as on a factor dependent on the sector's perceived risk.

2.4 Scenario development

To analyse the effects of the potential GH2 market ramp-up the following scenarios were defined:

1. A baseline scenario with an inactive GH2 module. This scenario sets the country's performance in terms of SDGs without considering any investments in the GH2 sector. This may serve as the business-as-usual (BAU) scenario with no consideration of the effects of GH2.

2. A baseline with organic GH2 growth. In this case, investments occur at the current stated growth path, with zero interventions. This is the real reference scenario for the countries where investments have started to flow into the GH2 economy because it reflects the current commitments in terms of investment.

3. A ramp-up with controllable factors. This scenario attempts to answer the question of what would happen if investments were boosted and first movers efforts lasted a longer period of time.

4. A ramp-up in the context of uncontrollable factors of some kind. This last scenario attempts to capture what would happen in the case of a fast rise in fossil fuel prices, which may seem good for GH2 price adequacy but may put the rest of the economy under stress.

These four scenarios have been captured through different parameter changes that are country specific and therefore described in each dedicated section.

2.5 Model limitations

Models are reliant on underlying assumptions and data. The assumptions in this model are based on those obtained from conversations with stakeholders, as well as from scientific and grey literature. The model outcomes in terms of SDG performance are based on country-specific data sources supported by a rigorous model calibration and validation process (see Annex on iSDG methodology). However, any model is subject to boundary limitations. In this analysis, the model boundary is limited to the evaluation of green hydrogen and omits other forms of hydrogen, including the transition and associated delays from grey to blue and blue to green hydrogen. The model fails to consider the effect of green hydrogen on the price of end-use products. Furthermore, the level of SDG attainment is subject to the degree of measurability and data availability for different indicators. Nonetheless, considering these limitations, the model intends to capture the rate of change of the green hydrogen ramp-up under the pre-defined investment and policy scenarios and also to capture the knock-on effects on a country's SDGs. Future research may include adapting the model structure to address its limitations and testing alternative model scenarios, which can additionally be performed using the online interactive interface.

References

IEA, WEO, 2021. International Energy Agency, World Energy Outlook 2021. Available at https://www.iea.org/reports/world-energy-outlook-2021

NWS, BMWI, 2020. The National Hydrogen Strategy. Available at: https://www.bmwk.de/Redaktion/EN/Publikationen/Energie/the-national-hydrogen-strategy.html

IRENA, 2021. Renewable Power Generation Costs. Available at: Renewable Power Generation Costs in 2021 (irena.org)

International PtX Hub Berlin, Training materials, 2022. Available at: https://ptx-hub.org/training

UNEP, 2014. United Nations Environment Programme. The adaptation gap report 2014. United Nations Environment Programme.

3. Model application for Brazil

3.1 Country background

Brazil's strategic position in the renewables landscape is unique and serves as a strategic advantage in the green hydrogen race. More than 80% of Brazil's installed electricity capacity is renewable (ANEEL, 2022), as well as 45 % of its total energy supply (EPE, 2022). The country's tradition in renewable energy goes back to the military regime (1964–1985). Two landmarks in Brazilian energy policies were initiated in 1975: the construction of the Itaipu Dam (the largest hydropower plant worldwide at that time) and the Brazilian ethanol programme. The national biodiesel programme started in 2004. Most cars in the country are flexible-fuel vehicles (FFVs) and a considerable share of such flexible-fuel technologies was developed in the country (ANFAVEA, 2022). Research to develop hydrogen FFVs has already started (UFMG, 2020).

The national interconnected system is a continental-scale electricity network that comprises 175,000 km of transmission grids (ONS, 2022). For comparison: Germany's transmission grid is about 35,000 km long (BMWK, 2022). The national system operator (ONS) is a highly digitalised organisation that measures multiple aspects of the national grid in real time, such as energy balance, production, load and demand. Such a level of digitalisation allows market actors to have detailed information about the energy they supply or receive, which also facilitates the creation of different types of energy contracts. Experts interviewed for this study mentioned the possibility for electrolysis operators to buy part of their energy from the grid as a way to hedge against local load variations.

Between 2011 and 2021, the centralised installed capacity of wind and solar grew from 1,300 to 25,000 MW (ONS, 2022). Wind capacity is set to grow an additional 13,000 MW by 2025 (ABEEólica, 2022). Nevertheless, the industrial policies adopted for each of these sources differed greatly. The case of wind is considered a success in terms of building up a national industry, while photovoltaic solar is a much more globalised hardware market, with most of the equipment being imported from Asia and installed directly in distributed generation systems.

A political consensus on green hydrogen quickly developed in the country. During the recent electoral period, members of the main parties spoke of the business opportunities created by the technology (EPBR, 2022). The most cited figure is USD 22 billion, which is the sum of investments in green hydrogen announced in the country in the form of Memorandums of Understanding, mostly in the north-eastern states of Ceará and Pernambuco (Valor, 2021; Estadão, 2022).

The choice of these states is not a mere coincidence. These locations have important synergies with current and projected generation capacity, growing industrial sectors, availability of ports and a shorter distance to export markets. Moreover, both states have lowered taxes on energy trading. However, the distance to the main domestic consumer markets (south-east region) is considerable. Both states are among the driest in Brazil. Interviewees have mentioned that the risk of local drought may potentially lead to pressures to halt exports and cap water use by the green hydrogen sector.

Brazil is a 200-year-old nation with a long history of struggles to minimise commodity dependence. By 2019, about two thirds of the country's exports were commodities, a 10 percentage point increase from the previous decade. In the same period, the participation of industry in GDP dropped from 27 % to 22 % (UNCTAD, 2021). Brazilian industrial policy has not been able to challenge this reality. Oil, mining, pulp and paper are among the main sectors financed by the National Development Bank (BNDES, 2022). Counteracting this trend by replacing outdated fossil fuel applications to increase the energy efficiency of the industrial sector – particularly oil refineries and steel mills – is considered an untapped opportunity for green hydrogen (McKinsey, 2021).

Some of the best known strategies to add sophistication to the country's economy consist of subsidising credit to develop downstream activities in the agricultural value chains, such as the attempt to create a national champion in the animal protein sector (Musacchio et al., 2014). Low value-added agriculture, the main exporting sector in the country, is highly exposed to upstream risks such as changing temperature and precipitation patterns (World Bank, 2021). Nevertheless, until the recent global fertiliser crisis, little attention had been dedicated to upstream activities such as the ammonia value chain, which now drives a lot of the expectation around green hydrogen production in the country.

Another challenge is human capital. Although Brazil's workforce has an initial stock originating in related sectors (oil and gas, liquid fuels, electricity etc.), the country's bureaucratic education sector and low quality of basic education are causing delays to upskilling this workforce (OECD, 2018). Although the north-east region is historically disadvantaged in terms of its development trajectory, both Ceará and Pernambuco are among the leading states when it comes to recent shifts in investment in primary, secondary and technical education.

Finally, one of the main issues involving green hydrogen in Brazil is conceptual. Official policy documents in the country employ the concept of low-carbon hydrogen instead of green hydrogen (EPE, 2021). According to experts interviewed, the Brazilian quest to relativise the green hydrogen concept is linked to the idea of maximising the country's strategic advantages. Since Brazil already has a relatively clean electricity matrix, a more relaxed sustainability standard could favour the use of existing capacity, while a more restricted definition is perceived as an instrument to prioritise production from dedicated sources in countries that do not necessarily have such a high share of renewable energy in their national grids. Additionally, interviewees mentioned a concern that investing in dedicated capacity could mean betting too many chips on one technological setup (dedicated wind and solar located near electrolysers and ports for exporting green hydrogen). Policymakers fear this bet could create dependence on green hydrogen exports, considering that green hydrogen might become a global commodity and that this dedicated capacity would not be so useful to the country as other setups could be.

3.2 Case study objectives for Brazil

The rate at which green hydrogen can become an effective energy solution is dependent on a variety of factors that affect the country's level of 'readiness'. Hence, to understand the potential role of green hydrogen in Brazil's decarbonisation strategy, it is important to understand the causal effects of green hydrogen on the energy system at a national scale. As outlined in the National Hydrogen Program (PNH2), the overall goal of the green hydrogen economy is to provide an alternative for sectors where carbon emissions are difficult to abate (hard-to-abate sectors), to enable energy storage and to favour the coupling of the energy sector to the industry and transport sectors. By developing a national green hydrogen strategy, Brazil can support its underlying development objectives in line with its Sustainable Development Goals (SDGs).

This analysis hence aims to investigate the effects of the green hydrogen economy on national goals under different ramp-up scenarios, with a particular focus on the performance of Brazil's SDGs until 2050, using the Integrated Sustainable Development Goal (iSDG) model.

3.3 Model set-up and assumptions for Brazil

A country model was developed specifically for this study, which connects the Brazilian calibration of the iSDG model – a consolidated multivariate model that computes national sustainable development performance – to a customised green hydrogen module. This integrated model has been calibrated with international data sources such as World Population Prospects, World Urbanization Prospects, World Bank (WDI and WGI), UNDP, IMF, WHO, FAO, UNSTATS, UNSD, IEA, EIA, WDPA, USDA, EMDAT, International Resource Panel, Global Carbon Project, What a Waste, Sea Around Us and Barro Lee for the various SDGs targets and indicators. Additional national data sources have been utilised: CNT (National Transport Confederation), IBGE (Brazil's Statistics Agency), SICONFI/STN (Treasury), ONS (National Energy System Operator), ANP (National Oil Agency), CPRM/SGB (Brazilian Geological Agency/Geological Survey of Brazil), ODS Brazil portal. In the technical annex, the levels of error (RMSPE) and Theil's bias of key calibration variables for this model are reported, ordered from highest to lowest, so that the more technically versed reader can develop an understanding of what areas of the model are farther from a perfect fit with the data. The calibration of this particular model, however, is very much in line with the usual quality standards we impose on iSDG country applications.

The tool will allow GIZ and its partner to create their own scenarios utilising a number of input variables to customise the simulations. To demonstrate the capabilities of the tool, we have run four scenarios:

- No GH2. The first scenario serves as a baseline to evaluate model behaviour without the effects from the GH2 sub-model (i.e. there is no exchange of model dynamics between the iSDG and GH2 sub-model during this run).

- Initial ramp-up/ramp-up as announced. This scenario simulates the effect of an initial investment strategy, considering the investments that have already been announced by private actors to be disbursed up to 2030 – mostly in the Ceará and Pernambuco states.

- Strong ramp-up. The third scenario aims to simulate the effects of higher investment and policy control, in the form of carbon taxation on alternative fossil fuel energy sources and tax breaks on green hydrogen products. In this scenario we arbitrarily double the yearly investment rate and make the investment period longer. The adoption time is assumed to be shorter, meaning that the green hydrogen technology diffusion is considered easier. We also assume a gradual carbon taxation (in line with what would be required to limit global climate change – see IMF, 2022 as an example) and national tax breaks for the green hydrogen sector.

- Strong ramp-up with fossil fuel price increase. The final scenario tested in the model captures the effects of the controlled ramp-up, but additionally assumes an external shock in the form of an increase in the price of fossil fuel energy sources.

More information on the changes to the respective model parameters under the scenarios are shown in Table 2. These four scenarios are specifically reported on in the analysis; to create additional policy scenarios, an online model-user interface is available for testing: https://exchange.iseesystems.com/public/millenniuminstitute/giz---effects-on-development-of-a-potential-green-hydrogen-industry-ramp-up.

In Table 2, 'adoption time' refers to the delay between the addressable market that becomes technologically viable over time and the actual adoption of the technology by market actors after factoring in price and network effects. In all scenarios we assume 50 % of the investment is in solar and wind generation and 50 % in electrolysis, logistics and storage. We also assume 10% of the electricity for electrolysers originates from the national grid as a way of hedging, as mentioned in the interviews. We adopt a non-linear declining electrolysis CAPEX and OPEX for all scenarios (Bloomberg NEF, 2022), as shown below. The only computation performed by the model on top of our cost assumptions is the slight effect of water scarcity on both CAPEX and OPEX. We assume a declining levelised cost of electricity (LCOE) for solar energy as shown below (IEA, WEO 2021). These are important pre-conditions for the analysis we present in the following sections. Actual occurrence of these pre-conditions does not depend on Brazil only. Most of the technology that has to be developed to achieve such parameters requires substantial international R&D efforts in electrolysis, storage, transformation and transportation.

Table 2 Parameters' values for the scenario definition for Brazil

	First movers' investment magnitude (real BRL/year)	Adoption time (years)	End of first movers' effort (date)	Target carbon tax (USD_{2010}/t CO_2 eq.)	Profit tax break (fraction of profits)	Infra-structure tax break (fraction of expen-diture)	Fossil fuel price (USD/MWh) [oil; gas; coal]
No GH2	0	NA	NA	NA	NA	NA	Stable
Ramp-up	BRL 12.8 billion/year	5	Dec 2030	NA	0	0	Stable
Controlled ramp-up	BRL 25.6 billion/year	2.5	Dec 2040	80	0.1	0.1	Stable
Controlled ramp-up with fossil fuel price increase	BRL 25.6 billion/year	2.5	Dec 2040	80	0.1	0.1	Increasing [36; 14; 6]

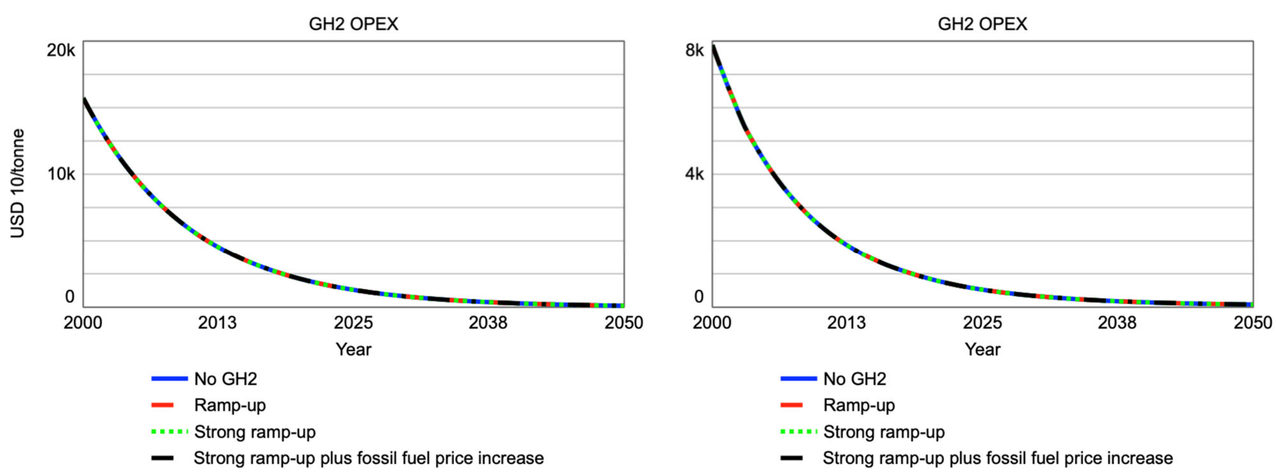

Figure 5 Brazil: OPEX and CAPEX expected evolution

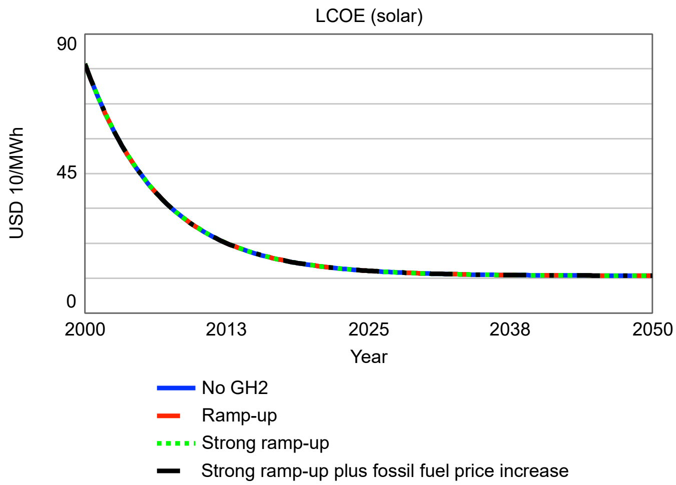

Figure 6 Brazil: LCOE based on solar PV's assumed evolution

3.4 Brazil's GH2 model results

The levelised cost of green hydrogen (LCOH2) was computed from CAPEX, OPEX and electricity prices including grid electricity ones. For the case of Brazil, a fraction of the electricity, set to 10 % by default, may be coming from the grid via power purchase agreements with national energy system actors, as was mentioned in the interviews. Across the different scenarios, the LCOH2 is projected to be around USD 2,100/tonne by 2030 and USD 1,100/tonne by 2050.

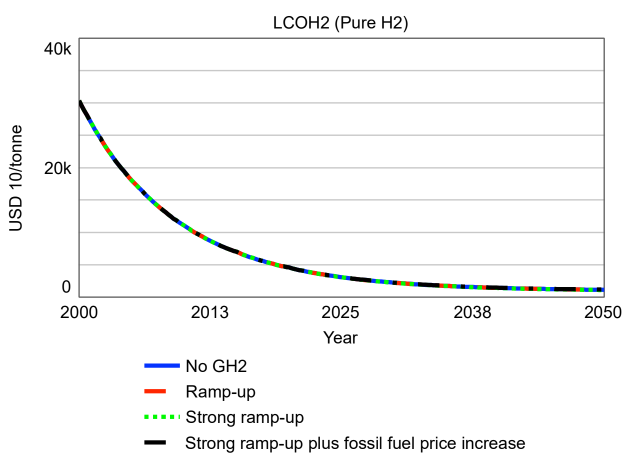

Figure 7 Expected evolution for LCOH2 (pure H2) in Brazil

The green hydrogen sector's contribution to GDP, in terms of its value added, may be as much as BRL 70 billion in 2050 in real terms (referred to as RLCU in the graphs– real local currency units). This corresponds to 1.6% of the projected GDP for the same year in the strong ramp-up with CO_2 price increase scenario. Of this projected sector contribution to GDP, green ammonia is the product that contributes the most (Figure 8). Green hydrogen contribution in terms of direct job creation is projected to be relevant, potentially surpassing 100,000 FTEs (Figure 9).

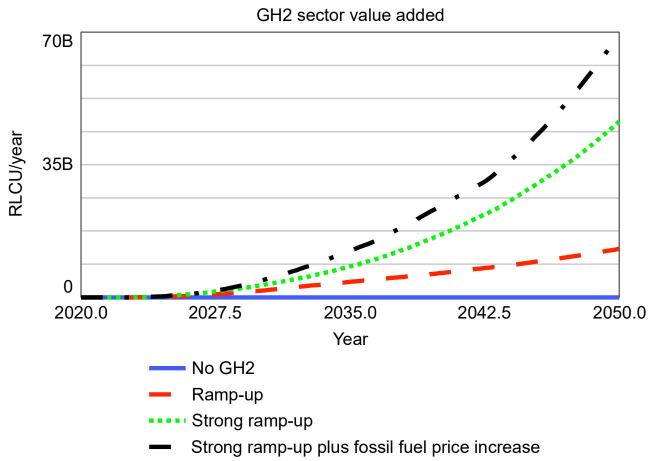

Figure 8 Expected value added by the GH2 sector in Brazil for the different scenarios

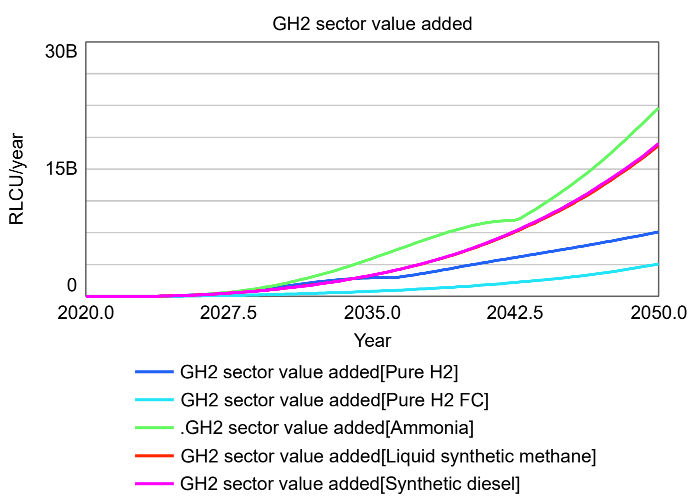

Figure 9 Expected value added per product in the GH2 sector in Brazil in the strong ramp-up with fossil fuel price increase scenario

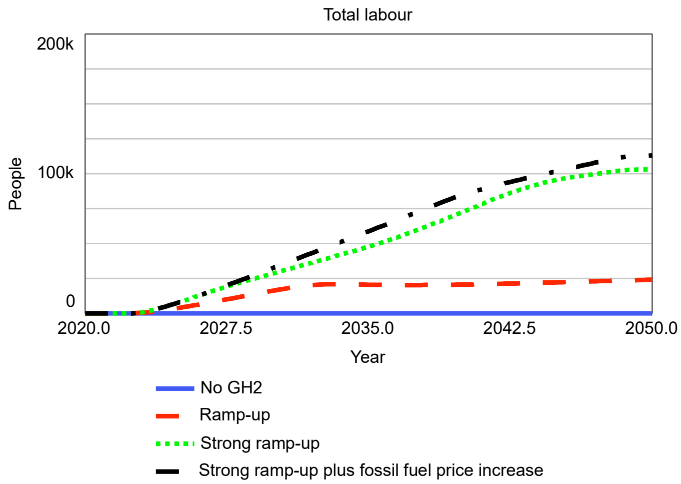

Figure 10 Brazil: Total labour creation projections in Brazil for the different scenarios

Of the five green hydrogen products tested in the model, ammonia is key for Brazil, achieving up to BRL 22 billion in value added (Figure 11). It is also very sensitive to fossil fuel prices due to the more direct substitution process. The consumption of green ammonia, projected at 5 million tonnes by 2043 in the two scenarios with strong ramp-up, would be sufficient to completely replace the imports of nitrogen fertilisers by that year.

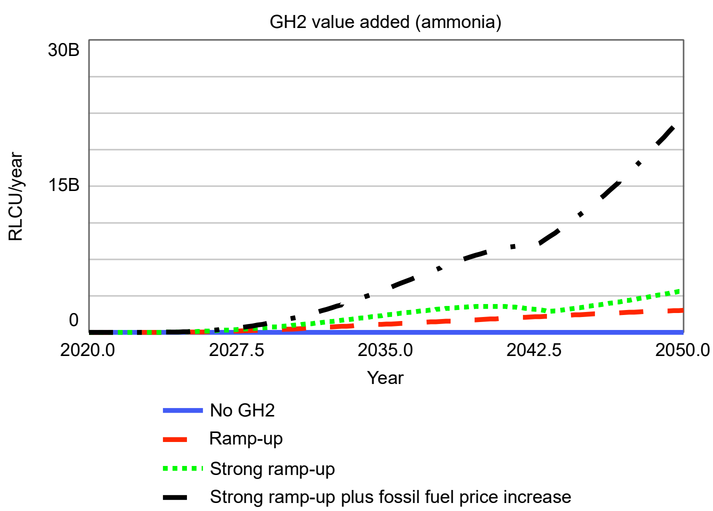

Figure 11 Brazil: Expected value added of the green ammonia sector in the different scenarios in real local currency units (RLCU)

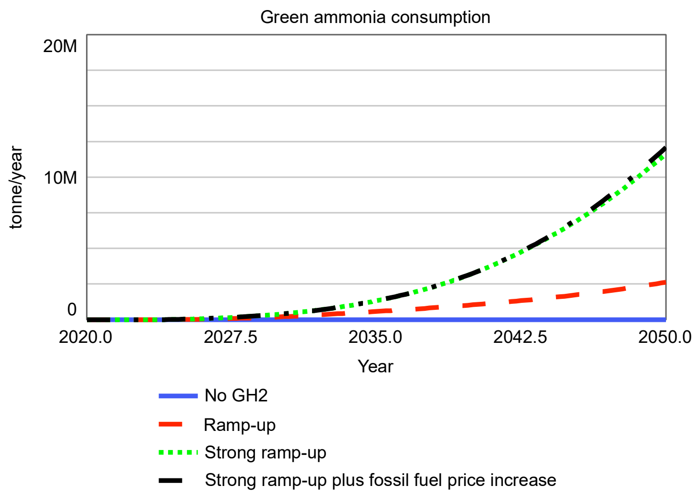

Figure 12 Brazil: Green ammonia consumption projected in the four scenarios analysed

Most of the jobs created by this emerging economic sector are projected to be in operational activities related to green ammonia, from electrolysis and downstream activities. In the strong ramp-up scenarios, installed green ammonia capacity would not peak in the simulation period, while in the ramp-up scenario a peak would happen in the early 2040s. Consequently, the labour needed for the construction of ammonia-focused infrastructure peaks in the early 2030s in the ramp-up scenario. There is also a peak for the strong ramp-up scenarios in the late 2040s, indicating that the installed capacity peak could occur in the 2050s.

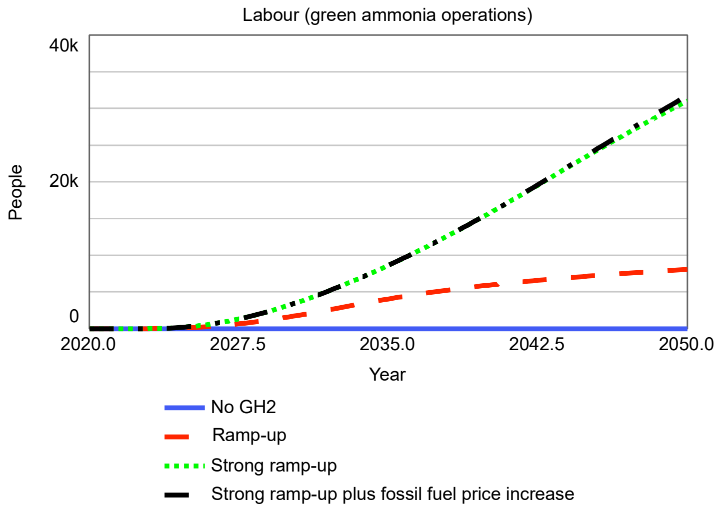

Figure 13 Brazil: Scenario projections for job creation in green ammonia operations

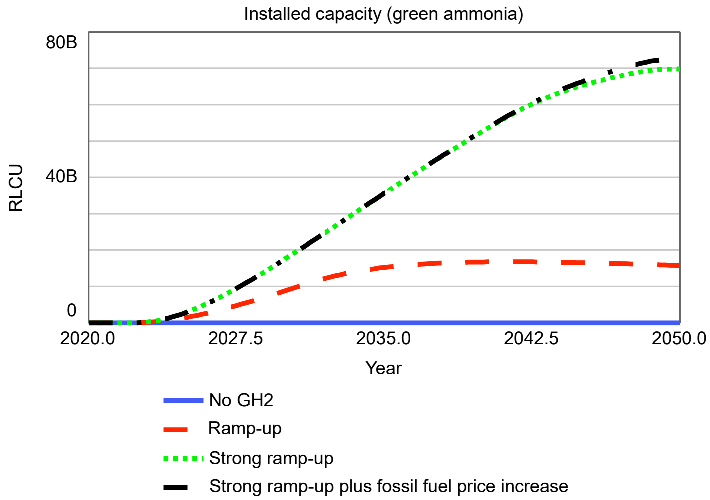

Figure 14 Brazil: Potential installed capacity for green ammonia production

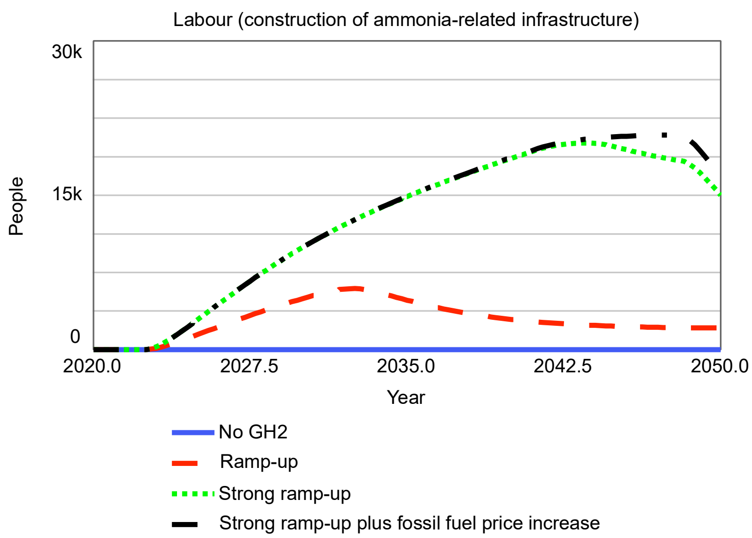

Figure 15 Brazil: Projections for the labour market related to construction of ammonia production infrastructure

A key distinction must be made between the two different investment cycles projected by our model. During the first movers' investment period, investment is arbitrarily defined by the model assumptions. Subsequently, there is an adjustment period in which investment depends on the profitability of the sector and the untapped demand left to be explored. In the strong ramp-up scenarios, the initial investment is not only more intense but also lasts longer. The figure below illustrates how the two cycles play out in the case of green ammonia.

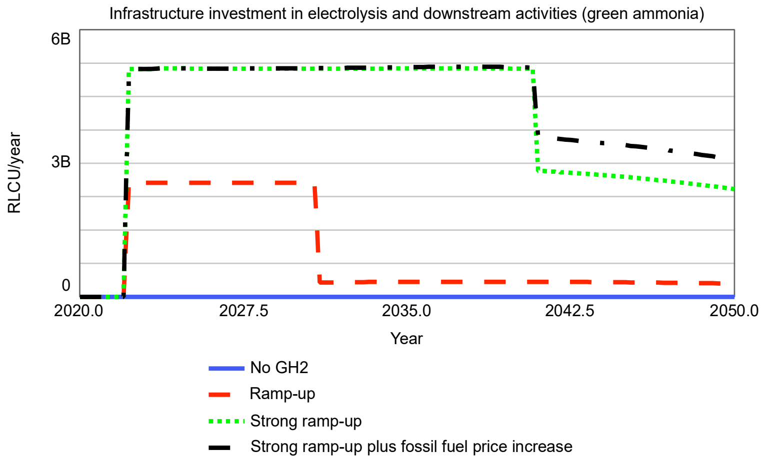

Figure 16 Projections for investment in electrolysis plants and downstream activities dedicated to green ammonia

According to the model, the necessary conditions for exports occur only for green ammonia and only in the strong ramp-up fossil scenario. A key limitation of this study is that we consider domestic consumption as the key purpose of green hydrogen production. A model to analyse the competitive strength of each country compared to its peers in the global markets would have to follow a different approach. For example, the dynamic computation of total demand for green ammonia is performed from the projected domestic use of nitrogen fertiliser (from the soil and agriculture sectors of Brazil's iSDG model). Price adequacy is then computed based on a comparison with traditional products, together with a computation of network effects. The addressable demand is therefore computed from the total demand, considering price adequacy and network effects. In the case of fuel cell H2, synthetic methane and synthetic diesel, the total market is defined by the projected energy consumption from the different economic sectors in the iSDG model. In the case of pure hydrogen, the logic is slightly different: we adjust the initial total demand to the projected industry production in the country.

The projected fraction of each product that is exported at each point in time is computed from a comparison between global substitute prices and an export cost that includes not only production costs but also transportation and additional storage costs. According to these criteria, the only product that is projected to be exported is green ammonia (and only in the strong ramp-up with fossil fuel price increase scenario).

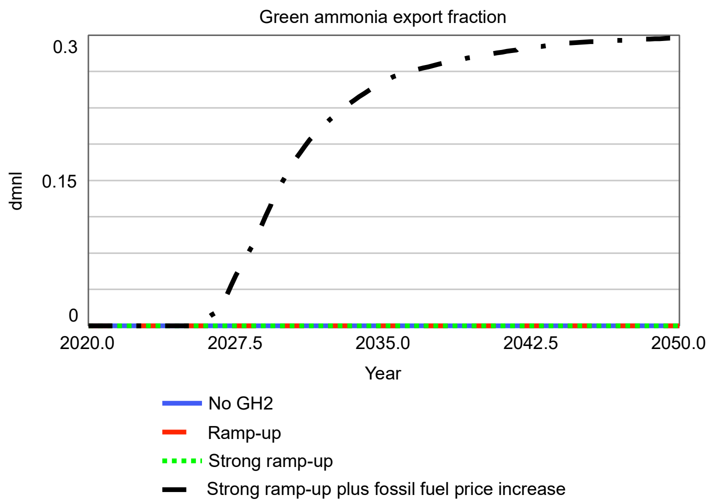

Figure 17 Green ammonia export fraction under the different scenarios considered (Dmnl refers to 'dimensionless', a model unit used for fractions)

Pure green hydrogen for industrial use is the second most important product, but its consumption levels are well below those of green ammonia.

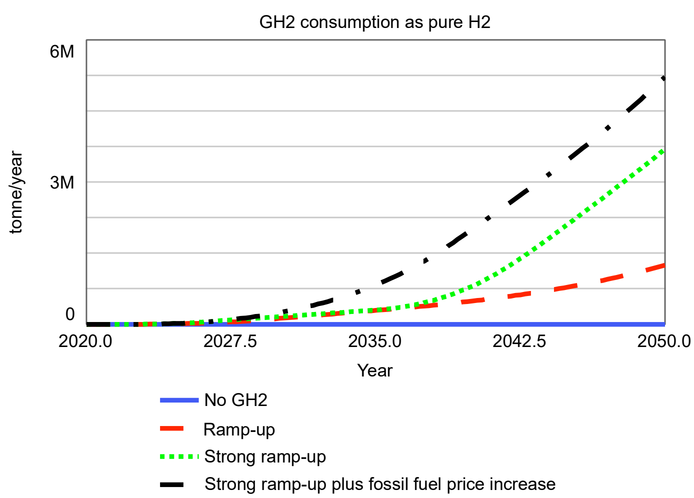

Figure 18 Projections for pure H2 production in Brazil

3.5 Brazil's SDG performance

In this section, we analyse the projected impacts of green hydrogen scenarios on the SDGs. We utilise the indicator structure built into the 2030 Agenda for Sustainable Development – the international framework within which the SDGs originated – to project them until 2050. More detailed projections (per SDG per scenario) are provided in the SDG annex to this report.

The first important observation is that we found no significant support for major SDG trade-offs in the four scenarios. In other words, our model indicates that green hydrogen has no relevant negative impact on any of the SDGs. The positive impacts seem more relevant on SDGs 7 (Affordable and clean energy), 13 (Climate action), 12 (Responsible consumption and production) and 8 (Decent work and economic growth), ordered by magnitude of projected impact (Figure 19). In general, the differences may look marginal, which is to be expected given that green hydrogen is only one industry sub-sector within a large economy (Brazil is one of the 10 biggest economies in the world). For a single sub-sector, a 2% overall increase in SDG performance is considered a very positive contribution.

Nonetheless, Figure 19 below portrays relevant impacts, especially on SDG 7 and 13. The international SDG framework contains some overlaps between SDGs, which we will explain in more detail below. Some of these overlaps have an effect on the results, so it is important to be mindful that not all the positive differences are a direct result of the ramp-up, but rather multiplied by the framework design. The graph shows the difference between each of the three scenarios with green hydrogen as compared to the no green hydrogen baseline.

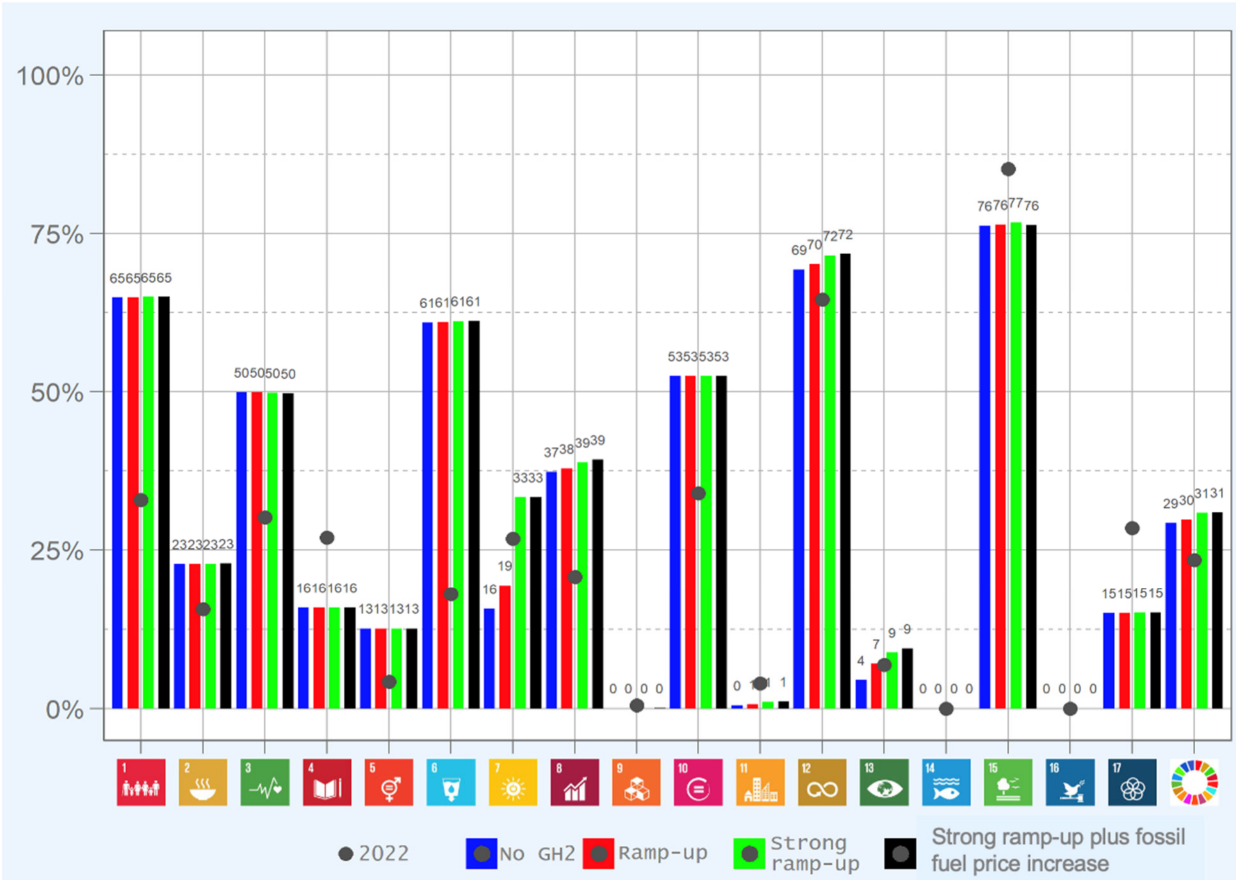

Figure 19 Brazil: SDG performance in 2050 (the black dots represent the levels of SDG attainment in 2022)

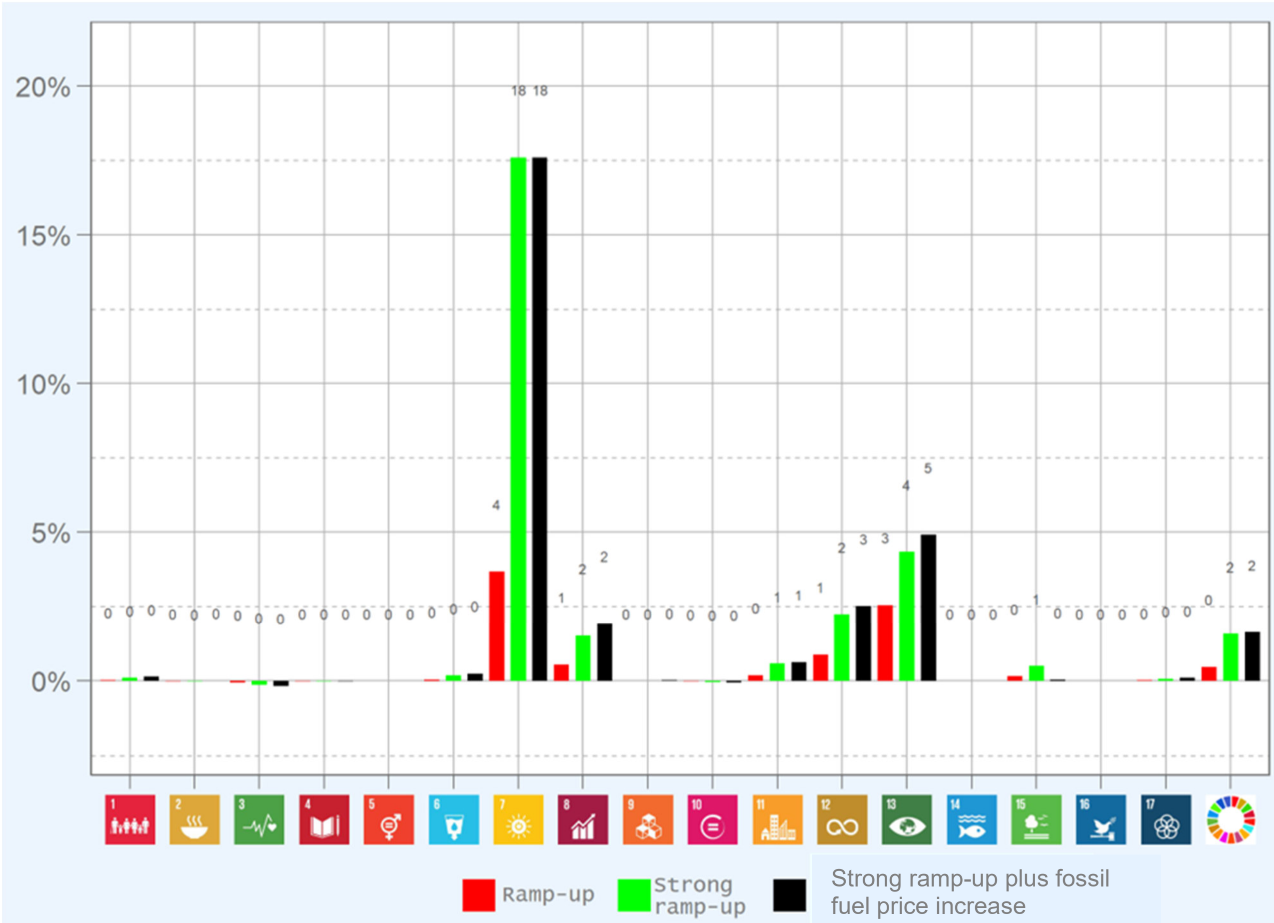

Figure 20 Brazil: Difference in SDG performance compared to the reference scenario (no GH2)

Before we jump into the analysis of the most relevant indicators driving overall SDG performance within the key SDGs, let us describe the main observed impacts on each SDG. It is important to bear in mind that some indicators (within each SDG) are already fully accomplished by the country by the end of the simulation period, which means no further gain due to the introduction of green hydrogen would be possible. For other indicators, the country is too far from even starting to move the needle so that no change across scenarios is observed. Nevertheless, we have analysed all SDGs to understand what is driving the projected changes across scenarios, whether numerically relevant or not.

SDG 1 – No poverty.

The negligible positive impact of green hydrogen is due to a slightly increased performance in indicator 1.1.1 – proportion of population below the international poverty line. This is due to GDP and labour spill-overs, although the positive impacts of job creation are limited by human capital constraints. In most cases, the green hydrogen sector would utilise workforce from other industry sub-sectors that pay similar wages.

SDG 2 – Zero hunger

No relevant difference observed across scenarios. According to our model analysis, the most relevant leverage points are in indicators 2.2.1 and 2.2.2 – prevalence of stunting and malnutrition respectively. Positive impacts on these indicators would depend on a structural change in food production and distribution patterns in the country. Nowadays, the country's crop and livestock production are very much focused on the international commodities market. A mindset shift, favouring nutritious, value-added crops for the domestic market, would be needed in order to amplify the positive effects of green hydrogen on these indicators through increased GDP and employment.

SDG 3 – Good health and well-being

No substantial difference observed. A subtle potential trade-off was identified regarding indicator 3.7.2 – adolescent birth rate. According to our model analysis, this is explained by the fact that recent investment in public basic education per student is already near the minimum threshold needed to discourage unplanned adolescent pregnancies. The addition of a new economic sector would mean that this kind of investment in education would grow (in proportion of GDP) to adapt to other effects of this kind of economic change, such as the perception that households can afford more children, which might overload the underinvested education system.

SDG 4 – Quality education

No relevant difference identified. Potential low-magnitude trade-offs could occur with indicators 4.1.2 – completion rates across the different education levels – and 4.6.1 – literacy – due to education system overload and underinvestment dynamics as described for SDG 3 above.

SDG 5 – Gender equality

No important effect observed. A low-magnitude contribution was observed for indicator 5.5.2 – women in managerial positions, due to the new opportunities created by the green hydrogen sector.

SDG 6 – Clean water and sanitation

A synergy has been identified with indicators 6.1.1 – access to water – and 6.2.1 – access to sanitation. According to the model calibration, a linear response is expected from an increase in GDP, owing to the contribution from green hydrogen, such that government would invest additional resources in water and sanitation infrastructure in proportion to the increase in GDP.

SDG 7 – Affordable and clean energy

As further detailed below, we identified an important contribution of the green hydrogen sector to SDG 7, via indicator 7.2.1 (renewable energy share in total energy consumption).

SDG 8 – Decent work and economic growth

As further detailed below, a relevant contribution was identified through indicators 8.4.1 (material footprint), 8.4.2 (domestic material consumption), 8.5.2 (unemployment) and 8.6.1 (youth not in education, employment or training).

SDG 9 – Industry, innovation and infrastructure

A low-magnitude positive contribution has been identified in the fourth scenario through indicator 9.2.1 (manufacturing value added). It is important to note that the baseline year of Agenda 2030 (2015) plays a key role in determining the country's performance on this indicator. By 2022, the country had already been through a deindustrialisation process as compared to the baseline year, which means this indicator will only become positive again if the manufacturing value added surpasses 2015 levels. This happens in only one of the simulated scenarios. We give details of this analysis below.

SDG 10 – Reduced inequalities

The computation of inequality in the iSDG model is quite complex and involves a series of distributive processes that depend on the output of each sector of the economy, taxation, the way education and health services are distributed across the different population cohorts, and other factors. We identify a low-magnitude potential trade-off between green hydrogen activity and indicator 10.2.1 (population below 50 per cent of median income). This is due to the introduction of a new value-added industry in the country and to the way the benefits of this sector are distributed given the historical and current levels of taxation, which is regressive in the country, and education, which suffers from underinvestment.

SDG 11 – Sustainable cities and communities

A relevant positive contribution of green hydrogen has been observed for indicators 11.6.1 (solid waste management) and 11.6.2 (local particulate pollution). Regarding solid waste management, the reasons are similar to those for SDG 6 described above. According to our country-specific model calibration, we observed that the policy response for solid waste tends to be linear – which means that growth is faster than any proportional rate (in this case, in proportion to GDP and in proportion to solid waste generated) whenever more resources are available and more waste is produced. Regarding particulates, this is related to fossil fuel substitution by green hydrogen in other industrial sectors, including electricity. This is more easily observable when we analyse SDGs 8 and 12.

SDG 12 – Responsible consumption and production

As further described below, a relevant contribution of green hydrogen was identified for indicators 12.2.1 (material footprint) and 12.2.2 (domestic material consumption).

SDG 13 – Climate action
As further detailed below, a relevant contribution of green hydrogen to indicator 13.2.2 (GHG emissions) was identified.

SDG 14 – Life below water
The country's performance on SDG 14 is absolute zero across all scenarios. This is the result of continuous underinvestment in ocean conservation and restoration in the country.

SDG 15 – Life on land
A slight increase in performance in the green hydrogen scenarios is projected due to a difference in indicator 15.5.1 (Red List Index), which relates to biodiversity. An increased availability of resources to protect biomes, combined with lower pollution levels drive this indicator upwards in the scenarios with green hydrogen.

SDG 16 – Peace, justice and strong institutions
No change is observed. It is important to note that we usually do not make inferences about this SDG, as the inbound linkages to the governance sector of integrated models are quite controversial in the specialised literature. In other projects, we often utilise assumptions about quality of governance as scenario assumptions to see their impact on other variables, not the other way around.

SDG 17 – Partnerships for the goals
A low-magnitude gain is projected due to an increased performance of indicators 17.1.1 (government revenue), 17.1.2 (proportion of budget funded by domestic taxes), due to the additional government revenue generated directly by the green hydrogen sector and indirectly by other sectors that become more profitable.

The drivers of change for the SDGs that showed the largest change in performance are further discussed below, along with changes in key environmental and social indicators across the green hydrogen scenarios.

3.5.1 SDG 7 – Affordable and clean energy

The main driver of the improved performance of SDG 7 in the ramp-up scenarios is indicator 7.2.1 (renewable energy share in total final energy consumption). In the scenarios with stronger ramp-up (i.e. investment level doubling), the country would achieve the goal fully by the final years of the simulation, which means it would achieve 100% renewable energy.

Brazil is in a unique position among mid-income countries to achieve this goal, given the country's tradition in renewable energy. According to our model analysis, green hydrogen could play a decisive role in achieving this result. The graph below shows that the ramp-up as announced would already benefit this indicator consistently, driving it above 50% achievement by the end of the simulation period. Doubling the investment would enable full attainment.

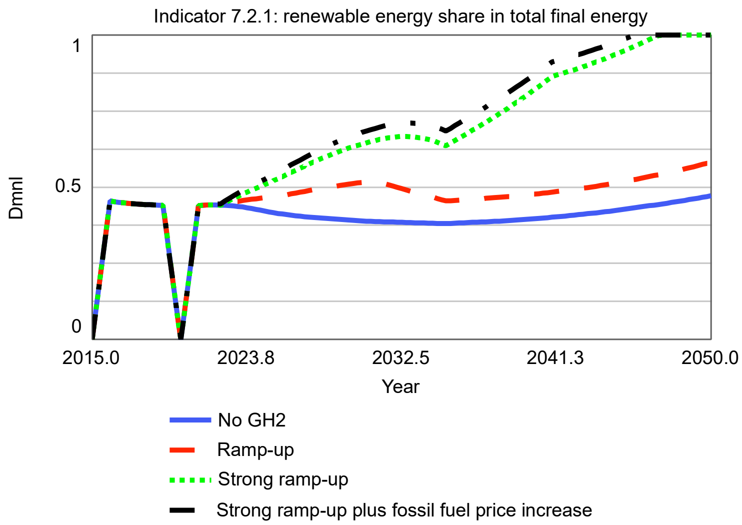

Figure 21 Brazil: Renewable energy's share in total final energy

In the simulated scenarios that include a ramp-up, we project an increase of wind and solar capacity due to the investments made in the green hydrogen sector, as per below:

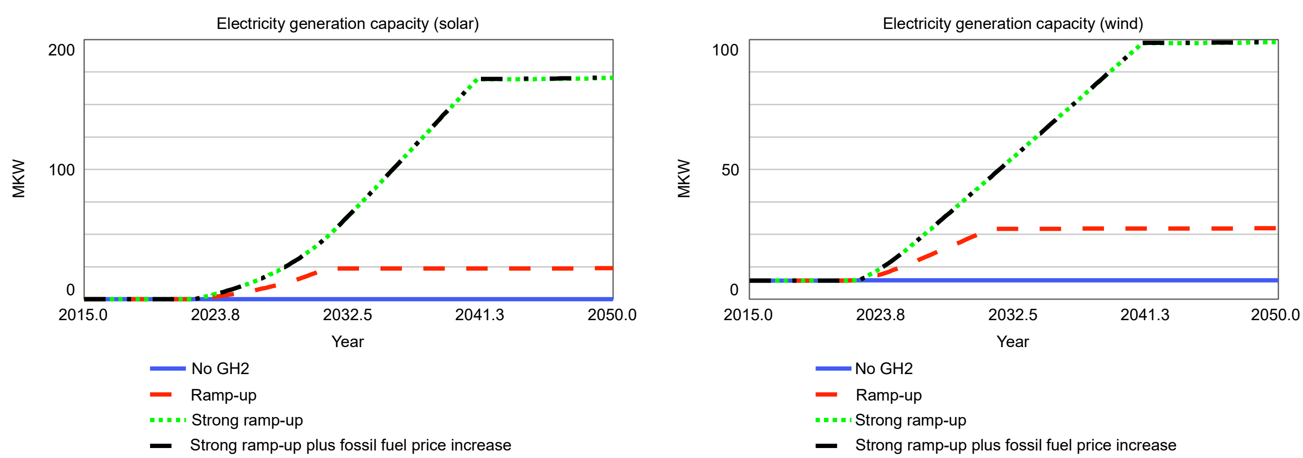

Figure 22 Brazil: Electricity generation capacity for solar and wind under the scenarios analysed

Although there is no projected change in target 7.3 (energy efficiency) compared to 2015 levels, primary energy intensity varies across scenarios, as seen in Figure 23. It means that, although the country as a whole will not improve its performance on energy efficiency as per the SDGs, there is plausible improvement in terms of reduced energy intensity. This means the country's economy is less dependent on energy when green hydrogen is present. In principle, this is a virtuous path where the economy becomes less energy intense, i.e. more competitive and, at the same time, less polluting.

However, there is a risk of rebound effects; economic expansion could partially cancel out the energy efficiency gains and GHG emissions could decrease at a lower rate than expected. But, if technology develops in a way that fossil fuels are replaced in all hard-to-abate sectors, the overall improvement described above does seem a possibility. It would depend on demand-management measures and electrification of the rest of the economy happening in parallel to GH2 development. According to our simulations, the country could achieve a zero-coal energy system in the strong ramp-up scenarios, which is relevant not only for SDG 7 but also for SDGs 8 and 12. This is due to a combination of factors, the most important one being the disproportionate growth in the wind and solar generation capacity driven by green hydrogen, assuming half of the investment is in wind and solar capacity as explained above. According to our simulations, the negative effects on fossil fuel-related employment levels are more than compensated for by the growth in other industrial sectors in the green hydrogen scenarios, meaning the overall effect on labour is actually projected to be positive.

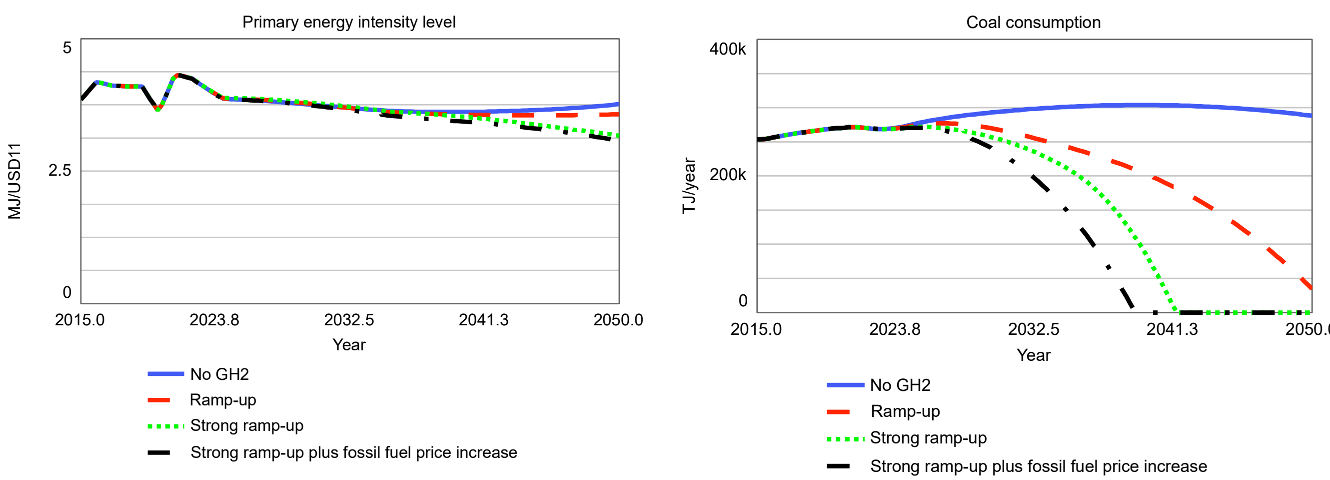

Figure 23 Brazil: Economy's energy intensity and coal consumption projections

In the strong ramp-up scenarios, all the oil and gas consumed by the country would, by the final years of the simulation period, be either for non-energy uses or for export of derivatives, since the energy matrix would be completely renewable. Gas consumption is more sensitive to the growth of green hydrogen and fossil fuel price increase due to a higher substitution potential.

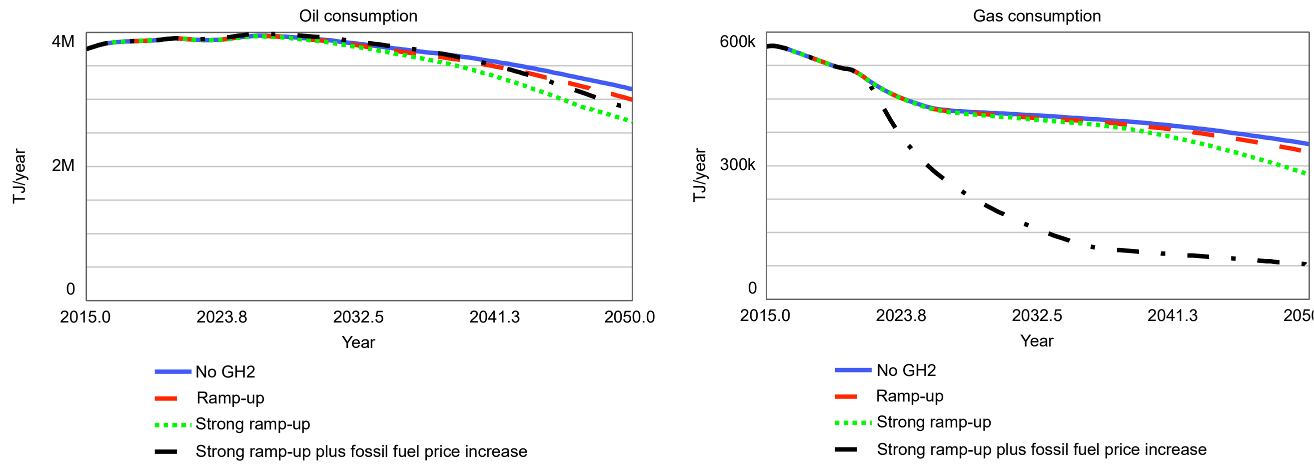

Figure 24 Brazil: Oil and gas consumption projections

3.5.2 SDG 8 – Decent work and economic growth – and SDG 12 – Responsible consumption and production

The two main indicators driving the improvement in progress towards SDG 12 in the country are also indicators for SDG 8 (material footprint and domestic material consumption). This duplication stems from the international framework set by the United Nations. Although the key contribution towards improving the performance on these indicators comes from biomass in all scenarios, the difference between the scenarios is explained by fossil fuels, as seen in the case of SDG 7.

Reading SDG indicators can be a tricky exercise. The names of some indicators denote something negative (e.g. 'material footprint'), but it is important to note that these indicators have been normalised to inform performance. Therefore, the higher the number, the higher the relative performance on each indicator. In other words, the country is performing better in terms of having a lower material footprint and a lower domestic consumption on the ramp-up scenarios as compared to the baseline.

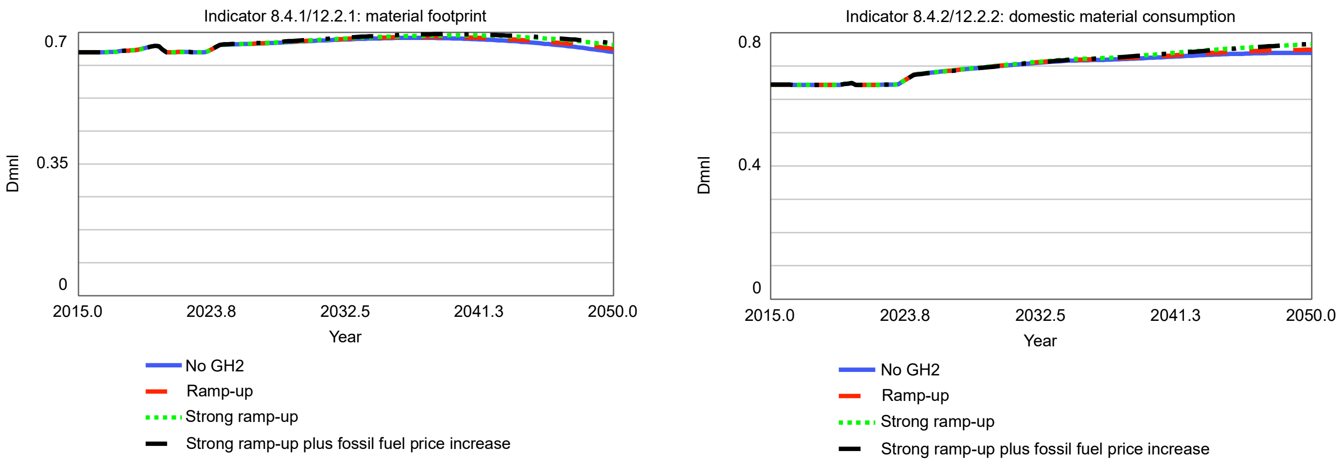

Figure 25 Brazil: Material footprint and domestic material consumption

The country would be closer to eradicating unemployment on the strong ramp-up scenarios, which also contributes to SDG 8, as seen in the figure below showing that Brazil is closer to achieving the ideal state on indicator 8.5.2. This is explained not only by the direct jobs created by the green hydrogen sector (up to 113,000 FTEs in the most optimistic scenario) but also by the spill-overs onto other sectors. Fewer young people would be economically inactive as a result of the new opportunities created directly and indirectly by green hydrogen. We are able to infer this due to the fact that we simulate labour dynamics – which are driven by the different economic sectors, education levels etc. – per age group.

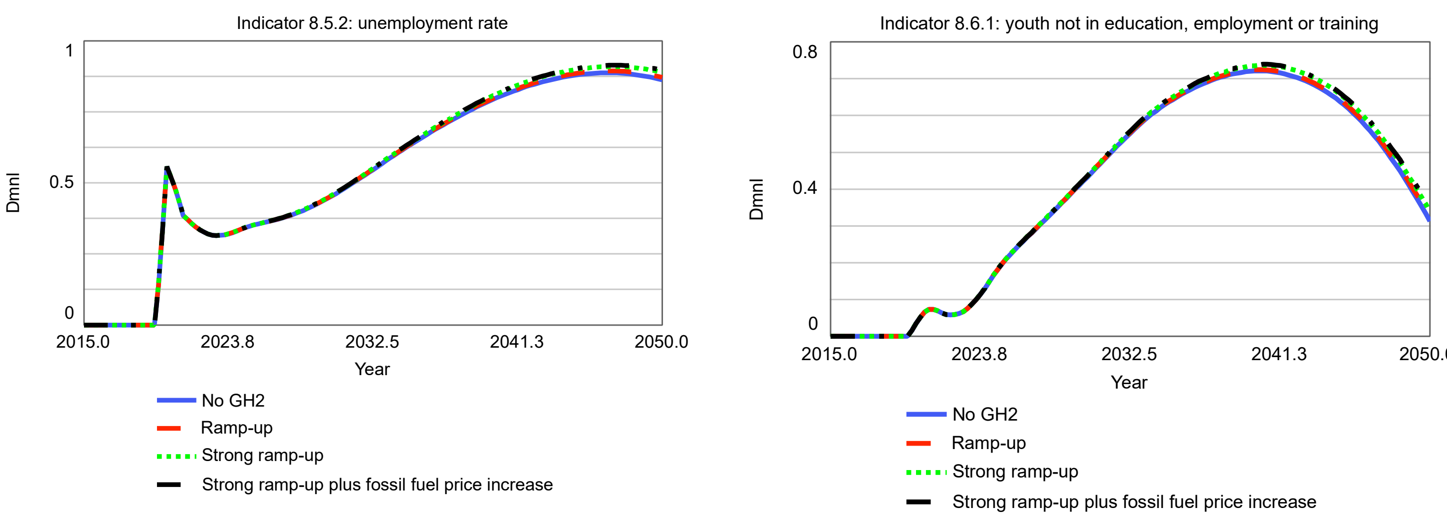

Figure 26 Brazil: SDG 8 indicators

3.5.3 SDG 9 – Industry, innovation and infrastructure – and SDG 13 – Climate action

SDGs 9 (Industry, innovation and infrastructure) and 13 (Climate action) are very much interrelated in the international framework due to the fact that the type of innovation the framework attempts to incentivise aims at decoupling economic growth from greenhouse gas emissions.

In the strong ramp-up scenarios, the country would close almost 20% of its gap to net zero by 2050, whereas in the base case the gap would be reduced by less than 10%, meaning there is a projected contribution in the order of 10% of total GHG emissions as a consequence of green hydrogen in the more optimistic scenarios. It is important to note that we did not consider national emission targets due to poor transparency and a high risk of bias. We would welcome collaboration with Brazilian climate authorities to enhance this exercise.

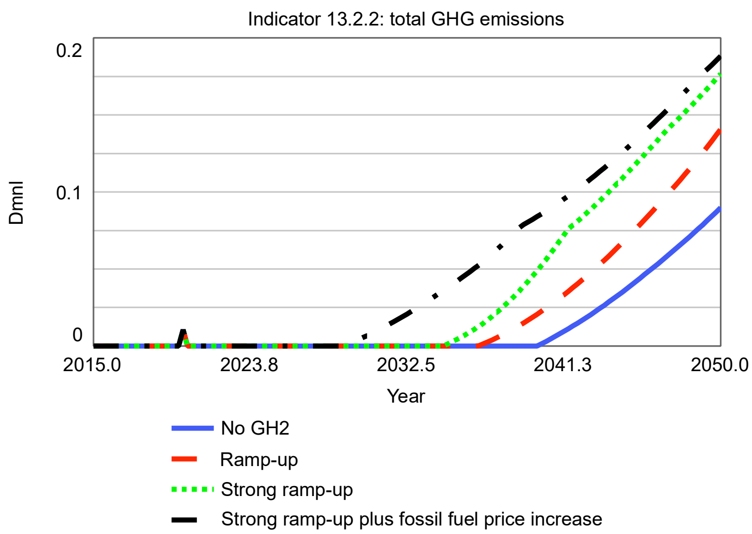

Figure 27 Brazil: GHG emissions reduction indicator

Despite the lack of improvement in indicator 9.4.1 (CO_2 emissions per unit of value added), we can observe differences across scenarios. These differences in CO_2 emissions per unit of value added are not completely explained by additional GDP (the denominator of the equation), which indicates there is a projected economic decoupling in the green hydrogen scenarios, which is very good news for the country and its quest for sustainable development. In other words, this is a sign that green hydrogen can help the country to decouple its economy from greenhouse gas emissions.

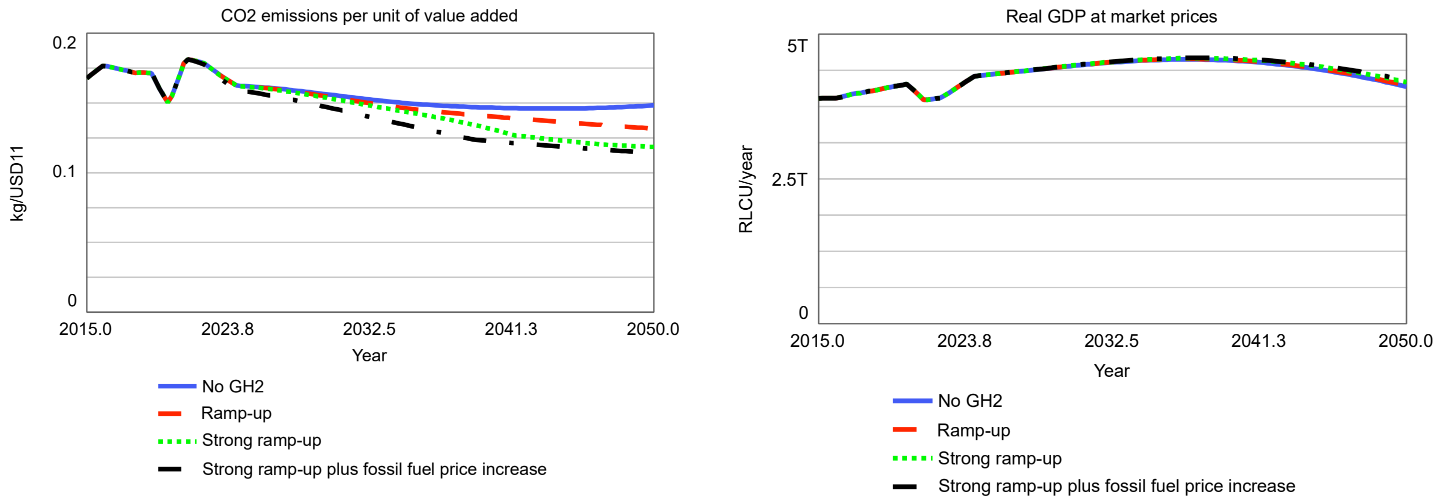

Figure 28 Brazil: CO_2 emissions per unit of value added and real GDP at market prices

Let us now analyse some of the components of the country's GDP in the different scenarios. While agricultural production is basically the same across scenarios, industry varies substantially. According to our model analysis, path dependence in agricultural production is mostly caused by projected climate variations (changing temperature and precipitation patterns), but also by demographic changes (fewer young people in rural areas). The fact that industrial production varies so much across sectors denotes an opportunity for the country to decouple its industry sector from extractive and agricultural activities in the context of green hydrogen. In other words, green hydrogen can serve as a pathway to economic diversification and sophistication.

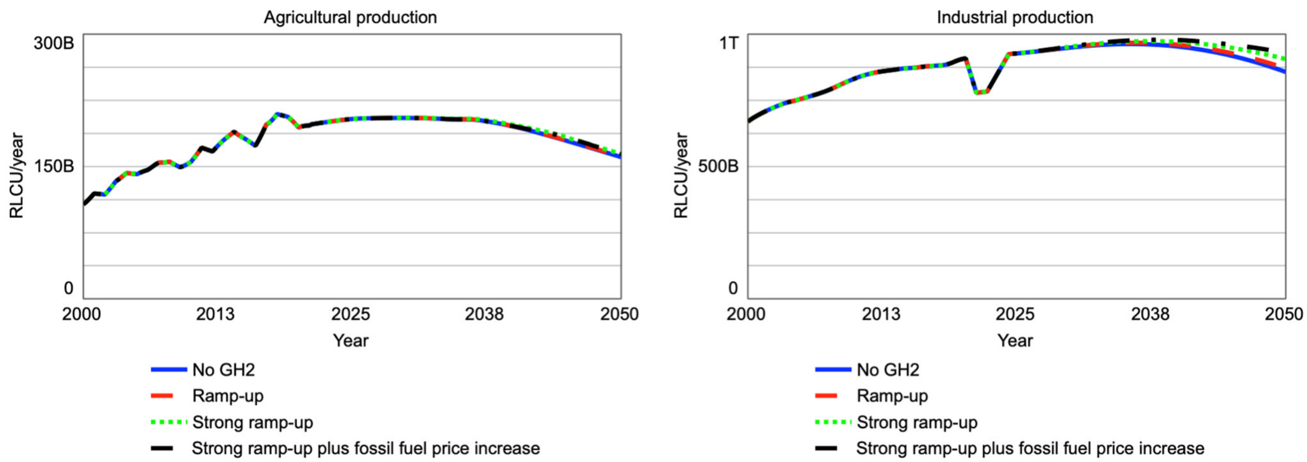

Figure 29 Brazil: Projected agricultural and industrial production

3.5.4 Key environmental indicators

Additional environmental indicators were analysed to assess natural resource constraints. Brazil's position as a country that has near-universal access to water and electricity gives it a comparative advantage compared to other low- and middle-income countries that compete for investments in the green hydrogen sector. As Figure 30 shows, none of the simulated scenarios modify these conditions.

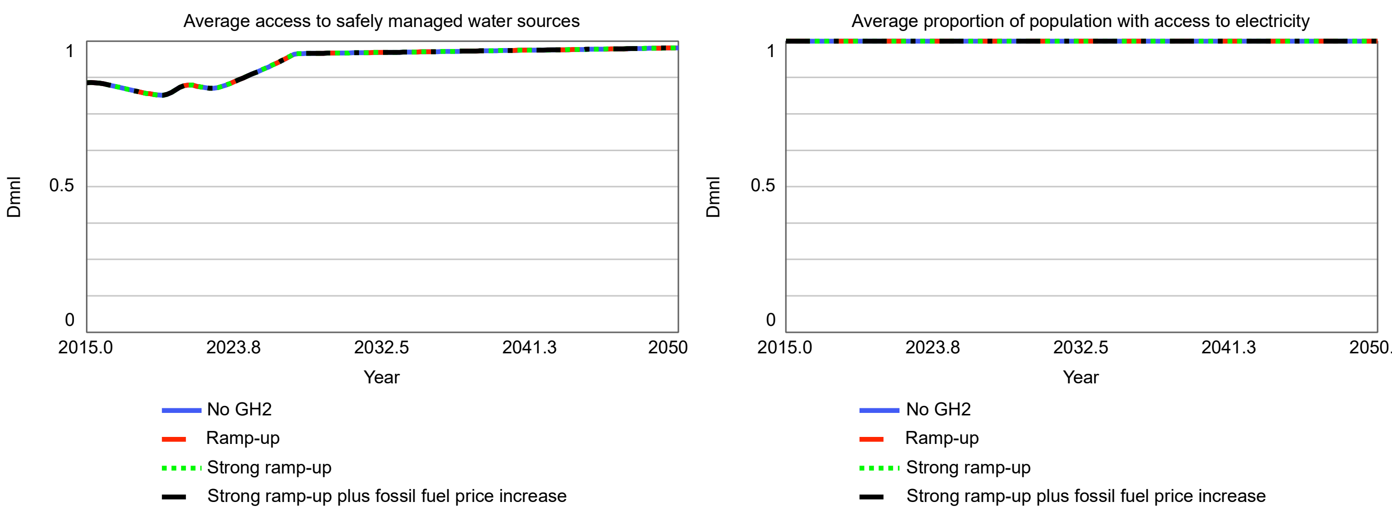

Figure 30 Brazil: Social indicators

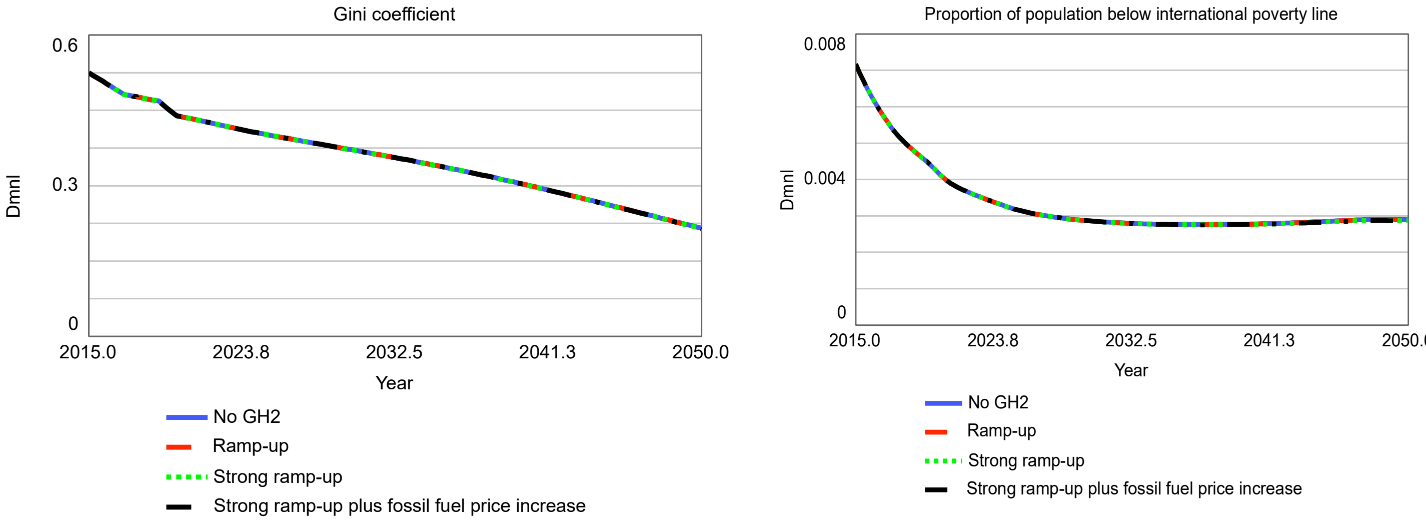

Figure 31 Brazil: Additional social indicators

3.5.5 Key social indicators

One could hypothesise that a GH2 economy might increase inequality, poverty, water or energy scarcity. None of these hypotheses would be supported by our simulations. Although we cannot completely refute such risks, the fact that no support is found by a model which is used by many countries and international organisations to project these exact indicators is noteworthy. Given all the projected gains with regard to SDGs 7, 8, 12 and 13, this result might be interpreted as a validation of green hydrogen as a tool for a just energy transition.

3.6 Key findings and recommendations

By integrating a green hydrogen module into the iSDG model calibrated for Brazil, we found support for increased projected overall SDG performance in the country by 2050 – in the magnitude of 2% towards all targets to be achieved. This is considered a meaningful projected contribution for a single sector of the economy. SDGs 7 (Affordable and clean energy), 13 (Climate action), 12 (Responsible consumption and production) and 8 (Decent work and economic growth) drive this expected performance increase. Moreover, a cut in overall GHG emissions, in the magnitude of 10% of total emissions, can be achieved if a prosperous green hydrogen sector develops.

Job creation is projected to achieve up to 113,000 FTEs in the most optimistic scenario, contributing to minimising unemployment, which could be as low as 6% by 2050. We found no indication that the societal transformations arising from the emergence of the green hydrogen sector would benefit the richer segments of Brazilian society, as no relevant impacts on income distribution or poverty levels are projected by our integrated model.

Our analysis points to a need for increased investment in education, not only to fulfil the needs of the emerging green hydrogen sector, but also to mitigate the risk of trade-off with SDGs 3, 4 and 10 in the context of the chronic underinvestment dynamics in the country.

Investment in climate adaptation, upgrading unpaved roads, reforestation and hydropower capacity (including modernisation of current capacity) seems to be very synergic with investment in green hydrogen according to our model analysis. Slowly declining subsidies to green hydrogen itself and fertiliser production in the country might help smooth the transition when the first cycle of investment in green hydrogen ends.

Finally, we recommend a multi-country modelling effort be conducted in order to consider competitiveness aspects that are not captured by single-country modelling.

3.7 Technical annex: calibration performance

When calibrating a model, it is necessary to measure how well the results provided by the simulation have been adjusted to the historical values observed in the real system. Good calibration, together with other types of test, help to build confidence in the model and the results provided by its simulations and therefore trust in its projections into the future. The root mean square error (RMSE) is a frequently used measure of the differences between values predicted by a model. The RMSE represents the square root of the quadratic mean of the differences between predicted values and observed values. It is the square root of the mean square error (MSE). Sterman (2000) provides an explanation for the decomposition of the error by dividing the MSE into three components: bias, unequal variation, and unequal covariation. Bias arises when the model output and data have different means. Unequal variation indicates that the variances of the two series differ. Unequal covariation means the model and data are imperfectly correlated, i.e. they differ point by point. Dividing each component by the MSE gives the fraction of the MSE due to bias (UM), the fraction due to unequal variation (Us), and the fraction due to unequal covariation (Uc). Since UM+ Us + Uc = 1, the inequality statistics provide an easily interpreted breakdown of the sources of error.

Table 3 Measures of the Brazil model calibration's goodness of fit

Variable	RMSPE	Variable	TBIAS
KPI.private savings RMSPE	0.036949	KPI.private savings TBIAS	0.81962479
KPI.yield RMSPE [crop]	0.019486	KPI.relative fish harvest in tonnes TBIAS [fish]	0.47294847
KPI.relative fish harvest in tonnes RMSPE [fish]	0.018926	KPI.relative forestry production in cubic metres TBIAS [wood]	0.38466828
KPI.services production RMSPE [services]	0.009473	KPI.livestock production in tonnes per hectare TBIAS [livestock]	0.3660588
KPI.industrial production RMSPE [industry]	0.009116	KPI.CO_2 emissions TBIAS	0.34583409
KPI.livestock production in tonnes per hectare RMSPE [livestock]	0.008354	KPI.access to safely managed sanitation facility TBIAS [area]	0.27956949
KPI.relative forestry production in cubic metres RMSPE [wood]	0.00485	KPI.domestic material consumption TBIAS	0.25985271
KPI.total export as share of GDP RMSPE	0.004839	KPI.agricultural land TBIAS [agriculture]	0.24730459
KPI.CO_2 emissions RMSPE	6.49E-05	KPI.access to safely managed water source TBIAS [area]	0.23010293
KPI.gross international reserves RMSPE	1.04E-05	KPI.employment by sector TBIAS [sector]	0.22160642
KPI.domestic material consumption RMSPE	9.65E-06	KPI.average years of schooling TBIAS [sex]	0.20526857
KPI.access to safely managed sanitation facility RMSPE [area]	9.33E-06	KPI.life expectancy TBIAS [sex]	0.2014025
KPI.proportion of population below poverty line RMSPE	8.63E-06	KPI.total water withdrawal TBIAS	0.19882853
KPI.forested land RMSPE	5.7E-06	KPI.proportion of population below poverty line TBIAS	0.19756255
KPI.employment by sector RMSPE [sector]	3.66E-06	KPI.infrastructure TBIAS [infra]	0.19675421
KPI.total water withdrawal RMSPE	3.46E-06	KPI.total fertility rate TBIAS	0.19450092
KPI.infrastructure RMSPE [infra]	3.43E-06	KPI.fish resources availability share TBIAS	0.19151136

Variable	RMSPE	Variable	TBIAS
KPI.access to safely managed water source RMSPE [area]	3.31E-06	KPI.forested land TBIAS	0.18730741
KPI.soil primary nitrogen balance RMSPE	2.93E-06	KPI.gross international reserves TBIAS	0.18571494
KPI.Gini coefficient RMSPE	1.81E-06	KPI.population by sex TBIAS [sex]	0.17865166
KPI.agricultural land RMSPE [agriculture]	8.17E-07	KPI.Gini coefficient TBIAS	0.17053316
KPI.life expectancy RMSPE [sex]	5.48E-07	KPI.soil primary nitrogen balance TBIAS	0.155109
KPI.total fertility rate RMSPE	6.29E-08	KPI.relative fish capture in tonnes TBIAS [fish]	0.13969608
KPI.fish resources availability share RMSPE	2.24E-08	KPI.total export as share of GDP TBIAS	0.09243474
KPI.average years of schooling RMSPE[sex]	2.11E-08	KPI.industrial production TBIAS [industry]	0.03957012
		KPI.yield TBIAS [crop]	0.00599509

3.8 Supplementary synergy analysis for Brazil

In this section of the report, we discuss the results of a different exercise conducted with the same model with the objective of finding policies that synergise with the green hydrogen ramp-up.

We ran an optimisation algorithm known as differential evolution (Storn and Price, 1997), which tested 2,000 different policy combinations on the iSDG model to find the ideal combination that would maximise SDG attainment in the context of the fourth scenario (strong ramp-up with fossil fuel price increase), while minimising the additional expenditure required.

The algorithm was allowed to pick any policy among the 28 that are part of the standard iSDG model, plus the possibility of direct price subsidies to the green hydrogen sector. We allowed the algorithm to choose a different policy mix for the period in which the first movers would still be investing in the green hydrogen sector (until December 2040) and another mix for the remaining years of simulation. We constrained this search in two different ways:

- The projected debt to GDP ratio in the country could not exceed 2x the 2000 levels
- The additional expenditure in any of the 28 policies could not exceed 1% of the country's GDP each year

It is important to note that this allocation is defined in addition to the baseline government budget allocation in the country. Our model computes the government spending in detail and is calibrated with historical data. The model also computes public debt, interest payment and its effect on investment capacity, meaning that we do compute the fact that spending more is not always beneficial in the long run. The algorithm has chosen the policy mix described below in proportion to the country's annual GDP (Table 4).

Table 4 Additional GDP expenditure per intervention type for the policy optimisation scenario

	2022–2040	2041–2050
General education	0.1%	0.0%
General health	0.0%	0.3%
Family planning	0.1%	0.0%
General agriculture	0.1%	0.2%
Fertiliser subsidies	0.0%	0.5%
Water access	0.1%	0.2%
Sanitation access	0.2%	0.2%
Paved roads	0.0%	0.0%
Unpaved roads	0.1%	0.6%
Railways	0.0%	0.1%
Waste management	0.1%	0.4%
Land protection	0.0%	0.4%
Marine protection	0.0%	0.0%

	2022–2040	2041–2050
Reforestation	0.4%	0.1%
Small-scale photovoltaic	0.2%	0.1%
Large-scale photovoltaic	0.1%	0.0%
Small-scale hydropower	0.4%	0.1%
Large-scale hydropower	0.3%	0.6%
Large-scale wind	0.2%	0.1%
Large-scale biomass	0.1%	0.3%
Vehicle efficiency	0.0%	0.3%
Industry energy	0.1%	0.3%
Households energy	0.0%	0.1%
Water efficiency	0.0%	0.3%
General transfers	0.0%	0.1%
Climate adaptation	0.7%	0.6%
Agriculture training	0.1%	0.0%
Green hydrogen subsidies	0.0%	1.0%

The key observations we are able to derive from this exercise are:

- Climate adaptation is a key investment area for the country to achieve the SDGs.
- Fertiliser subsidies and subsidies to green hydrogen become important after the first movers' investment period; they are needed to smooth the transition from the investment period to the consolidation phase of the green hydrogen sector.
- Upgrading unpaved roads is an important tool to increase farmer's access to market, as well as access to public services in remote locations, at a relatively low cost in the context of climate change.

- Reforestation and hydropower remain key sustainable development policies for the country. Hydropower does not necessarily involve expansion of current capacity but could also mean the modernisation of existing infrastructure.

For international development agencies, supporting programmes in these areas might be a good strategy to leverage the benefits of the future green hydrogen sector.

These synergistic investments could increase the average performance from 31% to 43.6% in the strong ramp-up with fossil fuel price increase scenario. The biggest projected differences are in SDGs 11 – Sustainable cities and communities, 13 – Climate action, 14 – Life below water, 1 – No poverty and 2 – Zero hunger.

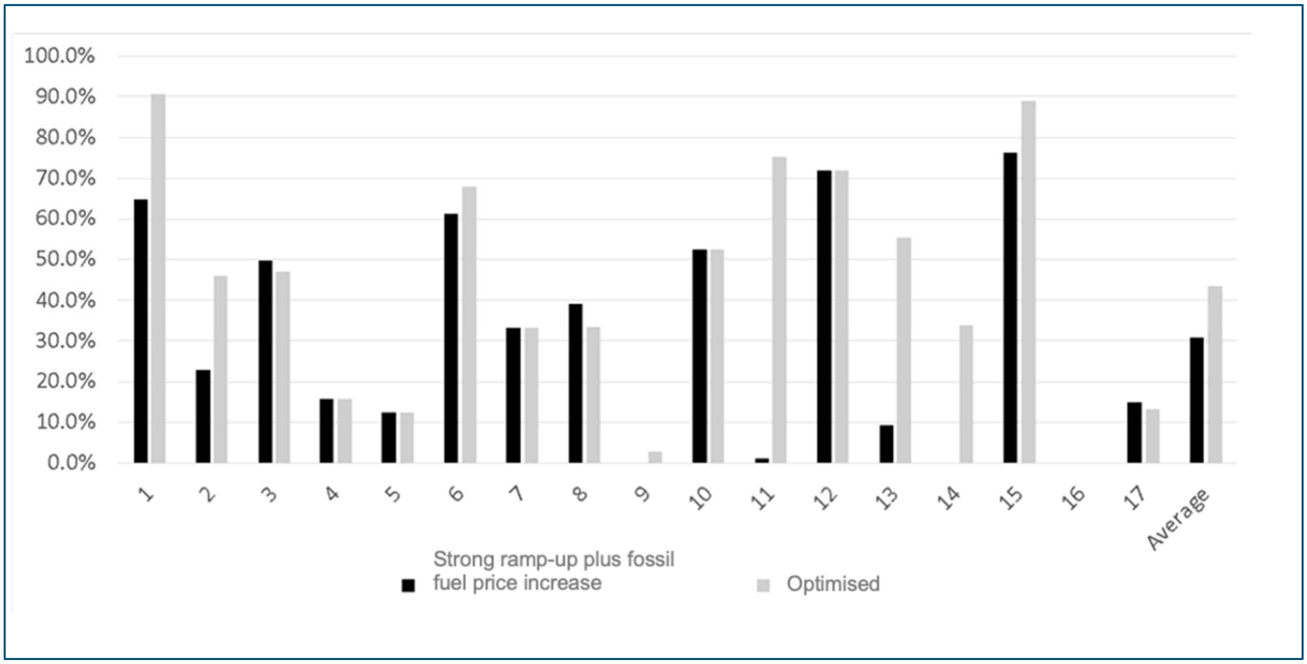

Figure 32 Brazil's SDG performance comparison between the strong ramp-up with fossil fuel price increase and the optimised policy scenarios

Additional studies should be performed to reveal the complex interrelationships across policy and programme portfolios. This remains an opportunity for future research in the field of development cooperation.

References

ABEEólica (Brazilian Wind Energy Association), 2022. Evolution of installed capacity. Available at https://abeeolica.org.br

ANEEL (Brazil's Electricity Regulator), 2022. SIGA. https://antigo.aneel.gov.br/siga

ANFAVEA (National Car Manufacturers Association), 2022. Anuário. Available at https://anfavea.com.br/anuario2022/2022.pdf

BMWK, 2022. Grids and infrastructure. Available at https://www.bmwk.de/Redaktion/EN/Artikel/Energy/electricity-grids-of-the-future-01.html

BNDES (Brazilian National Development Bank), 2022. Main funded entities. Available at https://www.bndes.gov.br/wps/portal/site/home/transparencia/consulta-operacoes-bndes/maiores-clientes

EPBR, 2022. Hidrogênio verde na agenda dos presidenciáveis. Available at https://epbr.com.br/hidrogenio-verde-na-agenda-dos-presidenciaveis

EPE (Brazilian Energy Research Corporation), 2021. Bases para a consolidação da estratégia brasileira de hidrogênio. Available at https://www.epe.gov.br/sites-pt/publicacoes-dados-abertos/publicacoes/PublicacoesArquivos/publicacao-569/NT_Hidroge%CC%82nio_rev01%20(1).pdf

EPE (Brazilian Energy Research Corporation), 2022. Annual Energy Balance. Available at https://www.epe.gov.br/pt/publicacoes-dados-abertos/publicacoes/balanco-energetico-nacional-2022

Estadão, 2022. Hidrogêncio verde: o próximo grande acontecimento em termos de energia para o Brasil e o mundo. Available at https://www.estadao.com.br/politica/blog-do-fausto-macedo/hidrogenio-verde-o-proximo-grande-acontecimento-em-termos-de-energia-para-o-brasil-e-o-mundo/

IMF, 2022. Carbon Taxes or Emissions Trading Systems?: Instrument Choice and Design. Staff Climate Notes. July 2022. Available at https://www.imf.org/en/Publications/staff-climate-notes/Issues/2022/07/14/Carbon-Taxes-or-Emissions-Trading-Systems-Instrument-Choice-and-Design-519101

McKinsey, 2021. Hidrogênio Verde: uma oportunidade de geração de riqueza com sustentabilidade para o Brasil e o mundo. Available at https://www.mckinsey.com/br/our-insights/hidrogenio-verde-uma-oportunidade-de-geracao-de-riqueza-com-sustentabilidade-para-o-brasil-e-o-mundo

Musacchio, A., Farias, A. M., & Lazzarini, S. G., 2014. Reinventing state capitalism: Leviathan in business, Brazil and beyond. Harvard University Press.

OECD, 2018. PISA Country Note (Brazil). Available at https://www.oecd.org/pisa/publications/PISA2018_CN_BRA.pdf

ONS (National Energy System Operator), 2022. O Sistema em Números. Available at https://www.ons.org.br/paginas/sobre-o-sin/o-sistema-em-numeros

Storn, R., & Price, K, 1997. Differential evolution – a simple and efficient heuristic for global optimization over continuous spaces. *Journal of global optimization*, *11*(4), pp. 341–359.

UFMG-Rota, 2030. Available at https://rota2030.fundep.ufmg.br/linha5/projetos/4-2 /

UNCTAD, 2021. State of Commodity Dependence 2021. Available at https://unctad.org/system/files/official-document/ditccom2021d2_en.pdf

Valor, 2021. Projetos de hidrogênio verde no Brasil já somam USD 22 bi. Available at https://valor.globo.com/empresas/noticia/2021/07/08/projetos-de-hidrogenio-verde-no-brasil-ja-somam-us-22-bi.ghtml

World Bank, 2021. Climate Risk Country Profile: Brazil. Available at https://climateknowledgeportal.worldbank.org/sites/default/files/2021-07/15915-WB_Brazil%20Country%20Profile-WEB.pdf

4. Model application for South Africa

4.1 Country background

South Africa (SA) – a country rich in culture, land, biodiversity, and energy resources – continues to experience energy instabilities. Although a large proportion of the urban and rural population (> 90%) has adequate access to electricity supply (Stats SA, 2017), the country is burdened by frequent power disruptions, known locally as 'load shedding' or 'rolling blackouts'. Recent statistics show that the country experienced over 1,900 hours of power outages in 2022, making it the most disrupted energy year since the onset of the power disruptions in 2007 (CSIR, 2022). According to the United Nations (UN) country classification, South Africa is a developing economy falling under the upper-middle income category (UN, 2019). Over the past decade, the country has experienced sub-optimal levels of economic growth and increasing levels of unemployment. Frequent power disruptions are a major cause of poor economic performance, whilst low economic growth and high unemployment levels further hinder efforts to resolve energy challenges. A just transformation towards energy stability therefore requires alternative energy solutions, such as those that can be secured from the benefits of a balanced economy based on alternative fuels and renewables.

South Africa's energy mix is primarily based on a core supply of fossil fuels, with around 80% of its electricity generated from coal sources (NBI, 2021). Due to the intensity of its fossil fuel-based economy, with the transport and industrial sectors being highly reliant on fossil fuels, South Africa is classified as the 14th largest greenhouse gas (GHG) emitter globally (DSI, 2021). As a signatory to the 2015 Paris Climate Agreement, it has a responsibility to decarbonise its energy system in pursuit of global and national climate ambitions. The national government advocates for a transition to a low-carbon and diversified energy system in its 2030 National Development Plan (NPC, 2017) and has launched several initiatives to accelerate the transition, such as the Renewable Energy Independent Power Producer Procurement Programme (REIPPPP). The REIPPPP aims to facilitate the expansion of renewables-based generation capacity to supplement and replace declining generation capacity from ageing fossil-fuel infrastructure. Moreover, increasing demand for liquid fuels (e.g. diesel, methanol) and chemical products (e.g. ammonia) from the transportation, industrial and agricultural sectors will require alternative energy feedstocks to replace traditional, fossil-fuel derived sources.

A variety of innovative decarbonisation strategies have emerged to address the transition towards a greener energy future in South Africa. Green hydrogen in particular has gained traction at national scale as a key enabler of the energy transition, owing to its low-emission and flexible production potential. Moreover, green hydrogen was identified as a 'big frontier' in the country's investment strategy. This led to the development of a national green hydrogen strategy, which included, for example, the Hydrogen Society Roadmap and dedicated working groups to lead research and development in this area (DSI, 2021). Currently, South Africa produces approximately 2 million tonnes of the global demand for hydrogen, all in the form of grey hydrogen and mostly produced from natural gas. In pursuit of a green hydrogen economy, it aims to leverage its natural renewable resources, land area, rich mineral endowment (e.g. platinum group metals), existing infrastructure and production capability to stimulate local demand and build a viable green hydrogen export market. Although water scarcity has been considered a potential constraint to the hydrogen production process, the water supply is deemed sufficient since the intention is not to use potable water sources but rather dedicated desalination and non-potable industrial water sources (NBI, 2021). A key principle that underlies green hydrogen production is the principle of 'additionality', such that the production process does not draw from existing demand, but rather provides its own production resources, which if supplied in excess can be fed into the grid. Initiating the green hydrogen economy could further accelerate the reduction in costs and upscaling of renewables and desalination infrastructure, which in turn can provide local social and economic benefits.

In a national context, the ramp-up of green hydrogen is expected to be gradual with the implementation of various private pilot projects to test commercial viability. To support these initiatives, close cooperation between the private and public sectors is necessary. Various strategic investment zones have been designated to kick-start the green hydrogen economy (Table 5). The various projects aim to support decarbonisation in different sectors of the economy, in particular the transport sector (e.g. long-haul transport) and hard-to-abate sectors of industry (e.g. steel manufacturing), and eventually create a viable export market for green hydrogen and associated derivates (e.g. green ammonia). South Africa also has capabilities in manufacturing hydrogen products and the metal deposits needed to produce hydrogen infrastructure and fuel cell components (Table 5). Although projections of green hydrogen production vary, owing to different assumptions and scales of assessment, it has been suggested that, with enablers in place – specifically the costs of electrolyser infrastructure and renewable electricity – green hydrogen could primarily replace portions of coal and natural gas in energy consumption and stimulate a local demand of 1.4 million tonnes by 2050 at an estimated rate of USD 1.6/kg (DSI, 2021; NBI, 2021).

Table 5 Green hydrogen Pilot Projects currently underway in South Africa*

Project	Area	Goal/impacts
SA's Platinum Valley (Hydrogen Valley) project	Consists of 16 pilot projects all with the intention of testing the viability of green hydrogen. This area was specifically selected due to a high concentration of industrial users, combined with access to renewable energy sources and water infrastructure.	It is projected that 185,000 tonnes of hydrogen will be produced across the 16 projects at a cost of USD 4/kg with the potential to contribute USD 3.9–8.8 billion to SA's GDP by 2050 and create 14,000–30,000 jobs per year.
Coal CO_2-X project	Specifically aims to test the viability of replacing coal with renewable energy feedstock to produce alternative fuels.	Near-term goals are to produce sulphuric acid and fertiliser (2020–2024) for local use. There could be opportunities to export these commodities in the longer term (> 2024).
Boegoebaai Special Economic Zone	Strategic Integration Project, led by Sasol, in partnership with national government. Dedicated green hydrogen testing facilities in the Northern Cape, particularly to test the feasibility of exporting ammonia.	Potential to produce 400,000 tonnes of green hydrogen per annum with 9 GW of renewable electricity.
Sustainable Aviation Fuels Project (LEN Consortium)	To test the feasibility of manufacturing jet fuel.	Estimates project that, with a 4.5% share in the SA fuel market, a project of this scale could create 55,000 jobs in rural farming and contribute to economic growth that will see ZAR 2 billion (USD 180 million) per annum added to GDP.

Project	Area	Goal/impacts
Hive green ammonia plant	Situated in the Coega Special Economic Zone in the Eastern Cape province of South Africa, Hive Hydrogen, in partnership with Linde, aims to produce green (solar) ammonia for export.	Potential to produce 780,000 tonnes of green ammonia per year, with the potential of creating 20,000 direct and indirect jobs.
Saldanha Bay green hydrogen project	Green hydrogen hub in the Saldanha Bay Industrial Development Zone. Partnership between Sasol and ArcelorMittal.	Aims to develop carbon capture technology to produce sustainable fuels and chemicals, along with green steel production using green hydrogen and derivatives.

*A total of 19 green hydrogen projects has been identified for development in South Africa; this table discusses only some of the projects analysed during the research and identified in the Hydrogen Society Roadmap (DSI, 2021). Additional information on projects is available in (Department of Public Works and Infrastructure: Strategic Integrated Projects, 2022).

4.2 Case study objectives for South Africa

The rate at which green hydrogen can establish itself as an effective energy solution is dependent on a variety of factors connected with the country's level of 'readiness'. Hence, to understand the potential role of green hydrogen in South Africa's decarbonisation strategy, it is important to understand the causal effects of green hydrogen in the energy system on a national level. As outlined in the South African Hydrogen Society Roadmap (DSI, 2021), the overall goal of the green hydrogen economy is to enable a just and inclusive transition towards a net-zero carbon future by 2050. This can also support underlying national development objectives in line with the country's Sustainable Development Goals (SDGs).

This analysis therefore aims to investigate the effects of the green hydrogen economy on national goals under different ramp-up scenarios, with a particular focus on the performance of South Africa's SDGs until 2050, using the integrated Sustainable Development Goal (iSDG) model.

4.3 Model set-up and assumptions for South Africa

To perform the analysis for South Africa, the iSDG model was adapted and calibrated to country-specific data, after which it was coupled to the green hydrogen (GH2) sub-model developed specifically for this analysis. National data was sourced from a variety of international databases (e.g., World Population Prospects, World Urbanization Prospects, World Bank (WDI and WGI), UNDP, IMF, WHO, FAO, UNSTATS, UNSD, IEA, EIA, WDPA, USDA, EMDAT, International Resource Panel, Global Carbon Project, What a Waste, Sea Around Us and Barro Lee) with some national data sourced from national accounts and statistics databases (StatsSA). This allowed country-specific data to provide data and parameter values to the GH2 model and enabled the GH2 model to be coupled back into the iSDG to measure knock-on effects on the country's SDGs. To evaluate these effects, four model scenarios were developed, taking into account different ramp-up strategies, defined as follows:

- No GH2. The first scenario serves as a baseline to evaluate model behaviour without the effects from the GH2 sub-model (i.e. there is no exchange of model dynamics between the iSDG and GH2 sub-model during this run).
- Initial ramp-up/ramp-up as announced. This scenario simulates the effect of an initial investment strategy, considering investments that had already been made to kick-start the green hydrogen economy.
- Strong ramp-up. The third scenario aims to simulate the effects of higher investments and policy control in the form of carbon taxation on alternative fossil fuel energy sources and tax breaks on green hydrogen products.
- Ramp-up with fossil fuel price increase. The final scenario tested in the model captures the effects of the controlled ramp-up, but additionally assumes an external shock in the form of an increase in the price of fossil fuel energy sources.

More information on the changes to the respective model parameters under the scenarios are shown in Table 6. These four scenarios are specifically reported on in the analysis; to create additional policy scenarios, an online model-user interface is available for testing: https://exchange.iseesystems.com/public/millenniuminstitute/gh2-ramp-upsouth-africa.

Table 6 Parameter values for the scenario definition for South Africa

	First movers' invest-ment (real rand)	Adoption time (years)	End of first movers' effort (date)	Target carbon tax (USD_{2010} /tCO_2 eq.)	Profit tax break (fraction of profits)	Infrastructure tax break (fraction of expenditure)	Fossil fuel price (USD/MWh) [oil; gas; coal]
No GH2	0	8	NA	0	0	0	Stable
Ramp-up	ZAR 50 billion	8	Dec 2030	0	0	0	Stable
Controlled ramp-up	ZAR 100 billion	4	Dec 2030	80	0.1	0.1	Stable
Controlled ramp-up with fossil fuel price increase	ZAR 100 billion	4	Dec 2030	80	0.1	0.1	Increasing [36; 14; 6]

For model validation purposes, model behaviour was simulated from 2000 in order to calibrate its behaviour until 2022, or until the latest available data. For the purpose of the GH2 analysis, model behaviour is investigated from 2020 until 2050 and SDG results are investigated from the start of the SDG analysis period (i.e. 2015) until 2050. Model behaviour is simulated in *yearly* time units. To initiate the green hydrogen ramp-up in the model, the following cost assumptions are simulated:

- The levelised cost of green hydrogen (LCOH) decreases over the course of the simulation, owing to lower costs for renewable electricity sources, capital and operational requirements (Figure 33a).
- It is assumed for this analysis that the energy source share for green hydrogen production is based on 50% solar PV and 50% onshore wind; hence the levelised cost of renewable electricity (LCOE) is based on solar PV and wind electricity costs, taken from the iSDG model (Figure 33b).
- It is assumed that capital costs associated with electrolysers decrease as shown in Figure 33c. The analysis does not differentiate between different types of electrolyser and associated costs.
- Investments are divided equally between green hydrogen and associated derivatives, as investment figures for different GH2 products and derivatives are not known.

- The model does not formulate hydrogen derivative feedstock supply dynamics. It is assumed that feedstock supply needed for the production of green hydrogen derivatives is available for production (e.g. nitrogen for ammonia production).

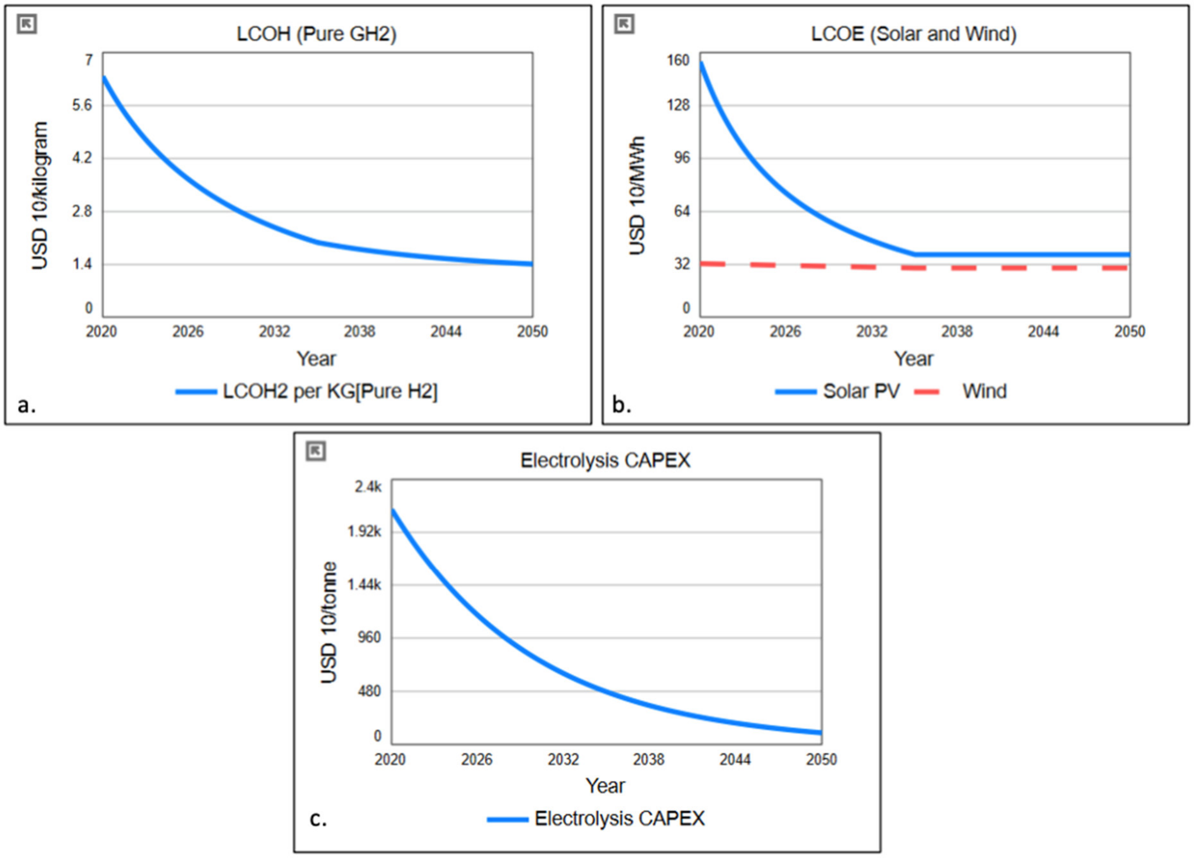

Figure 33 South Africa: Levelised cost of green hydrogen (USD/kg) and associated reductions in levelised costs of renewable electricity (USD/MWh) and electrolyser infrastructure (USD/tonne)

4.4 South Africa's GH2 model results

Figure 34 shows the total consumption of green hydrogen products and the sector's value added under the initial investment ramp-up scenario (i.e. with current investments in place). In the model, green hydrogen consumption consists of pure green hydrogen (pure GH2), but also includes fuel cell demand (pure H2 FC) from the transport sector, ammonia, liquified synthetic methane and synthetic diesel, as forms of power-to-X (PtX) products. Owing to the lack of information on the total investments in different GH2 products, it is assumed that the investment is equally divided into amongst GH2 products. Under these assumptions, total green hydrogen consumption exceeds 4.5 million tonnes/year by 2050, with pure GH2 equating to approximately

1.2 million tonnes/year (Figure 34a). Similarly, the total value of the green hydrogen sector under the initial ramp-up scenario contributes approximately ZAR 80 billion/year (USD 4.6 billion/year[1]) by 2050, with pure green hydrogen production contributing ZAR 18 billion/year (USD 1.05 billion/year) in revenue (Figure 34b). This is consistent with 2050 projections reported in DSI (2021), which amounts to 1.4 million tonnes of green hydrogen, with a lower model projection for total green hydrogen derivatives compared to government estimates of 6–13 million tonnes by 2050.

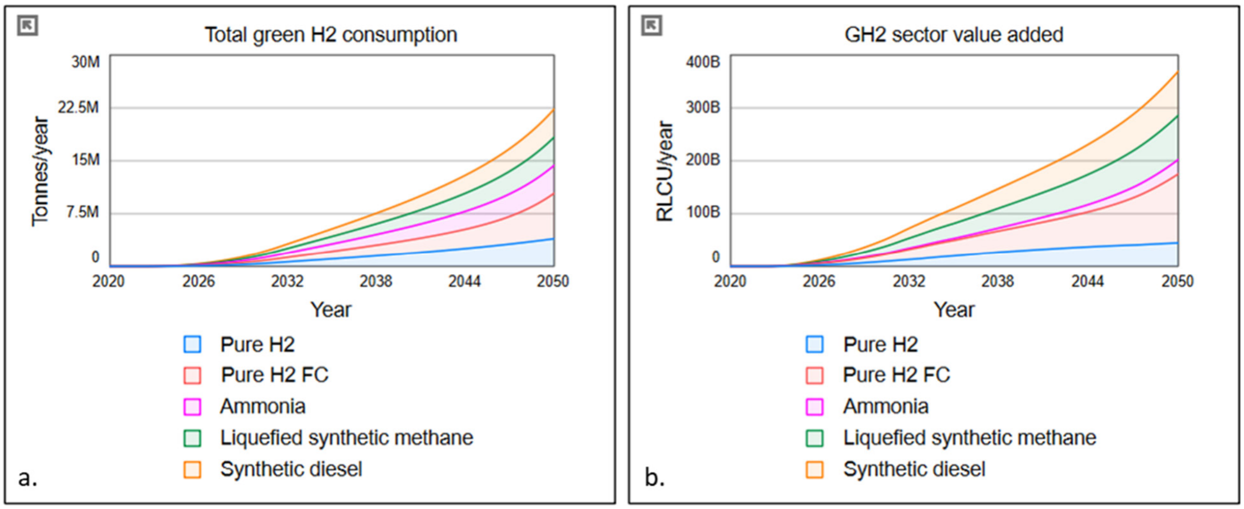

Figure 34 South Africa: Local consumption of green hydrogen products (tonnes/year) (a) and associated value added (rand/year) under the initial ramp-up scenario

Further explanation of the results in the scenario analysis focuses particularly on the results of green hydrogen (pure GH2) since it is the main fuel source and feedstock needed to produce downstream green hydrogen derivatives. Ammonia is additionally of interest, particularly owing to the viability of green ammonia for the export market.

Figure 35 shows the results of green hydrogen production (pure GH2), the sector's value added and its labour potential under the four model scenarios. Under the different investment and policy scenarios, it is projected that green hydrogen consumption may vary from a lower range of approximately 1.1 million/tonnes to an upper range of 4 million tonnes/year by 2050, with the latter figure corresponding to the highest level of investment, carbon taxation, and an increase in the price of fossil fuel energy sources, primarily natural gas, oil and coal (Figure 35a). It is also only under this scenario that an export supply of approximately 700,000 tonnes/year of ammonia, with ZAR 22 billion/year (USD 1.28 billion/year) value added, is projected by 2050 (Figure 35b). Similarly, the sector value of green hydrogen (pure GH2) ranges between ZAR 14 billion/year (USD 820 million/year) and ZAR 44 billion/year (USD 2.6 billion/year) (< 0.01% current GDP), with the total sector value ranging from ZAR 77 billion/year (USD 4.5 billion/year) to ZAR 370 billion/year (USD 22 billion/year) (1–5% GDP) (Figures 35c and d). Finally, in terms of

[1] Current USD figure based on exchange rate in 2022 (USD 1 = ZAR 17.00).

labour potential, the total green hydrogen industry – across construction and operation activities – can contribute a total of 556,000 jobs during the peak of the development period, which in the model occurs in 2032 and concludes with approximately 200,000 jobs in 2050 (Figure 35e). Between the two different investment strategies (ramp-up vs. controlled ramp-up) the total labour potential in the green hydrogen (pure GH2) sector alone is projected to range from 12,000–50,000 jobs during the peak construction period and between 2,500–8,000 jobs during operation (Figure 35f).

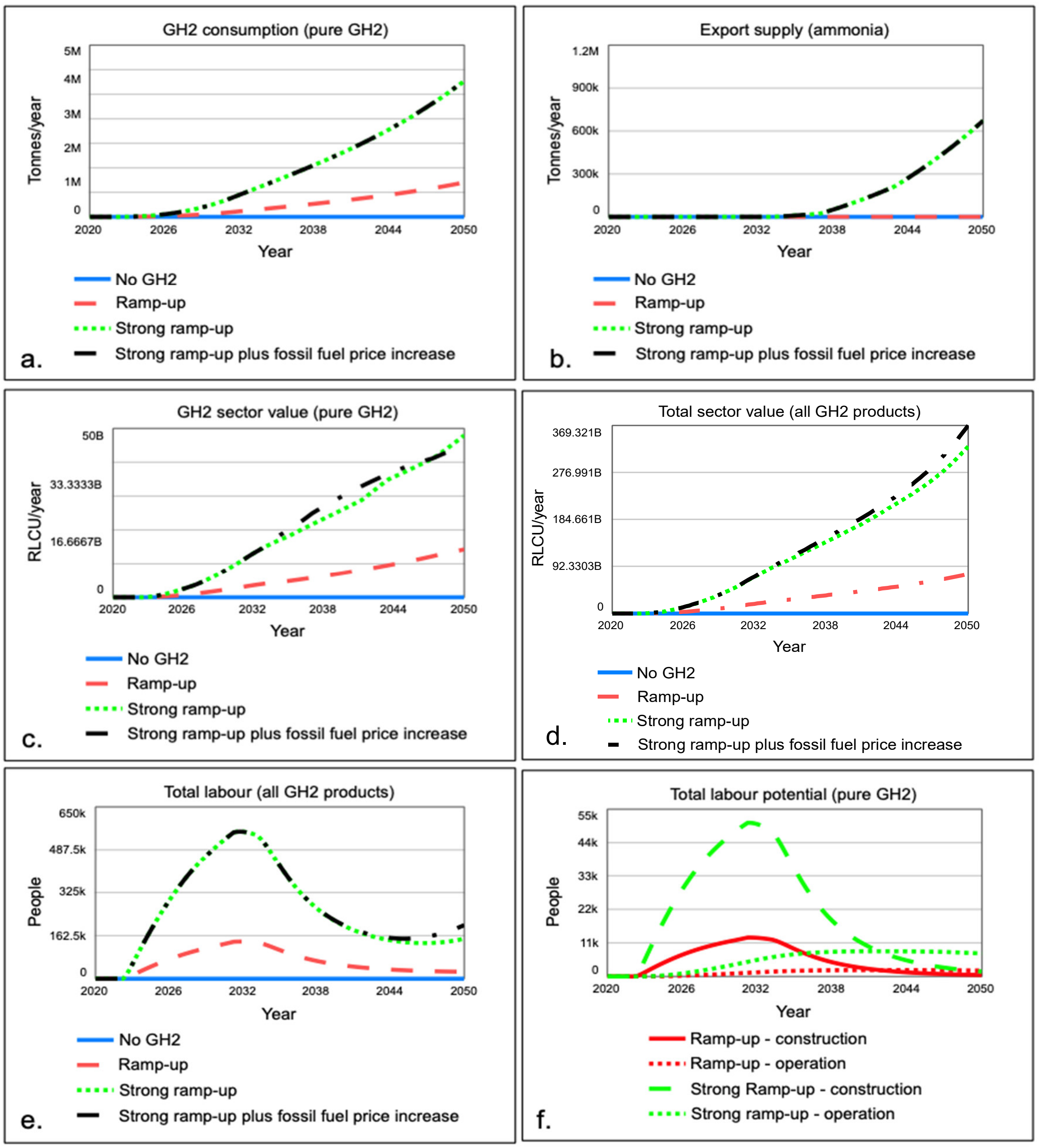

Figure 35 South Africa: Green hydrogen consumption (tonnes/year), sector value (rand/year) and labour potential (persons) under the four model scenarios. Pure GH2 consumption (a), ammonia export supply (b), pure GH2 sector value (c), total sector value (d), total labour (e) and total labour potential in pure GH2 (f).

4.5 South Africa's SDG performance

To evaluate the effect of the green hydrogen ramp-up on the country's national development status, the 17 Sustainable Development Goals and associated indicators were measured. It is important to note that the iSDG model does not include all the indicators within the UN SDG framework, but focuses on 78 key indicators across the different goals based on measurability and data availability (see Annex). In addition, the effects of GH2 on SDG performance in 2050 are measured in relation to 2030 targets, since no 2050 SDG targets exist.

Figures 36 and 37 shows the performance of the SDGs in 2050 under the four GH2 model scenarios. Figure 36 shows the final goal attainment, whereas Figure 37 shows the difference in SDG performance for the green hydrogen scenarios. The results show that the overall SDG attainment is 0%, 2% and 2% for the initial ramp-up, controlled ramp-up and ramp-up with fossil fuel price increase scenarios respectively. Furthermore, across the green hydrogen ramp-up scenarios, the largest increases in SDG performance are observed for SDG 7 (Affordable and clean energy) ranging between 2–12%, SDG 8 (Decent work and economic growth) with a 3–4% increase, SDG 12 (Responsible consumption and production) with a 1–8% increase, and finally SDG 13 (Climate action) with a 3–6% increase (Figure 36). The largest gain in SDG performance for the respective goals is shown for the scenario with the external fossil fuel price increase, resulting in even higher demand and hence consumption of green hydrogen as an alternative fuel source. Marginal gains (1–2%) are also observed for SDG 2 (Zero hunger), SDG 3 (Good health and well-being), SDG 9 (Industry, innovation and infrastructure), SDG 14 (Life below water) and SDG 16 (Peace, justice and strong institutions). The results also show that the following SDGs experience a minor decrease in SDG performance under two of the model scenarios (Figure 37). SDG 10 (Reduced inequalities) shows a 2% decline, and SDG 5 (Gender equality) and SDG 6 (Clean water and sanitation) experience a 1% decline (Figure 37) because of adverse knock-on effects from the integration of green hydrogen into the national economy. The reasons for the observed differences in SDG performance are discussed below.

SDG 1 – No poverty

The performance of SDG 1 does not show a large improvement in goal attainment across the green hydrogen scenarios (~1%) (Figure 37), although the indicator that showed the greatest improvement was 'the proportion of population below the national poverty line' (i 1.2.1). Based on the model structure, this would be because green hydrogen makes a slight contribution to the economy in terms job creation and GDP growth (see section 5.2) – although the magnitude of the contribution depends on the level of investment and production of green hydrogen, in relation to existing sectors of the economy.

SDG 2 – Zero hunger

SDG 2 also shows a minor improvement in goal attainment (~1%) – mainly in terms of small reductions in the 'prevalence of undernourishment' (i2.1.1), 'prevalence of stunting among children' (i2.2.1), and 'prevalence of malnutrition' (i2.2.2). A more positive contribution with regard to this goal would depend on the integration of green hydrogen, in the form of green ammonia, into the domestic agricultural sector. This would further depend on the effect of alternative fertilisers on the price of farm goods and services, which was beyond the scope of the model. The viability of green ammonia as an alternative fertiliser also holds the potential to improve performance in the 'proportion of agricultural area under productive and sustainable agriculture' (i2.4.1), but this result was not captured in the model.

SDG 3 – Good health and well-being

A minor improvement for SDG 3 (~1%) was observed across the model scenarios. This improvement was mainly observed through changes in 'maternal mortality ratio' (i3.1.1), 'under-five mortality rate' (i3.2.1), and 'mortality rate attributed to cardiovascular disease, cancer, diabetes or chronic respiratory disease' (i3.4.1), with a slight reduction also observed in the 'proportion of woman of reproductive age with access to family planning' (i3.7.1). These changes may not be directly attributed to the integration of green hydrogen, but are more likely the result of indirect knock-on effects from economic growth and hence changes in healthcare factors over the simulation period.

SDG 4 – Quality education

Minor changes were observed in quality of education (< 1%). The zero to minor improvement in the quality of education is due to the fact that no direct or indirect impacts affect the inclusive education indicators. Improvements in the quality of education are related to goals such as (i7.1.1) 'access to electricity', which is dependent on energy security and electricity supply. Improving this goal requires a holistic energy transformation strategy, which addresses electricity shortages and supplementary electricity supply to educational facilities across the country.

SDG 5 – Gender equality

The performance of SDG 5 shows a minor reduction across the scenarios (~1%), with the change surprisingly observed for the level of contraceptive prevalence (i5.6.1). In the model this is related to the change in family planning (i3.7.1) originating from indirect effects through changes in healthcare dynamics. Although the model fails to capture results in relation to gender equality targets, green hydrogen policies should aim to focus on changes in the level of participation of woman in the sector, with an emphasis on the 'proportion of woman in managerial positions' (i5.5.2).

SDG 6 – Clean water and sanitation
The performance of SDG 6 similarly shows a minor reduction in goal attainment (~1%), with the change emanating from the 'level of water stress' (i6.4.2). Although the green hydrogen sector is reliant on an alternative and dedicated water supply through desalination or from non-potable water sources, the growth of the industrial sector in the model increases water demand and hence affects the national water vulnerability index.

SDG 7 – Affordable and clean energy
A great improvement is observed for SDG 7, in the range of a 2–12% increase across the scenarios (Figure 37), particularly observed through changes in the 'renewable energy share in total energy consumption' (i7.2.1). Additional minor improvements are observed for the 'proportion of population with access to electricity' (i7.2.1). Further details on the dynamics behind the performance of SDG 7 are discussed below.

SDG 8 – Decent work and economic growth
Overall, SDG 8 experiences a 3–4% improvement in performance through increases in economic growth mainly in terms of 'real GDP per capita' (i8.1.1), 'real GDP per employed person' (i8.2.1), 'material footprint per capita' (i8.4.1) and 'domestic material consumption' (i8.4.2), with less obvious improvements in employment e.g. 'unemployment rate' (i8.5.2). Further details on the dynamics behind these changes are discussed below.

SDG 9 – Industry, innovation and infrastructure
The performance of SDG 9 shows a slight overall improvement of 2%, mainly due to changes in 'manufacturing value added as a proportion of GDP and per capita' (i9.2.1), which provides an indication of increased industrial production, alongside reductions in 'CO_2 emissions per unit of value added' (i9.4.1). Further details on the dynamics behind changes in SDG 9 are discussed below.

SDG 10 – Reduced inequalities
By contrast, the performance of SDG 10 shows a reduction in goal attainment of approximately 2%. By tracing the causal connections, the model shows that the change emanates from a reduction in 'labour share of GDP' (i10.4.1). This is due to the introduction of a new value-added industry and the uneven distribution of benefits from the sector. This observation underlines concerns regarding equality in the green hydrogen sector and implies that additional policies may be necessary to facilitate an equal distribution of sectoral benefits (i.e. economic gain, electrification) beyond industry stakeholders and government.

SDG 11 – Sustainable cities and communities
The overall goal attainment of SDG 11 is minor (< 1%), though small improvements are observed for indicators related to solid waste management (i11.6.1) and levels of particulate matter in cities (i11.6.2). The improvement in solid management is indirectly attributed to economic

growth, whereas changes in levels of particulate matter are attributed to the substitution of fossil fuels by green hydrogen which can result in lower levels of air pollution.

SDG 12 – Responsible consumption and production

A more substantial gain in goal performance is observed for SDG 12 (Figure 37) with an ~8% increase observed for the final two scenarios. This change is predominantly from improvements in the ‘material footprint per capita and per GDP’ (i12.2.1) and ‘domestic material consumption’ (i12.2.2). The lower material consumption is similarly associated with decreased consumption associated with fossil-fuel intensive sectors and hence with smaller ‘footprints’.

SDG 13 – Climate action

SDG 13 also shows a higher level of improvement in goal attainment (~3–6%) across the model scenarios. It is important to note that the goal is measured through only two indicators in the model: ‘Mortality associated with natural disasters’ (i13.1.2) and ‘Total greenhouse gas emissions per year’ (i13.2.2), with the latter showing the major contribution to increased goal performance. Further details on the dynamics behind change in SDG 13 are discussed below.

SDG 14 – Life below water

SDG 14, measured through changes in levels of ‘sustainable fish stocks’ (i14.4.1) and ‘coverage of marine protected areas’ (i14.5.1), does not show a major improvement in goal attainment (< 1%) across the model scenarios. There is merely a minor increase in marine protection, mainly attributed to indirect effects of economic growth. More policies dedicated to management of the ocean space are necessary to increase goal attainment in this area. In addition, site-specific analyses may be necessary to investigate the effects of green hydrogen infrastructure, such as desalination, on the coastal marine environment.

SDG 15 – Life on land

The performance of SDG 15 does not show changes in the level of goal attainment across the model scenarios (< 1%), suggesting that supplementary environmental policies and regulations need to be developed as part of the green hydrogen strategy to improve environmental status in terms of ‘land protection’ (i15.1.1 & i15.1.2) and ‘biodiversity conservation’ (i15.5.1).

SDG 16 – Peace, justice and strong institutions

A minor improvement is observed (~1%) for SDG 16 (Figure 37), with an unexpected improvement in the ‘number of victims of international homicide’ (i16.1.1) which is attributed to a small decrease in the level of mortality associated with violence, possibly from indirect effects of economic growth and associated changes in healthcare. No direct changes from the effect of green hydrogen are observed.

SDG 17 – Partnerships for the goals
SDG 17 also shows a minor (< 1%) improvement in goal performance. Tracing the causal effects in the model, the indicator that showed the largest contribution to this change is ‘total government revenue as a proportion of GDP by source’ (i16.6.2), again attributed to indirect effects from economic growth.

The differences in SDG performance between the green hydrogen scenarios are further investigated in relation to the model indicators associated with national energy goals (SDG 7), economic performance (SDG 8), industrial innovation (SDG 9) and climate action (SDG 13). These SDGs were chosen because they align with the goals of the green hydrogen strategy and were hypothesised to show the largest effects from green hydrogen during project scoping. Key environmental and social indicators that show differences across the green hydrogen scenarios are additionally evaluated.

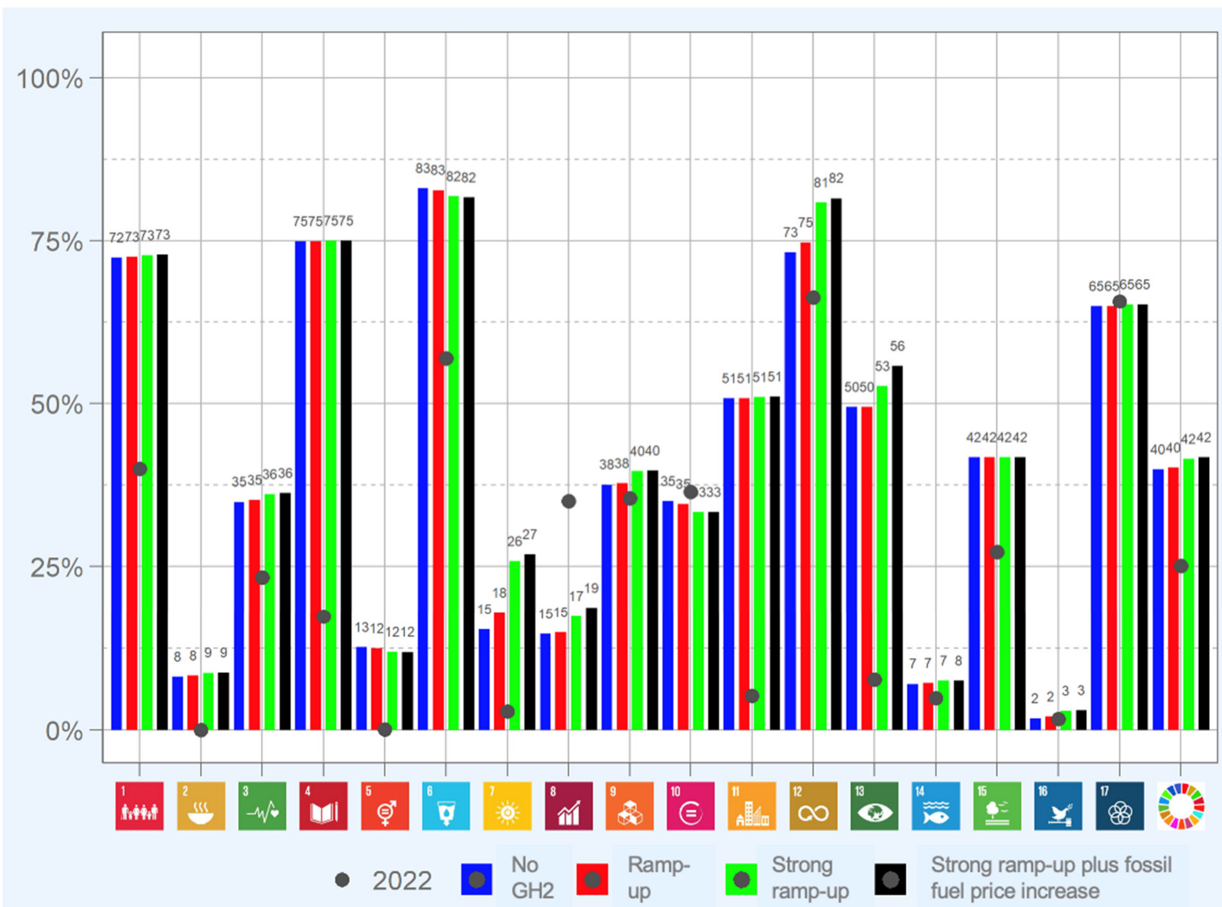

Figure 36 South Africa: SDG scenario attainment in 2050 across different green hydrogen ramp-up scenarios

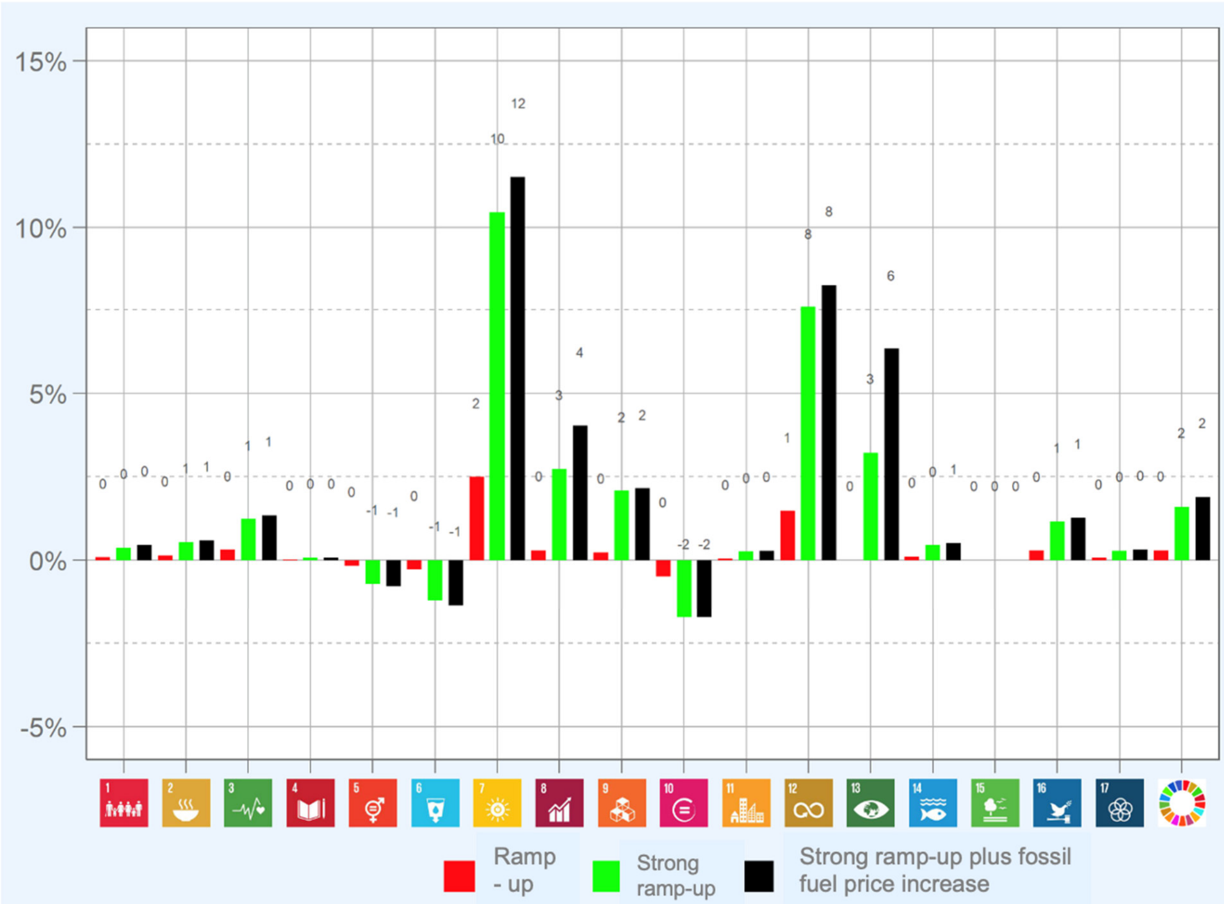

Figure 37 South Africa: Differences in final SDG performance under the GH2 ramp-up scenarios in reference to the no-GH2 scenario

4.5.1 SDG 7 – Affordable and clean energy

The iSDG model measures the performance of SDG 7 using the indicators shown in Figure 38. Figure 38a shows an increase in the performance of the goal across the scenarios. The increase is greater for the controlled ramp-up scenarios, but the overall performance of SDG 7 remains below 50% until 2050. The scenario results further show that there are no observed improvements to the 'proportion of the population with access to electricity', although improvements were seen in the 'share of renewables in total energy consumption' and there was a marginal improvement in the 'primary energy intensity level'. The increase in the performance of SDG 7 in this instance is predominantly due to renewables having a higher share in energy consumption and electricity generation, resulting from the consumption of green hydrogen in sectors of the economy, particularly industry, transport and agriculture. Furthermore, the integration of green hydrogen does not have a great effect on access to electricity, possibly because consumption of green hydrogen and its derivatives is driven by dedicated demand in particular sectors that aim to substitute existing demands. An increase in access to electricity could possibly occur in the case of excess energy supply from green hydrogen being distributed to other users or fed into the national grid.

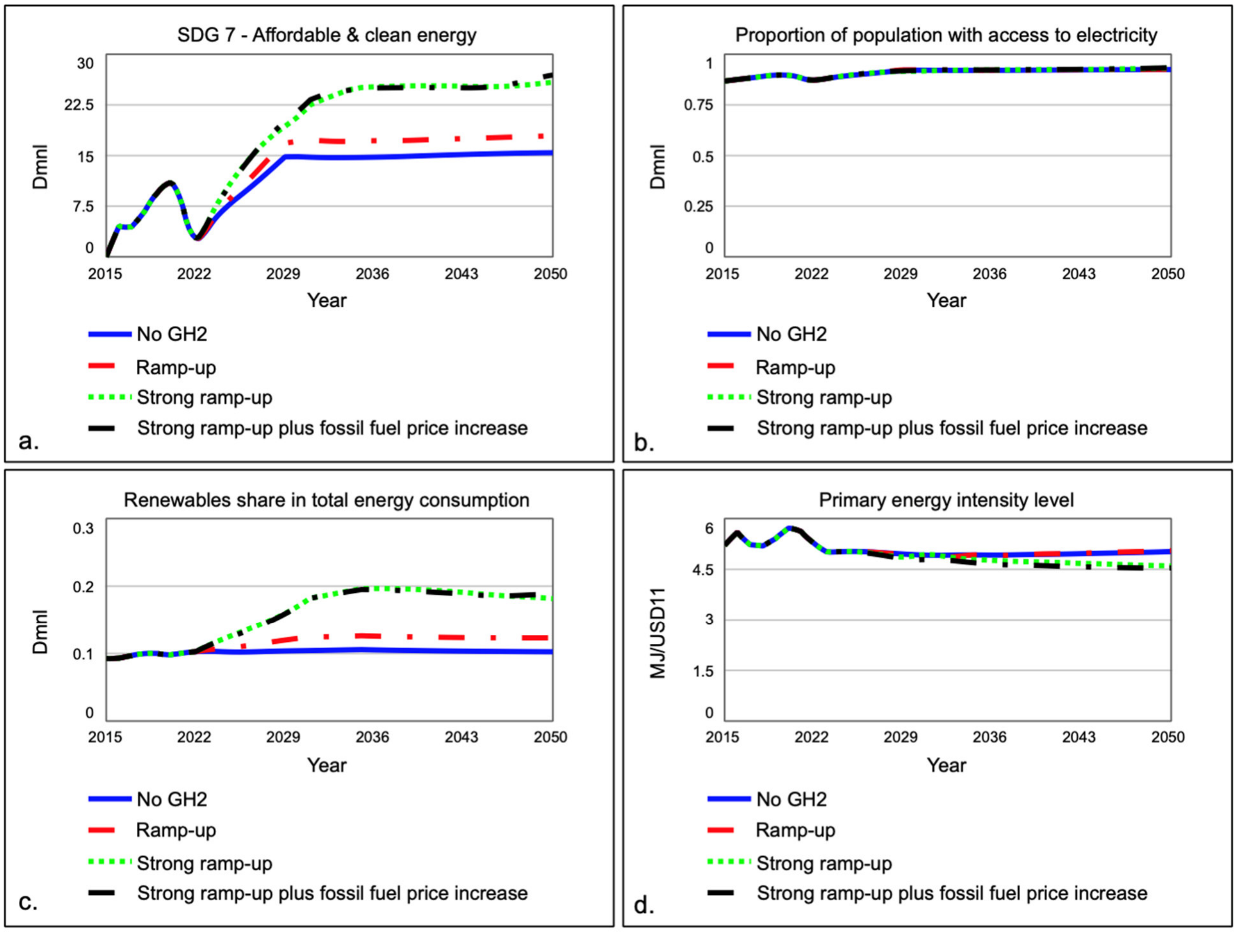

Figure 38 South Africa: Performance of SDG 7 (Affordable and clean energy) and associated indicators. Note that 100% equals full SDG attainment but for readability purposes, the y-axes have been rescaled ('Dmnl' means 'dimensionless' in modelling terminology, which is equivalent to a fraction, proportion or percentage of a number)

Figures 39 and 40 further substantiate the results associated with SDG 7. Figure 39 shows that, as the rate of green hydrogen consumption increases, a larger share of fossil fuel energy sources is substituted by green hydrogen. The share of substitution is more noticeable for the controlled investment scenario (Figure 39b). The increase in renewables in electricity generation, particularly wind and solar PV, which is a result of an upward trend in renewables capacity for green hydrogen production, further accelerates the progress of SDG 7 (Figures 40a and b).

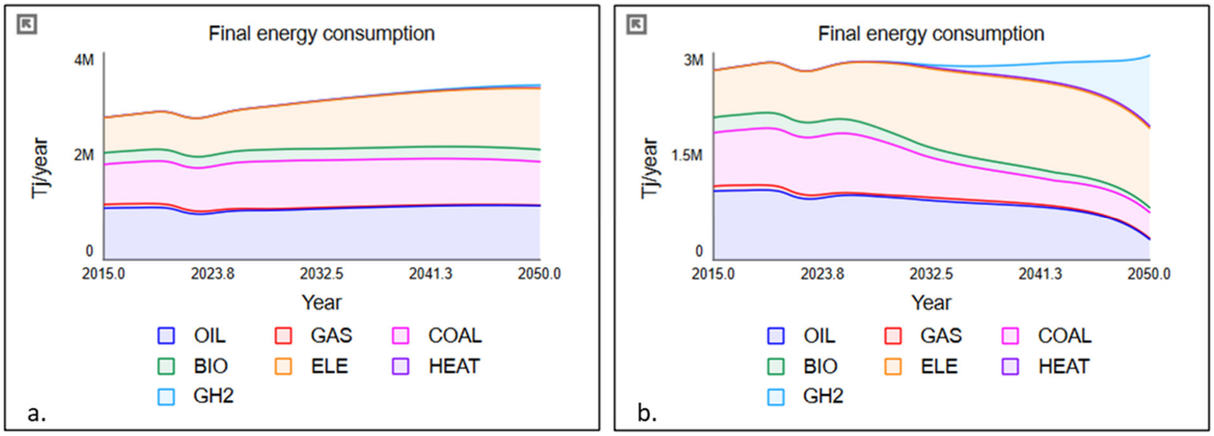

Figure 39 South Africa: Energy substitution as shown by final energy consumption by source (terajoule/year or TJ/year) for the initial ramp-up (a) and controlled ramp-up (b) scenarios

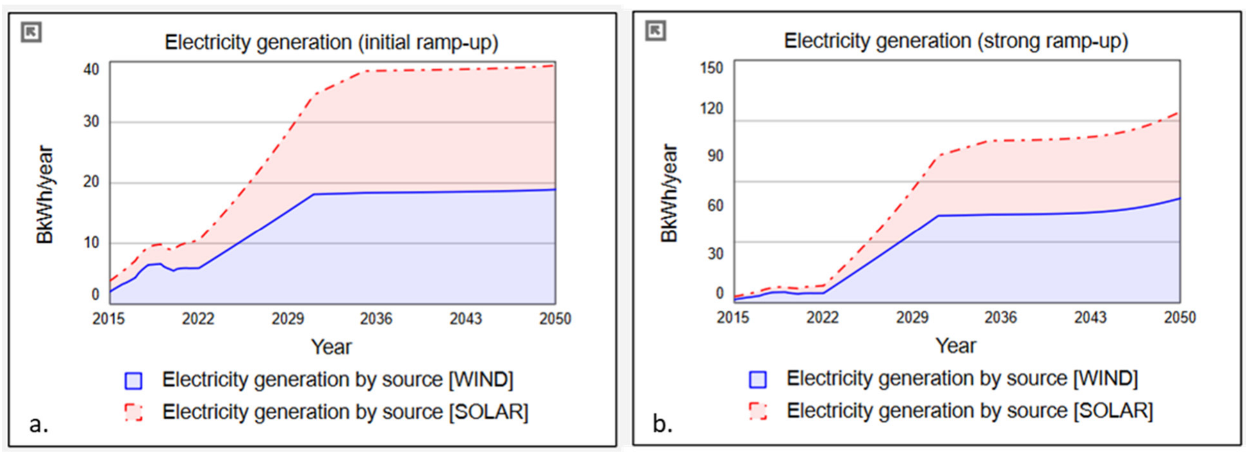

Figure 40 South Africa: Total electricity generation capacity from wind and solar PV under initial ramp-up (a) and strong ramp-up (b) scenarios. Units are BkWh/year (Note the different scaling on the y-axes)

4.5.2 SDG 8 – Decent work and economic growth

The performance of SDG 8 in the analysis is measured and investigated in terms of changes in gross domestic product (GDP), unemployment and changes in the level of domestic material consumption (Figure 41). The results show marginal gains in the economic indicators, particularly in terms of real GDP and domestic material consumption. The difference between the controlled ramp-up and the fossil fuel scenario shows an addition of approximately ZAR 350 billion/year to GDP, which corresponds to the total value of the green hydrogen sector with most of this value stemming from industrial production (Figure 41b). Although the green hydrogen economy is projected to create jobs as shown in section 5.2, the total level of employment does not significantly affect levels of unemployment. Additional analysis may be required to measure the full spectrum of employment opportunities in the green hydrogen sector, other than those arising during construction and operational phases of development. Moreover, although green hydrogen has the potential to create jobs, the degree to which it may improve levels of unemployment will depend on the size of the sector in relation to the broader scope of sectors of the economy. Finally, increased construction materials necessitate changes in domestic material consumption to develop the green hydrogen economy (Figure 41d).

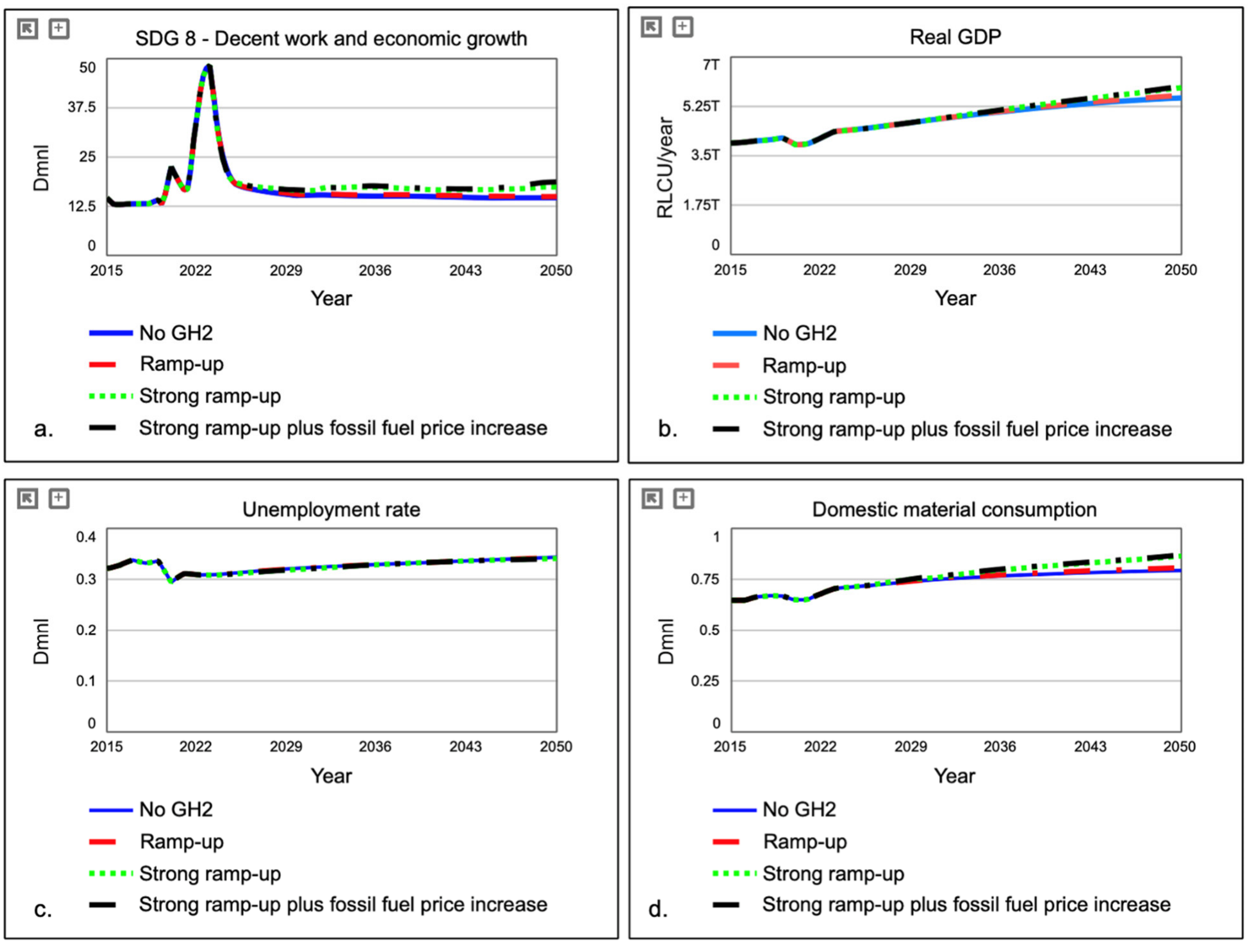

Figure 41 South Africa: Performance of SDG 8 (Decent work and economic growth) and associated indicators

4.5.3 SDG 9 – Industry, innovation and infrastructure

Progress in terms of industrial development is represented by changes in SDG 9 and associated indicators. Marginal increases are shown among SDG 9 indicators across the ramp-up scenarios, with greater increases for the higher investment scenarios (Figure 42a). In all three ramp-up scenarios, there is an increase in the value of industrial production (Figure 42b) and industrial employment – mainly over the construction period (Figure 42c) – and a decrease in the amount of carbon dioxide (CO_2) emissions per unit of value added (Figure 42d). These scenarios therefore show that, even with an increase in industrial development, 'green' developments can nevertheless result in industrial activities producing lower emissions in the long-term.

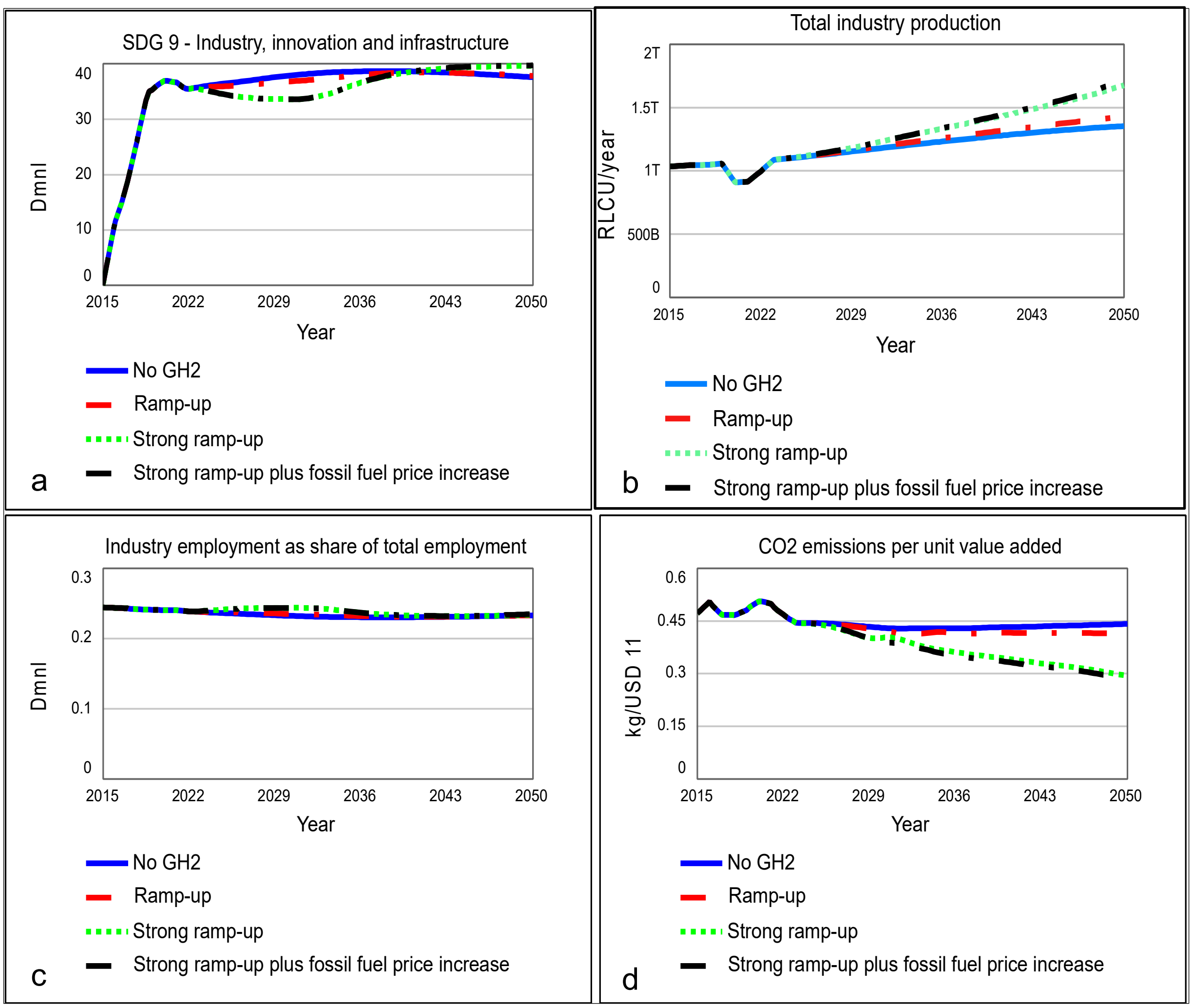

Figure 42 South Africa: Performance of SDG 9 (Industry, innovation and infrastructure) and associated indicators

For comparative purposes, Figure 43 shows the evolution in the value of crop production in the agricultural sector. It illustrates that value creation is much more prominent in the industrial sector than in agriculture, owing to the consumption of green hydrogen in hard-to-abate sectors. It is assumed that agricultural production could increase as a result of higher consumption of green ammonia-based fertilisers, but this effect of local consumption of ammonia in agriculture is not captured in the model (Figure 43).

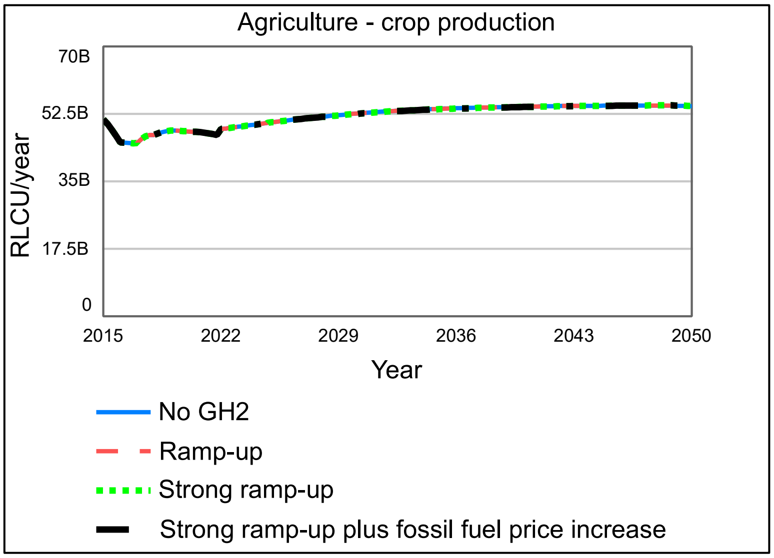

Figure 43 South Africa: Total value added from the agricultural sector in terms of total crop production (rand/year)

4.5.4 SDG 13 – Climate action

The performance of SDG 13 (Climate action) in the iSDG model is measured using two indicators: the 'disasters human impact index' and 'total greenhouse gas (GHG) emissions produced per year' (Figure 44). The performance of the climate goal in this analysis is, however, mainly assessed in terms of the latter – primarily due to the scale of relevance, but also because the former indicator showed no significant change under the green hydrogen scenarios. Therefore, although the performance of SDG 13 improves only marginally, there is a decrease in the level of GHG emissions under the GH2 ramp-up scenarios. The greatest reduction is observed in scenario 4, which reduces emissions by approximately 180 million tonnes/year, from ~620 million tonnes/year in the no-GH2 scenario to ~438 million tonnes/year by 2050 (Figure 44b). Emissions still remain too high under this scenario to achieve the 2030 climate goal, which is to halve national emissions compared with 2015. In the case of South Africa, the goal equates to approximately 234 million tonnes/year by 2030. Thus in 2050, emissions would still be double what they should have been in 2030, let alone close to net zero, which was the emissions target for 2050.

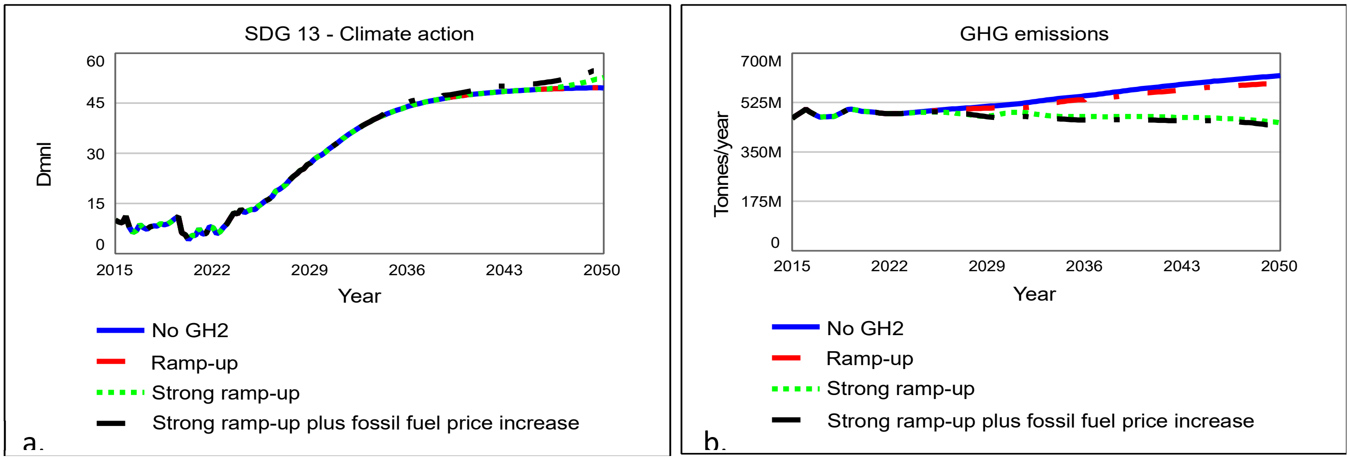

Figure 44 South Africa: Performance of SDG 13 (Climate action) and its results in terms of GHG emissions

4.5.5 Key environmental indicators

Additional environmental indicators were reviewed to assess natural resource constraints, specifically water and land resources (Figure 45). Figures 45a and b show that water and land use requirements increase with higher GH2 ramp-up. Ranging from the lowest to highest GH2 ramp-up scenarios, water demand increases between 90 to 400 million CM/year (or m^3/year) and land requirements increase from 340,000 to 1.5 million hectares, with the upper estimate corresponding to ~1% of South Africa's total land area (122 million hectares). Land availability therefore does not pose constraints on development. Moreover, the effect on the water resource vulnerability index (Figure 45c), a measure of total water supply against total water demand, increases only marginally under current water use projections, owing to an indirect increase in water withdrawal caused by an increase in industrial scale production (Figure 45c and d). The increase in water use requirements does not have a direct effect on water withdrawal in the model, as it is assumed that GH2 production will rely on alternative, dedicated forms of water supply (e.g. desalination or industrial wastewater), although indirect water demand from industry and a growing economy do effect the national water vulnerability index. Additional, site-specific assessments may be necessary to determine water resource constraints at different development scales.

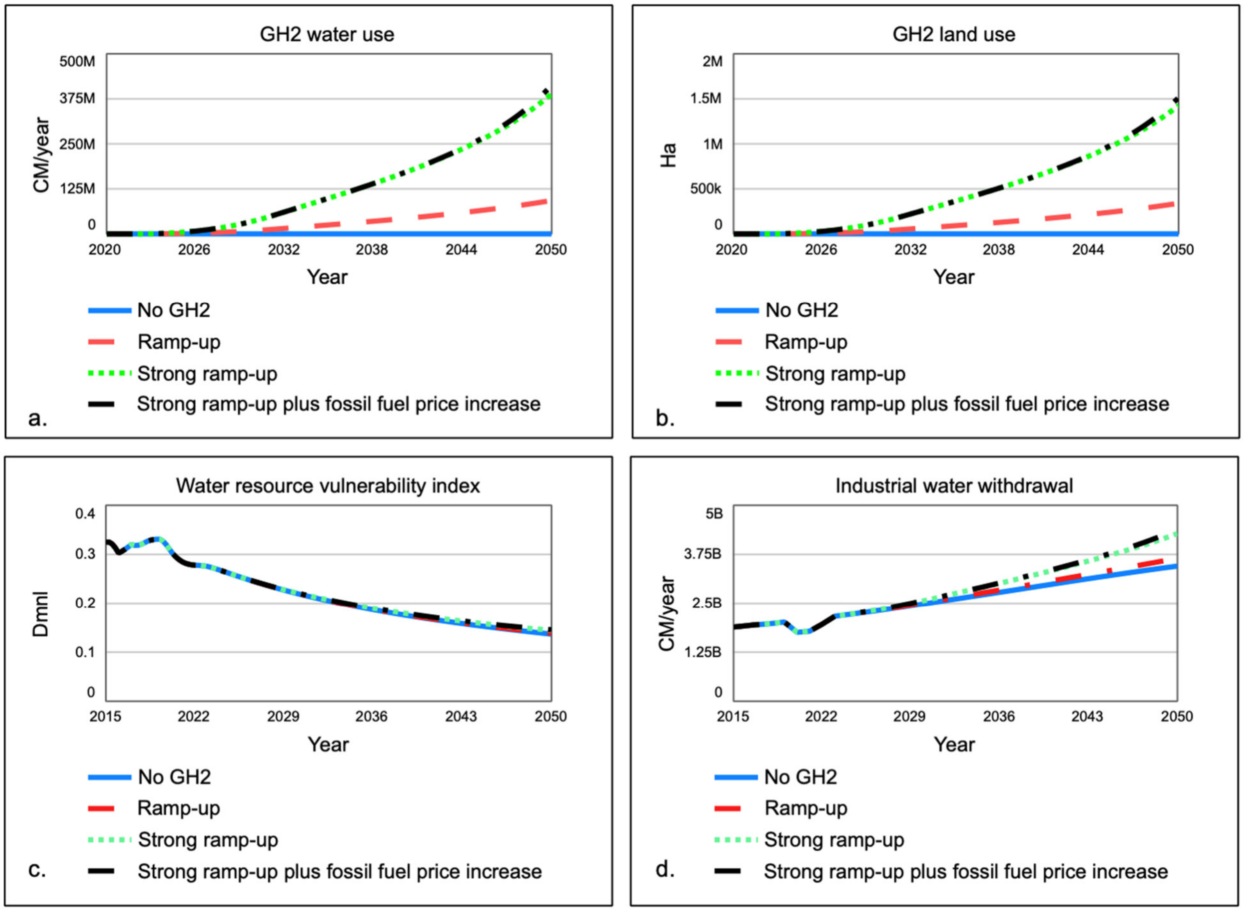

Figure 45 South Africa: Potential effects of green hydrogen production on national water and land resources. CM stands for cubic metres

4.5.6 Key social indicators

Key goals of the energy transition in South Africa are to bring about a just and equitable transition, ensuring that the benefits are distributed equally. The model investigates the 'Gini coefficient' and 'proportion of the population below the national poverty line' in order to evaluate social and poverty impacts (Figure 46). The results do not show a great reduction in inequality or poverty, although small improvements are evident, particularly in the controlled and fossil fuel ramp-up scenarios (Figures 46a and b). The effect of GH2 on inequality and poverty is small due to the scale of the green hydrogen economy and its value in relation to the rest of the economy. Although green hydrogen has potential as an effective decarbonisation solution, additional model adaptations would be needed to effectively capture the just transition in South Africa's energy system and along the decarbonisation value chain.

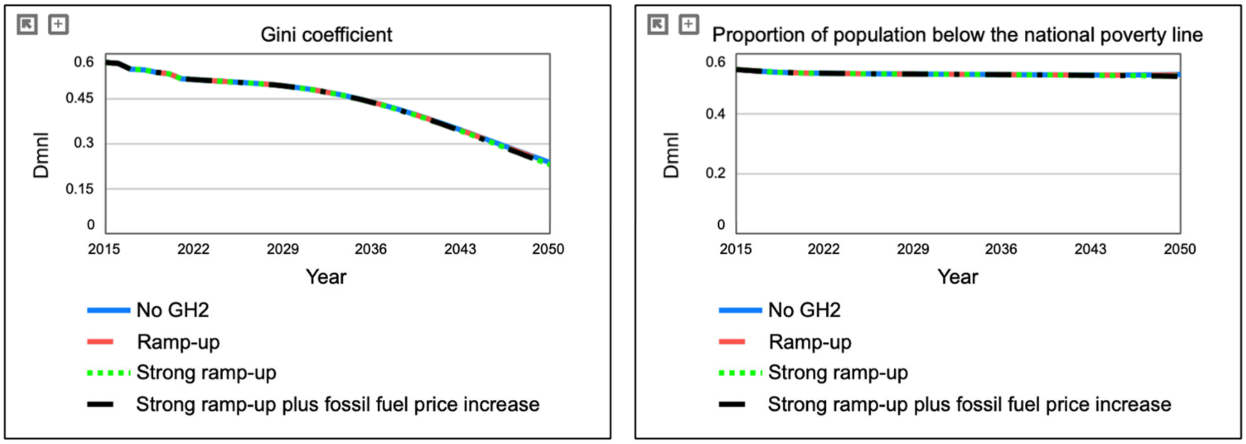

Figure 46 South Africa: Potential effects of green hydrogen production on levels of inequality and poverty

4.6 Key findings and recommendations

The aim of the analysis was to assess how green hydrogen can achieve its potential as an alternative energy vector in South Africa's energy system and decarbonisation agenda. From a national development perspective, this involved investigating the effects of the green hydrogen economy on the performance of the country's Sustainable Development Goals (SDGs). To perform the analysis for South Africa, the Integrated Sustainable Development Model (iSDG) was adapted and calibrated to country-specific data, after which it was coupled to the green hydrogen (GH2) sub-model developed for this analysis. Three comparative green hydrogen (GH2) ramp-up scenarios were simulated with varying assumptions on investment decisions, policy controls (e.g. carbon taxation) and external shocks.

Under the different GH2 scenarios, varying between scenario 2 (initial ramp-up) to scenario 4 (ramp-up with fossil fuel price increase), it is projected that green hydrogen consumption in the form of pure green hydrogen could be between 1 million and 4 million tonnes/year by 2050, with revenue generation varying between ZAR 14 and 45 billion/year (USD 820 million–2.6 billion/year) and labour potential projected to range from 12,000–50,000 jobs during the peak construction period (~2032) and between 2,500–8,000 jobs during operation. Moreover, under enabling conditions – including higher investment, lower transportation costs and higher costs for traditional fossil fuels – an export supply of 700,000 tonnes/year of ammonia, valued at approximately ZAR 22 billion/year (USD 1.28 billion/year), is projected for 2050. In total, by including the demand for all GH2 products (pure GH2, pure GH2 in the fuel cell sector, ammonia, synthetic methane and synthetic diesel), it is projected that GH2 consumption could range between 1.1–6.4 million tonnes/year by 2050, with a total sector value between ZAR 77 billion/year (USD 4.5 billion/year) and ZAR 370 billion/year (USD 22 billion/year), which corresponds to between 1 and 5% of GDP. In terms of total job creation, from direct and indirect

GH2 consumption, the sector could contribute a total of 556,000 jobs during the peak of the development period and end with approximately 200,000 jobs in 2050.

In terms of SDG performance, the largest gains observed are 2–12% for SDG 7 (Affordable and clean energy), 3–4% for SDG 8 (Decent work and economic growth), 1–8% for SDG 12 (Responsible consumption and production) and 3–6% SDG 13 (Climate action), depending on the GH2 model scenario. Marginal gains (1–2%) were also observed for SDG 2 (Zero hunger), SDG 3 (Good health and well-being), SDG 9 (Industry, innovation and infrastructure), SDG 14 (Life below water) and SDG 16 (Peace, justice and strong institutions). In contrast, SDG 10 (Reduced inequalities) showed a 2% reduction in final performance, with SDG 5 (Gender equality) and SDG 6 (Clean water and sanitation) also decreasing by approximately 1%. To investigate the underlying factors affecting SDG performance, the associated SDG indicators and causal relations were assessed. The increase in SDG 7 performance in this instance is predominantly a result of the increase in the share of renewables in total electricity generation. For SDG 8, the performance was attributed to an increase in the country's real GDP, which was also associated with the increase in industrial production value as reflected in the performance of SDG 9. SDG 9 also showed that, although industrial activity is increasing, 'green' developments, such as the green hydrogen sector, can result in lower emissions in the long-term, as evidenced by the decrease in the amount of carbon dioxide (CO_2) emissions per unit of value added. These results are consistent with the performance observed for SDG 13, which shows a decrease in greenhouse gas (GHG) emissions by approximately 180 million tonnes/year by 2050. Although this is not in line with the global and national climate goals – which is to halve emissions by 2030 and reach net-zero by 2050 – it is encouraging to see that green hydrogen has potential with regard to emission reduction pathways. Based on the evaluation of key environmental indicators, it appears that natural resources – specifically water and land – do not constrain development under current model projections. Lastly, minor to no improvement is observed on levels of inequality, poverty and unemployment – possibly owing to the small scale of the green hydrogen economy in the broader national context. Additional analysis may be required to measure the full spectrum of employment opportunities in the green hydrogen sector, other than during the construction and operational phases of development. Finally, a more focused, narrower analysis may be necessary to understand the impacts of a just transition from a fossil-fuel to renewables-based economy in South Africa, since the contribution of green hydrogen as a sector reflects only one decarbonisation pathway amongst several others, so that only marginal improvements are reflected in the results.

4.7 Technical annex: Calibration performance

Refer to the explanation of model statistics under section 3.7.

Table 7 South Africa: Model calibration's goodness of fit

RMSPE	Value (element 1)	Value (element 2)
KPI.population by sex RMSPE [sex]	0.013516369	0.00741052
KPI.total fertility rate RMSPE	0.020211794	
KPI.life expectancy RMSPE [sex]	0.07635239	0.056969751
KPI.average years of schooling RMSPE [sex]	0.046144493	0.030539411
KPI.average access to basic health care RMSPE	0.032900498	
KPI.infrastructure RMSPE [infra]	0.129775331	0.455203859
KPI.employment by sector RMSPE [sector]	0.134749998	0.112347371
KPI.Gini coefficient RMSPE	0.077105606	
KPI.proportion of population below poverty line RMSPE	0.442313857	
KPI.yield RMSPE [crop]	0.057257333	0.186675046
KPI.livestock production in tonnes per hectare RMSPE [livestock]	0.049723484	
KPI.relative fish capture in tonnes RMSPE [fish]	0.268456264	
KPI.relative fish harvest in tonnes RMSPE [fish]	0.2992637	
KPI.relative forestry production in cubic metres RMSPE [wood]	0.069858473	
KPI.industrial production RMSPE [industry]	0.032361454	0
KPI.services production RMSPE [services]	0.044955368	0.042677152
KPI.private savings RMSPE	0.322564034	
KPI.total export as share of GDP RMSPE	0.070463274	

RMSPE	Value (element 1)	Value (element 2)
KPI.agricultural land RMSPE [agriculture]	0.04890527	0
KPI.forested land RMSPE	0.052553029	
KPI.access to safely managed water source RMSPE [area]	0.13867981	0.012960176
KPI.access to safely managed sanitation facility RMSPE [area]	0.17838404	0.090650586
KPI.total water withdrawal RMSPE	0.041231522	
KPI.soil primary nitrogen balance RMSPE	0.213814356	
KPI.domestic material consumption RMSPE	0.262579464	
KPI.CO_2 emissions RMSPE	0.093231217	
KPI.fish resources availability share RMSPE	0.125903431	
KPI.gross international reserves RMSPE	0.109664087	
KPI.final energy consumption by sector RMSPE [agr, final_energy_with_GH2]	0.158002589	0
KPI.final energy consumption by sector RMSPE [ind, final_energy_with_GH2]	0.115198497	0.308858881
KPI.final energy consumption by sector RMSPE [ser, final_energy_with_GH2]	0.973836961	5.551561286
KPI.final energy consumption by sector RMSPE [res, final_energy_with_GH2]	0.158028814	0.150432573
KPI.final energy consumption by sector RMSPE [tra, final_energy_with_GH2]	0.057114615	0.632455532
KPI.final energy consumption by sector RMSPE [oth, final_energy_with_GH2]	0.342471476	0

TBIAS	Value (element 1)	Value (element 2)
KPI.population by sex TBIAS [sex]	0.399061353	0.69920933
KPI.total fertility rate TBIAS	0.444760429	
KPI.life expectancy TBIAS [sex]	0.93452257	0.621357219
KPI.average years of schooling TBIAS [sex]	0.005654059	0.005915568
KPI.average access to basic health care TBIAS	0.784437258	
KPI.infrastructure TBIAS [infra]	0.000342833	0.481198398
KPI.employment by sector TBIAS [sector]	0.399821748	0.044632545
KPI.Gini coefficient TBIAS	0.037544199	
KPI.proportion of population below poverty line TBIAS	0.819444834	
KPI.yield TBIAS [crop]	0.272087868	0.41436416
KPI.livestock production in tonnes per hectare TBIAS [livestock]	0.007033002	
KPI.relative fish capture in tonnes TBIAS [fish]	0.000950374	
KPI.relative fish harvest in tonnes TBIA S[fish]	0.061260297	
KPI.relative forestry production in cubic metres TBIAS [wood]	0.011712581	
KPI.industry production TBIAS [industry]	0.041299546	0
KPI.services production TBIAS [services]	0.105348544	0.007368743
KPI.private savings TBIAS	0.01661422	
KPI.total export as share of GDP TBIAS	0.002758271	
KPI.agricultural land TBIAS [agriculture]	0.717607285	0
KPI.forested land TBIAS	0.857977668	
KPI.access to safely managed water source TBIAS [area]	0.68879499	0.93413251
KPI.access to safely managed sanitation facility TBIAS [area]	0.55999257	0.010456082

TBIAS	Value (element 1)	Value (element 2)
KPI.total water withdrawal TBIAS	0.095264136	
KPI.soil primary nitrogen balance TBIAS	0.105362094	
KPI.domestic material consumption TBIAS	0.929803033	
KPI.CO_2 emissions TBIAS	0.619795527	
KPI.fish resources availability share TBIAS	0.631063714	
KPI.gross international reserves TBIAS	0.003156334	
KPI.final energy consumption by sector TBIAS [agr, final_energy_with_GH2]	0.001395427	0
KPI.final energy consumption by sector TBIAS [ind, final_energy_with_GH2]	0.149340099	0.194130706
KPI.final energy consumption by sector TBIAS [ser, final_energy_with_GH2]	0.003155007	0.137700937
KPI.final energy consumption by sector TBIAS [res, final_energy_with_GH2]	0.782575089	0.10943578
KPI.final energy consumption by sector TBIAS [tra, final_energy_with_GH2]	0.018355521	0.4
KPI.final energy consumption by sector TBIAS [oth, final_energy_with_GH2]	0.436607139	0

References

CSIR, Council for Scientific and Industrial Research, 2022. Statistics of utility-scale power generation in South Africa in 2021, CSIR Energy Centre.

Department of Public Works and Infrastructure, 2022. Government Notices: Strategic Integrated Projects, 5.

DSI, Department of Science and Innovation, 2021. Hydrogen Society Roadmap for South Africa: Securing a Clean, Affordable and Sustainable Energy Future for South Africa. https://www.dst.gov.za/images/South_African_Hydrogen_Society_RoadmapV1.pdf

IEA, 2021. Net Zero by 2050: A Roadmap for the Global Energy Sector. International Energy Agency, 224. https://www.iea.org/reports/net-zero-by-2050

NBI, National Business Initiative, 2021. Just Transition and Climate Pathways Study for South Africa: Decarbonising South Africa's Power System.

NPC, National Planning Committee of the Republic of South Africa, 2017. National Development Plan 2030: Our future – make it work, The Philippine Journal of Nursing.

Stats SA, 2017, Sustainable Development Goals: South Africa Indicator Baseline Report 2017, Statistics South Africa.

UN, United Nations, 2019. World Economic Situation and Prospects Report: Statistical Annex.

5. Model application for Namibia

5.1 Country background

With a coastline of approximately 1,500 km, abundant sunshine, wind and space, Namibia possesses ideal natural resources for the production of green hydrogen. In the Harambee Prosperity Plan II, President Hage Geingob designated the development of a green hydrogen industry as central to the country's attainment of zero carbon emissions and energy independence (SASSCAL, 2021). The Namibian Government envisions production of 10 to 15 million tonnes of hydrogen equivalent per year by 2050 (Ministry of Mines and Energy Namibia, 2022). The Namibian Government has set ramp-up targets of 1–2 Mtpa of hydrogen equivalent by 2030, 5–7 Mtpa by 2040 and 10–15 Mtpa by 2050. The green hydrogen developer Hyphen Hydrogen Energy (Pty) Ltd. is making an initial investment in green hydrogen of USD 9.5 billion over approximately eight years and predicts that Namibia will produce 15 million tonnes of green hydrogen per year for the production of green fertiliser, shipping fuel, aviation fuel and green steel by 2050, generating some USD 36 billion in export earnings (Hyphen 2021). Hyphen also forecasts that the green hydrogen industry in Namibia will support more than 200,000 permanent jobs by 2050 in renewable energy for green hydrogen alone (Hyphen 2021). The Ministry of Mines and Energy of Namibia predicts that the green hydrogen industry could add USD 6 billion to Namibia's GDP by 2030, an increase of 30% over projections without green hydrogen development (Ministry of Mines and Energy Namibia, 2022). The Ministry estimates that 280,000 jobs could be created by 2030, increasing to 600,000 by 2040. About 30% of these would be direct jobs, 20% are expected to be indirect jobs in goods and services, and 50% would be generated by increased household incomes. About 10% of the direct employment would be highly skilled jobs in engineering and management. The Government of Namibia is investing in training to address any skills shortfall (Ministry of Mines and Energy Namibia, 2022).

In addition to job creation and boosting GDP, the green hydrogen industry is expected to improve access to electricity by developing renewable electricity capacity beyond that needed for green hydrogen production. The excess electricity generated will be made available to the national energy grid (currently only about 56 per cent of the population of Namibia has access to electricity). The same principle applies to potable drinking water, as developers intend to develop desalination capacity in excess of the level needed for green hydrogen production. Table 8 provides a breakdown of green hydrogen projects in Namibia currently under development or proposed.

Table 8 Information on current green hydrogen projects in Namibia

Project	Implementing institutions	Funding	Timeline	Location	Goal
Southern Corridor Development Initiative (SCDI) Namibian Green Hydrogen Project	Hyphen Hydrogen Energy (Pty) Ltd.	USD 9.4 billion financed by the German and Namibian governments (Namibian contribution: 24% of total), other unknown	Present – start of production by the end of 2026; full production capacity by 2030	Tsau Khaeb National Park, south-west Namibia	300,000 tpa green hydrogen by end 2030
Renewstable® Swakopmund	HDF Energy	USD 178.4 million through a financial partnership with European Investment Bank	Present - production start planned in 2024	Swakopmund	Approx. 3,000 tpa green hydrogen
Green Hydrogen Applications in the Port Environment	Cleanergy Solutions Namibia, CMB Germany GmbH & Co. KG, and Namport, University of Namibia	EUR 5.66 million	-	Walvis Bay Port	5 MW Electrolyser and H_2 mobile refueller (945 kg at 500 bar
Hydrogen pilot plant and refuelling station in Walvis Bay	CMB.TECH, Ohlthaver & List Group (joint venture = Cleanergy Solutions Namibia)	EUR 25 million	-	Walvis Bay	5 MW Electrolyser

Hydrogen-diesel dual fuel locomotive pilot project proposal for Namibia with supporting research projects	CMB.TECH, UNAM, Hyphen Technical, TransNamib, NGHRI, Nicholas Holding	EUR 7.63 million	-	Walvis Bay to Kranzberg corridor in Namibia, to be operated by TransNamib railway company	50 locomotive fleet conversion to GH2 dual fuel
Daures Green Hydrogen Village	NGHRI, University of Stuttgart, Enapter, Windwise, Enersense Nam	EUR 15.1 million	-	Erongo region, Daures constituency	1.5 GW (current phase: 508 kg of green ammonia/day)

Several areas of risk due to green hydrogen industrial development can be considered: sectoral risk (risk to the success of the industry itself), fiscal risk to the Government of Namibia, local social and environmental risks, and risks to decarbonisation.

- Sectoral risks. There is considerable uncertainty regarding the potential demand for green hydrogen and green hydrogen products. The World Energy Council and PWC (Price Waterhouse Coopers) estimate that global hydrogen demand by 2050 could range between 150 and 500 million tonnes per year, depending on direct electrification, use of carbon capture, energy efficiency and other factors (Elston, 2022; PWC 2022). Estimates of global uptake of green hydrogen are largely predicated on expectations of cost reductions for electrolysis and renewable energy (Hyphen, 2022). Global green hydrogen markets may not develop if costs do not decline as anticipated and if investments are not made in developing supply chains for green hydrogen products. Related to this is the risk that governments may lack the political will to implement policies that could drive demand for green hydrogen products (Goldthau and Tagliapietra, 2022).
- Fiscal risks. The Namibian Government may take as much as a 24% stake in the initial financing of green hydrogen; some researchers caution that Namibia could incur large debts if the Namibian green hydrogen sector fails to develop at the hoped-for speed or scale (Elston, 2022).
- Local environmental risks. The Southern Corridor green hydrogen project is located in the Tsau Khaeb National Park, a centre of sensitive biodiversity and endangered species in both terrestrial and coastal marine habitats. Some studies in other geographies have warned of possible damaging effects of desalination operations and brine discharges into coastal marine environments (Petersen et al, 2022; UNEP). Hyphen Hydrogen Energy has

commissioned a detailed study to report implications of the project on terrestrial and marine and environment and eco-tourism (Hyphen 2022).

- Local social risks. Few studies have examined social impacts of green hydrogen development in Southern Africa. A review by Hamukoshi et al. (2022) focuses on social-economic benefits. A proposed social impact assessment (SIA) by the Namibia Green Hydrogen Research Initiative will examine social impacts including possible negative impacts on marginalised groups (NGHRI).
- Decarbonisation risks. Recent discoveries of vast oil deposits in Namibia, by some estimates in excess of 120 billion barrels (Burkhartdt and Cranny, 2022), threaten Namibia's aspirations to contribute to global decarbonisation.

5.2 Model configuration and key assumptions for the Namibian analysis

For the Namibian green hydrogen study a sub-model of the green hydrogen sector was developed and integrated with an iSDG model specified for Namibia. In similar fashion to the other two country models developed for this study, the green hydrogen sub-model and iSDG components are interactive and exchange information continuously during simulation. This coupling makes it possible to study the green hydrogen sector within the broader national context, examining impacts on SDG attainment and other indicators of sustainable development. The iSDG component of the Namibia green hydrogen model was calibrated with data obtained from international sources. The development of the green hydrogen module was guided by available literature, presentations, and reports. Data for green hydrogen cost projections, etc. were obtained from international sources such as the International Energy Agency.

As described in the methods in section 2.4, four basic scenarios are simulated to assess possible impacts of a developing green hydrogen sector on the SDGs and other development indicators of interest. Similar to the other two countries, the scenario descriptions are as follows:

1) No GH2. This serves as a reference scenario with no investment or development of a green hydrogen sector.
2) Ramp-up. This scenario simulates possible impacts of ramp-up investments that have been officially announced without other policies.
3) Strong ramp-up. This scenario adds tax incentives, carbon taxation, and increases the investment used in the ramp-up scenario.
4) Strong ramp-up with fossil fuel price increase. This scenario adds the effects of a global increase in fossil fuel prices to the strong ramp-up scenario.

Table 9 shows the parameters used to model the four scenarios in Namibia. The interactive user interface developed for this model will allow users to easily design and simulate their own real time scenarios by adjusting an array of input parameters [https://exchange.iseesystems.com/public/millenniuminstitute/gh2-ramp-upnamibia].

Table 9 Namibia: Parameters values for scenario definitions

	First movers' investment amount (real NAD)	Timeline of first movers' investments	GH2 consumers adoption time (years)	Domestic carbon tax (USD_{2010}/tCO_2-eq.)	International (EU) carbon tax (USD_{2010}/tCO_2-eq.)	Tax break on profits (fraction of profits)	Tax break on infrastructure expenditure (fraction of expenditure)	Fossil fuel price (USD/MWh) [oil; gas; coal]
No GH2	NA	NA	NA	NA	NA	NA	NA	Stable
Ramp-up [as announced]	NAD 70.5 billion	2022 to end 2030	8	0	0	0	0	Stable
Strong ramp-up	NAD 105.75 billion	2022 to end 2030	4	25 with 1% increase per year	80 with 1% increase per year	0.1	0.1	Stable
Strong ramp-up with fossil fuel price increase	NAD 105.75 billion	2022 to end 2030	4	25 with 1% increase per year	80 with 1% increase per year	0.1	0.1	Increases to [36; 14; 6]

The purpose of the model is to assess potential impacts of green hydrogen development on sustainable development as revealed through the SDGs and other indicators. Such a broad approach necessitates simplifying assumptions, some of these are:

- The model does not explicitly take into account specifics of electrolyser type, downstream processing of pure hydrogen into green hydrogen products, storage or transport facilities, or desalination. These are considered to be integral components of capacity infrastructure. Importantly, the model *does* explicitly account for the development time lags that are critical aspects of the green hydrogen development dynamics.

- As with the other country models in this study, the Namibian model assumes that the levelised cost of electricity (LCOE) decreases at a gradual exponential rate. The rate of decline is defined exogenously and reflects global technological development (Figure 28b).
- A similar assumption of gradually falling cost of electrolysers and green hydrogen technology is made.
- The Namibia model assumes that renewable electricity is sourced equally from solar and wind (as with the South Africa model).
- The Namibia model assumes that water is sourced entirely from desalinated coastal water and therefore does not impact the availability of freshwater from natural sources.
- The Namibia model assumes that all electricity for electrolysis, and other uses in processing pure hydrogen to derivative products, is from renewable sources (solar and wind) independent of the national grid.

5.3 Namibia GH2 model results

Our analyses cover the time horizon from 2020 to 2050. The simulations shown in Figure 47 shows the simulated consumption and value-added of green hydrogen products under the four scenarios described above. We assume that consumption is equal to production, this includes both domestic and export consumption. The mix of green hydrogen products includes pure hydrogen, pure fuel cell hydrogen, ammonia, liquified synthetic methane, and synthetic diesel. The exact mix of green hydrogen products that will be produced is unknown; however, indications are that ammonia is a priority for investors, at least in early stages (Reuters, 2022). To account for the emphasis on ammonia, the model distributes 30 per cent of investment to ammonia, with 17.5 per cent distributed to pure H2, pure fuel cell H2, liquified synthetic methane, and synthetic diesel each.

In the ramp-up scenario (parameters shown in Table 9), approximately 1.75 million tonnes of GH2 products will be produced and consumed by 2050, contributing just over NAD 22 billion (USD_{2010} 2.22 billion) in value added to the Namibian economy. In the strong ramp-up scenario, almost 2.2 million tonnes of GH2 products are produced with about NAD 26.25 billion (USD_{2010} 2.65 billion) in value added in 2050. In the strong ramp-up with fossil fuel price increase scenario approximately 2.75 million tonnes of GH2 products are produced with almost NAD 56 billion in value added in 2050 (USD_{2010} 5.66 billion). Only the strong ramp-up with fossil fuel price increase scenario generates exports, specifically of green ammonia. This accounts for the increased share of green ammonia for consumption and value-added shown in Figures 47e and 47f.

Green ammonia is of prime interest to GH2 investors in Namibia. Figure 47a shows green ammonia consumption under the different scenarios. The no-GH2 scenario is not shown since it is assumed that there is no production or consumption of GH2 products. As expected, consumption is given a boost under the scenarios with the greater ramp-ups in investment and investment incentives (tax breaks and carbon taxes listed in Table 9). Similar to the South African case (Figure 47b), the ramp-up scenario with fossil fuel price shock makes green ammonia attractive enough in price compared to conventional ammonia to incentivise exports.

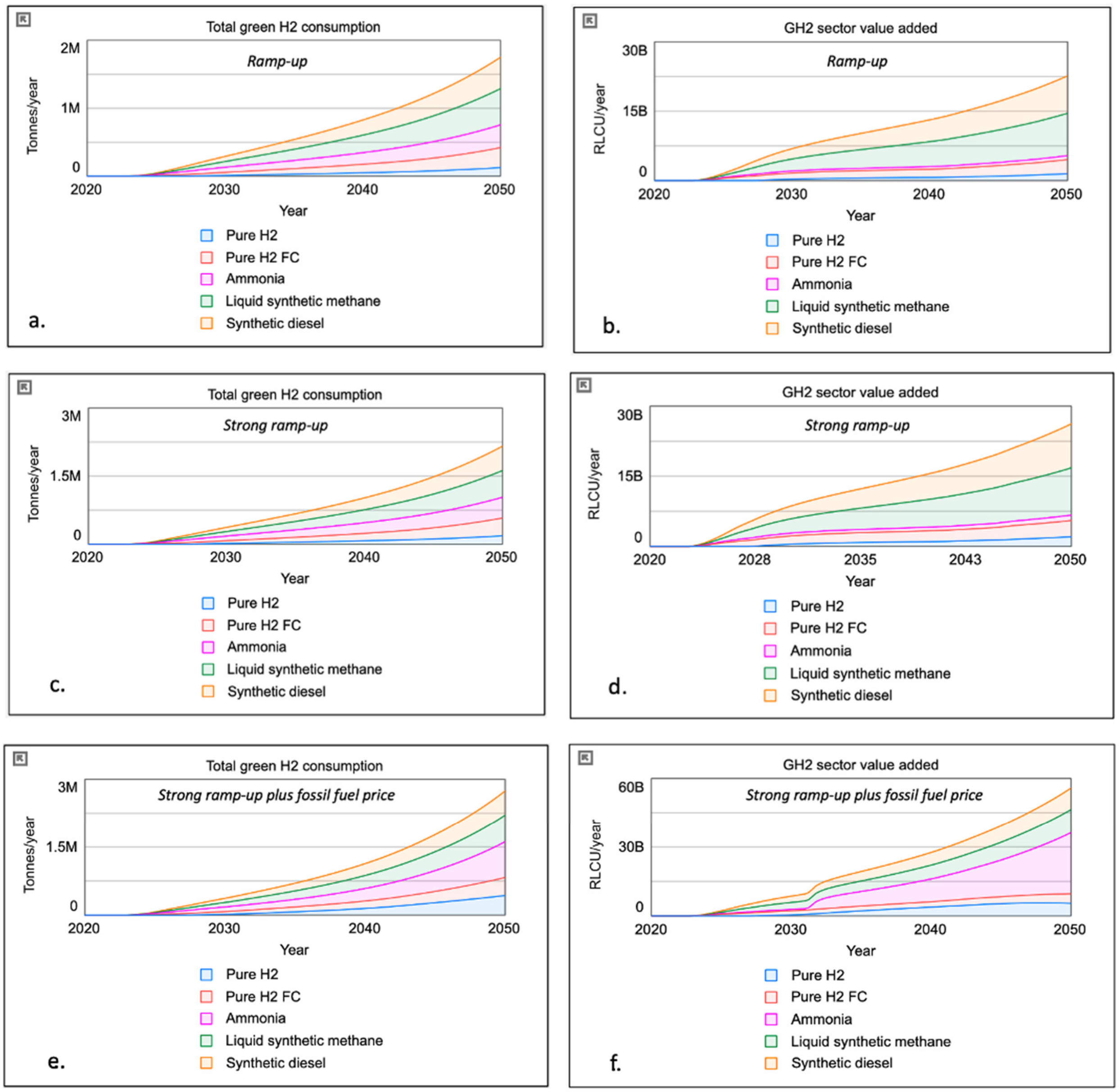

Figure 47 Namibia: Consumption and value added of GH2 products under ramp-up, strong ramp-up, and strong ramp-up with fossil fuel price increase scenarios

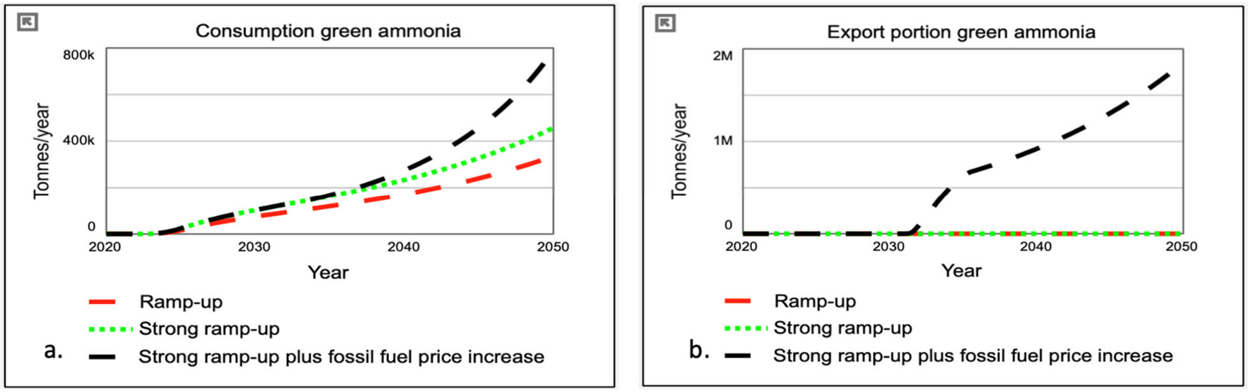

Figure 48 Namibia: Green ammonia consumption

Figure 48b shows that infrastructure capacity under development rises sharply in response to the implementation of the ramp-up investment. There is a time lag, assumed to be five years, during which infrastructure capacity under development becomes operational. Also, the operational infrastructure decays over an assumed average useful lifetime of 30 years.

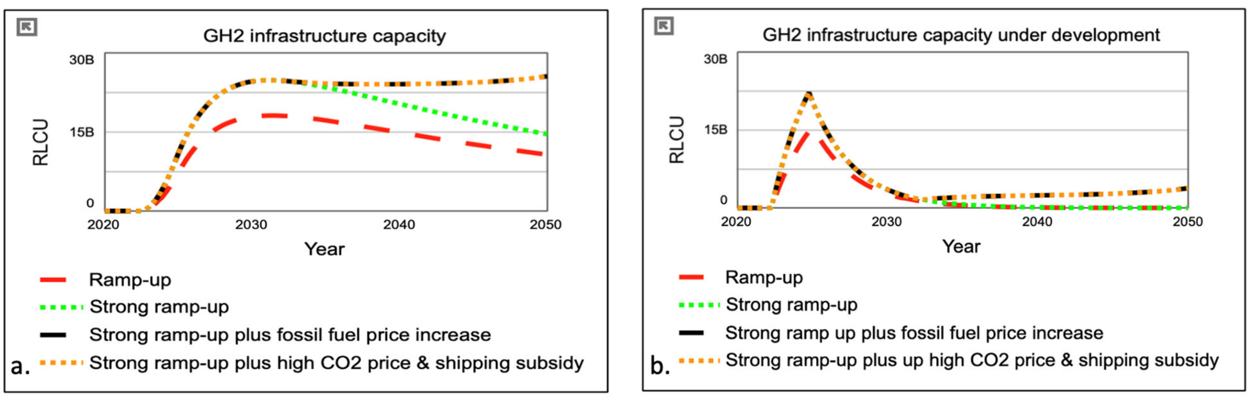

Figure 49 Namibia: Simulations showing overshoot patterns for GH2 infrastructure capacity in operation and under development

Under the ramp-up and strong ramp-up scenarios, an overshoot and decline pattern of capacity in operation occurs because – in the model – the return to capital is inadequate to incentivise reinvestment after the initial ramp-up period is concluded. Also, the return to capital under the ramp-up and strong ramp-up scenarios is inadequate to encourage rebuilding of decaying capacity; therefore production infrastructure capacity gradually diminishes over time. The infrastructure capacity build-up after the ramp-up investment is more than adequate to cover domestic demand and suppresses the prices and returns to capital for GH2 products. In the ramp-up and strong ramp-up scenarios, the GH2 products remain too expensive for export consumption – primarily due to shipping costs. Under the strong ramp-up with fossil fuel price increase green ammonia becomes attractive for export even with shipping costs due to the elevated fossil fuel cost. The export of green ammonia under the strong ramp-up with fossil fuel price increase scenario suggests that exports can be achieved with price or cost reduction incentives, such as high carbon prices coupled with subsidies for shipping costs. It also provides evidence that without incentives for export a large scale and sustainable export-based GH2 industry in Namibia might fail to materialise. As a test, the strong ramp-up with high carbon price and shipping subsidy scenario uses a carbon price of USD 200 per tonne of carbon equivalent per year, combined with a shipping subsidy that halves shipping costs. The issue of incentives for export will be returned to in section 5.5.

As expected, job creation is greater under the strong ramp-up scenarios (Figure 50a). Figure 50b shows construction and operations staff numbers over time. When the ramp-up investment is initiated, construction shoots steeply upward in response and then begins a steep decline. The decline in numbers of construction staff is somewhat moderated by the need to employ construction staff to build replacement capacity infrastructure as existing capacity infrastructure depreciates and is retired. Operations staff also shows an overshoot pattern, although more moderate. The overshoots in staffing occur because staffing is directly linked with changes in infrastructure capacity. The GH2-related jobs include only those directly involved in construction and operation of GH2 facilities and do not include those related to support services and knock-on development. Direct employment is expected to represent only about 30% of the employment generated by the green hydrogen industry (Ministry of Mines and Energy Namibia, 2022).

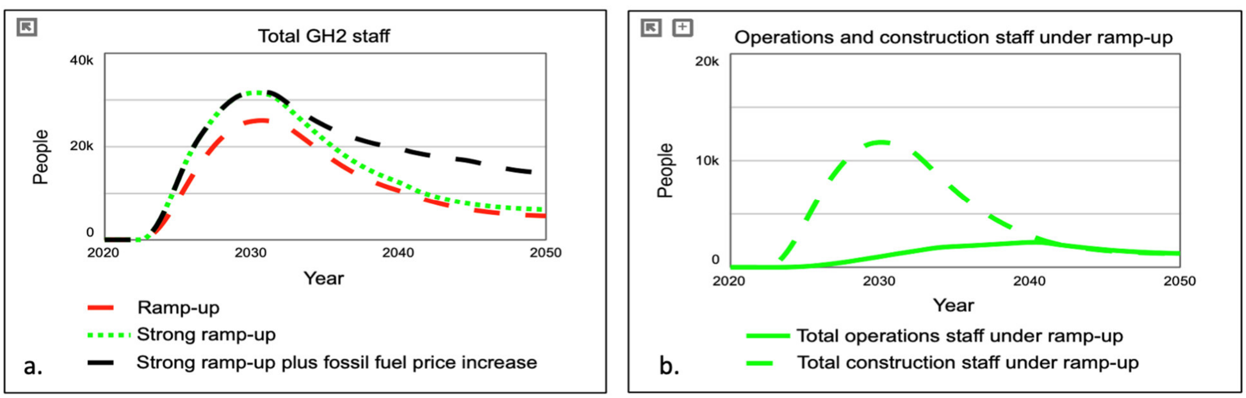

Figure 50 Namibia: Staffing dynamics in the GH2 sector demonstrating overshoot patterns over time

5.4 Potential impacts of GH2 on Namibia's SDG performance

A central purpose of this study is to assess impacts of a GH2 sector on the SDGs. Figure 51 plots possible influences on SDG attainment under the four scenarios of GH2 development used in this study. These influences are from GH2 alone, as no other SDG policies apart from GH2 investment are explicitly included in the simulations. The SDGs are tracked to 2050. The SDGs are formally targeted to year 2030 but they are nevertheless the most widely used and comprehensive sustainable development indicators available and remain useful well beyond their mandated time horizon. Figure 51 plots all 17 SDGs showing the level of attainment in 2050. The ramp-up scenarios out-perform the no-GH2 scenario for all SDGs except for SDG 10 (Reduced inequalities) where no GH2 performs best and SDGs 11 (Sustainable cities and communities) and 13 (Climate action) where no progress is observed.

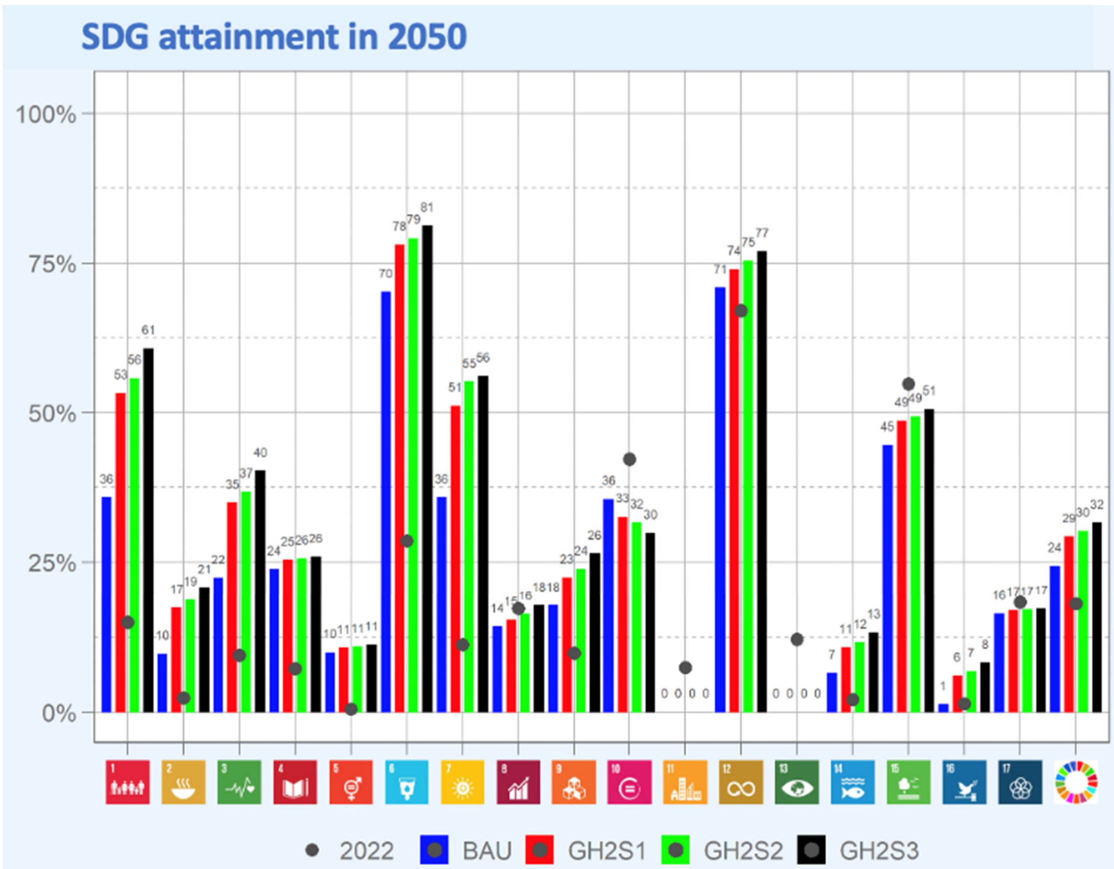

Figure 51 Namibia: Plot of SDG attainment in 2050

In the case of SDG 10, no GH2 outperforms the ramp-up scenarios due to an iSDG modelling assumption that impacts the simulated performance of SDG indicator 10.4.1: the share of GDP to labour. The ramp-up scenarios all result in a greater share of GDP to labour (which, ceteris paribus, favours more equitable income distribution) than the no-GH2 scenario, indicating 0.66, 0.58, and 0.56 in 2050 for strong ramp-up with fossil fuel price increase, strong ramp-up, and ramp-up respectively where no-GH2 in 2050 is 0.47. No GH2 outperforms the other scenarios in the simulation because it is closest to the default setting of 0.5 for the desired share to labour. A better understanding of the Namibian Government's desired level of GDP share to labour is needed to assess the performance of this indicator and the influence of GH2 on SDG 10. The results shown here for SDG 10 should therefore be considered inconclusive. Figure 52 shows differences between the ramp-up scenarios and the no-GH2 scenario for SDG achievement.

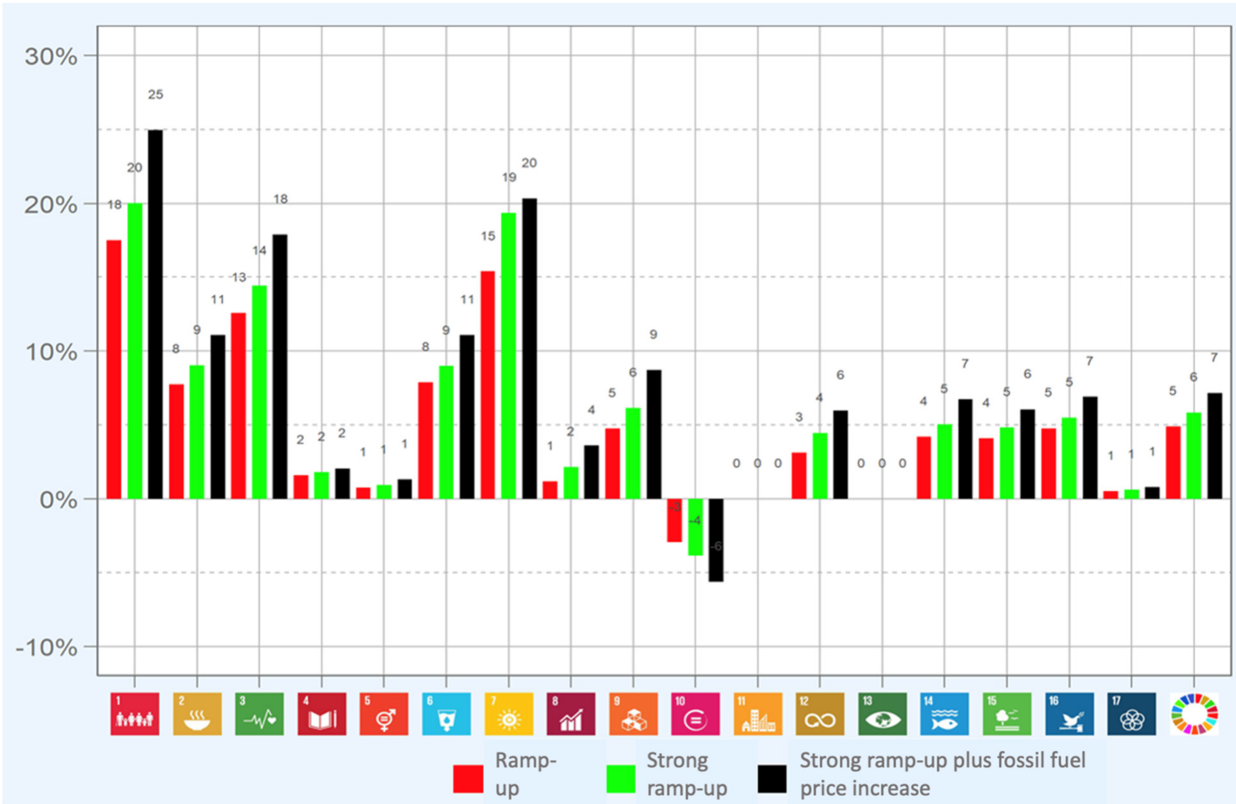

Figure 52 Namibia: Differences between the ramp-up scenarios

Special attention is given to SDGs 7, 8, and 9 in this study. Below we examine their performance along with three accompanying indicators.

5.4.1 SDG 7 – Affordable and clean energy

Figure 53 shows the simulated progression for SDG 7 along with three indicator variables. Each ramp-up scenario outperforms the no-GH2 baseline. The proportion of the population with access to electricity is improved; this is not a direct impact of GH2 but is multifactorial, influenced by intertwined effects including rising GDP and government investment and lowered poverty rates. However, there is likely a direct link from GH2 that is not captured in this model: investors at Hyphen have stated that renewable energy development in the GH2 project they are funding will develop renewable energy capacity beyond what is needed for GH2 production, making this excess electricity available to the national grid. This will also contribute to the share of renewables in energy consumption (Figure 53c). Much of the progress for SDG 7 due at least in part to GH2 appears to result from an increase in the indicator for energy efficiency. The target for the indicator is reached in the strong ramp-up with fossil fuel shock scenario and is very nearly reached in the strong ramp-up and ramp-up scenarios.

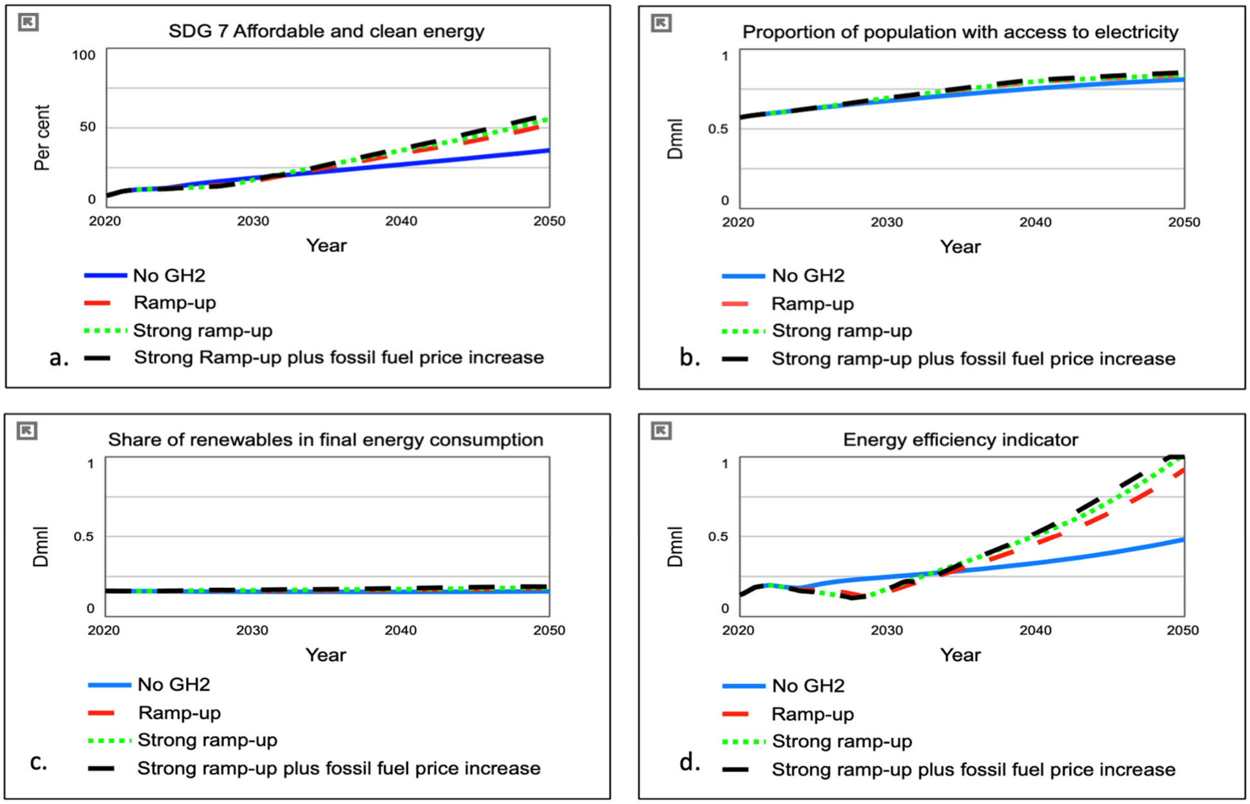

Figure 53 Namibia: Performance of SDG 7 and associated indicator variables under simulated scenarios

5.4.2 SDG 8 – Decent work and economic growth

GH2 has no notable overall impact on SDG 8, as shown in Figure 54a. However, the GH2 industry provides a boost to GDP and lowers the unemployment rate through knock-on effects captured during the simulation. There is marginal progress in the domestic material consumption indicator, which is a measure of the efficiency of resource use.

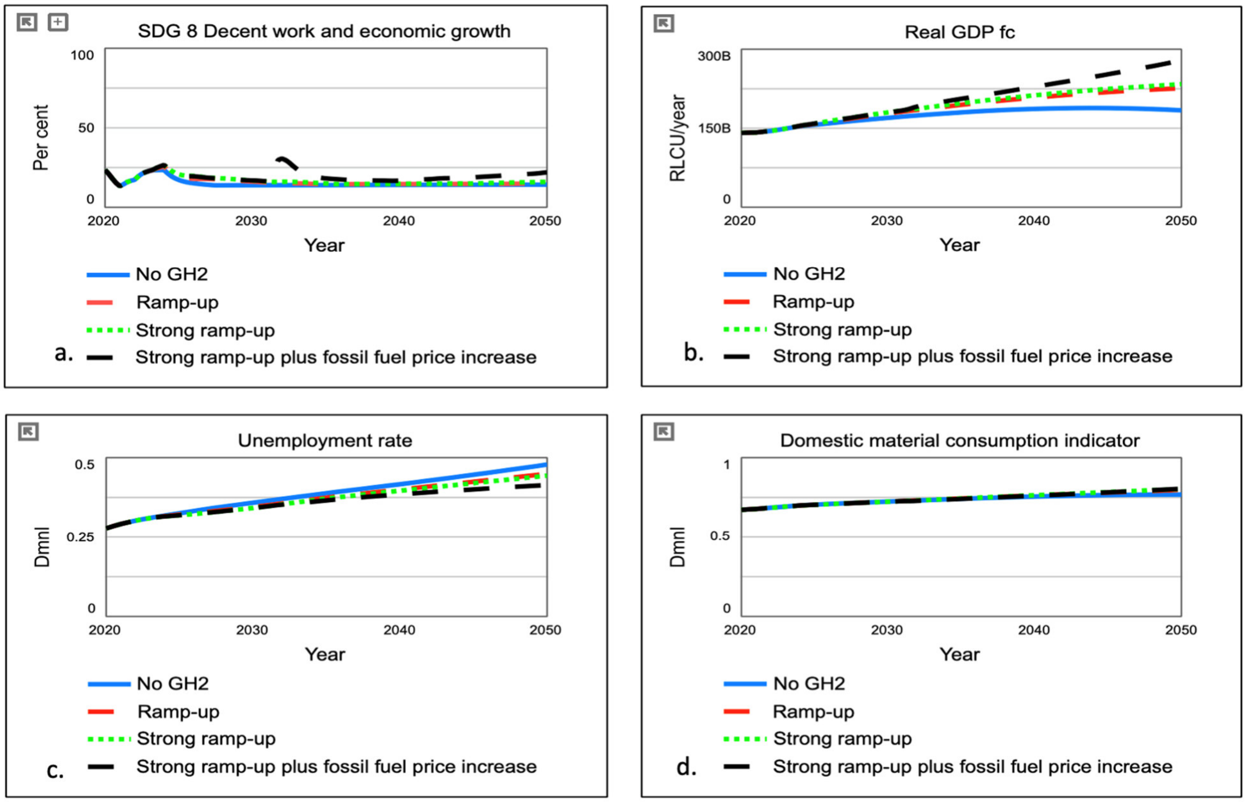

Figure 54 Namibia: GH2 influences on SDG 8 and associated indicator variables

5.4.3 SDG 9 – Industry, innovation and infrastructure

Figure 55 shows influences of the GH2 sector on SDG 9. Overall performance of SDG 9 is improved. Especially noteworthy is the pattern revealed in Figure 55d: a growing industry sector and economy coupled with declining CO_2 emissions due to adoption of GH2 products causes CO_2 emissions to fall by around half by 2050.

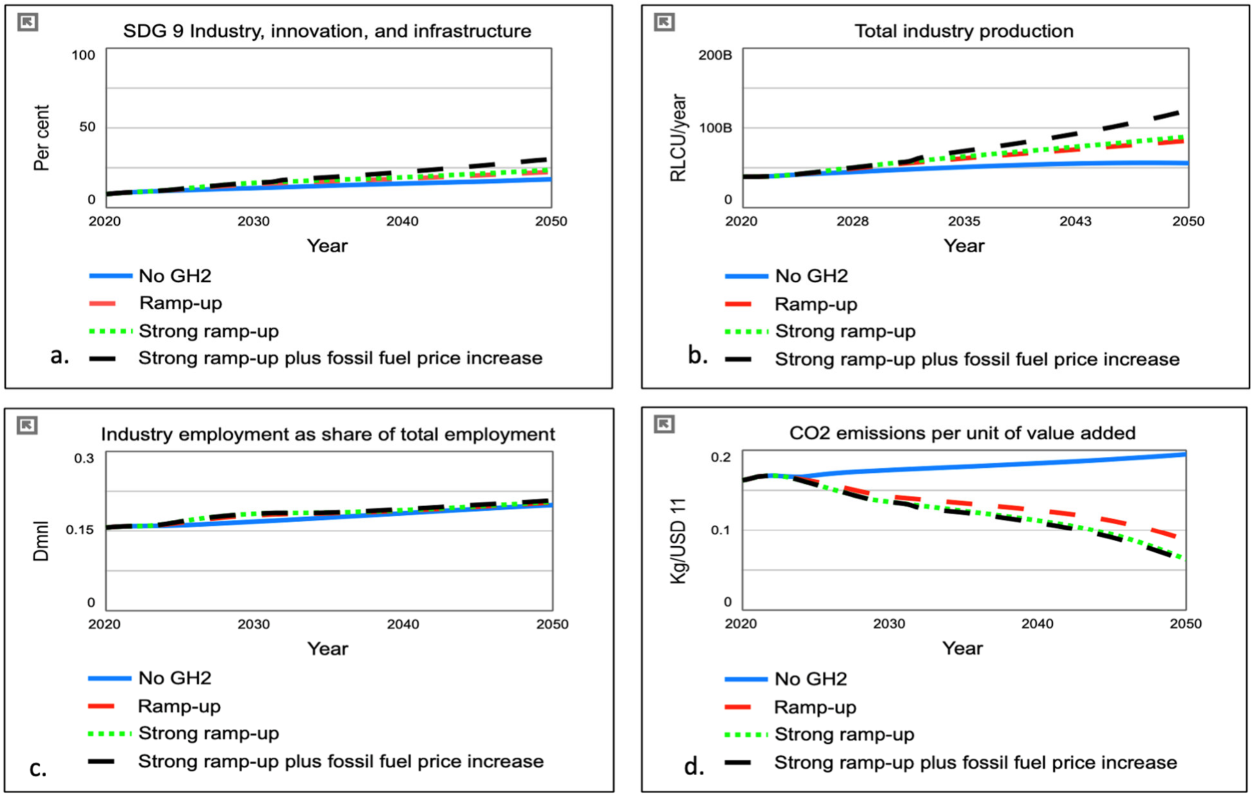

Figure 55 GH2 influences on SDG 9 and indicator variables

5.4.4 SDG 13 – Climate action

GH2 shows little to no effect on progress on SDG 13 in our simulations (Figure 56a). This is related to the structure of SDG 13 more than to any effects on the climate itself. SDG 13 emphasises the occurrence of disaster events caused by climate warming and their effects on the national economy and lives and welfare of the population. Disaster events caused by climate warming call for climate change adaptation strategies and investments. Actions to adapt to disasters caused by climate warming are outside the scope of this study. The simulations do, however, indicate favourable impacts on GHG emissions as shown in Figure 56b. Reductions in emissions are caused by the replacement of fossil fuels by green fuels produced by the GH2 industry and by green ammonia replacing grey. It is also possible that the nascent steel industry in Namibia could adopt the use of hydrogen as a reductant substitute and replace coke oven gas with green hydrogen, producing green steel for the domestic market and export (Owais, 2022; Bhaskar, 2020).

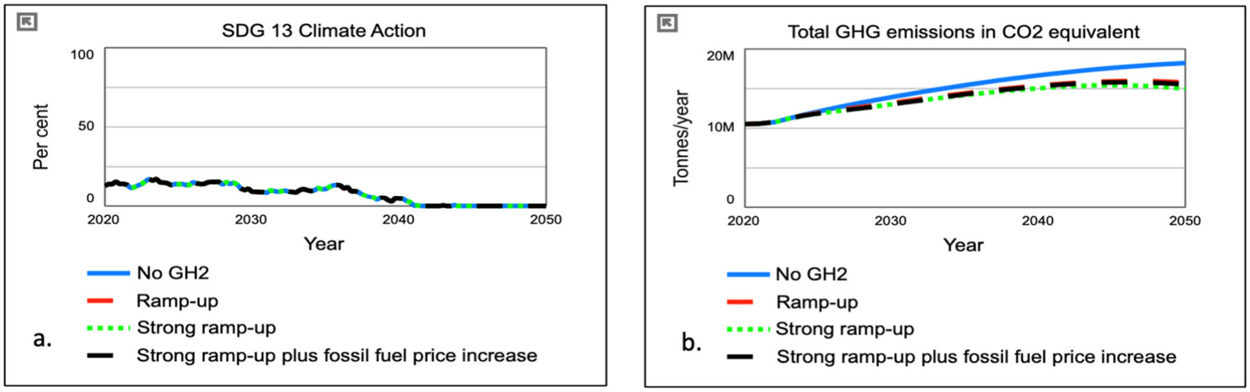

Figure 56 Namibia: GH2 influences on SDG 13 and GHG emissions

5.4.5 Other social issues: income distribution and poverty

Income distribution is an issue of great concern in Namibia, which is characterised by a high Gini coefficient. The Gini coefficient is lowered somewhat after GH2 is introduced, indicating more equitable income distribution. The proportion of the population below the international poverty line is also lowered. There are many chains of causation underlying income distribution and poverty occurrence, making it difficult to discern the primary influences from the GH2 sector, but it is encouraging to see these effects when GH2 ramp-up scenarios are simulated in isolation.

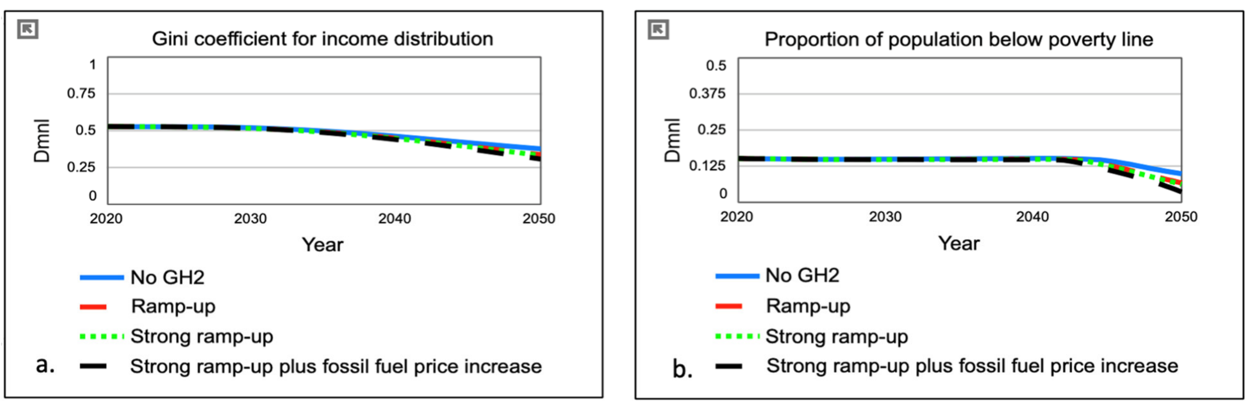

Figure 57 Namibia: Patterns of income distribution and poverty

The SDG plot and charts shown in section 5.3 provide evidence that GH2 is supportive of progress with the SDGs. In many instances the effects are not direct but are nevertheless linked through complex causal chains and feedback loops. Performing this exercise in isolation from other policies lends confidence to the idea that GH2 contributes in multiple ways to sustainable development at national scale. Policies that are successful in scaling up the GH2 sector are likely to promote many socio-economic and environmental benefits.

5.5 Key findings and recommendations

The simulations, conducted in isolation from other policies targeting the SDGs, provide evidence that the development of a green hydrogen sector has the potential to bring numerous social, economic and environmental benefits to Namibia. This is indicated by the patterns observed for SDG and other indicators contained in the iSDG model components. The findings suggest that policies that scale up the GH2 sector may bring greater benefits for Namibian sustainable development.

However, the scale of the Namibian GH2 industry as simulated in this study does not reach that of the stated ambitions of the Namibian Government or investors. For example, the Ministry of Mines and Energy estimates that the green hydrogen industry could add USD 6 billion per annum to Namibian GDP by 2030 (Ministry of Mines and Energy Namibia, 2022). The simulation with the strong ramp-up, carbon taxes, tax breaks, and continuously increasing fossil fuel prices reaches about USD 5.6 billion but not until 2050. Hyphen projects 200,000 jobs working in renewable energy for green hydrogen production by 2050 (Hyphen 2022). The strong ramp-up with fossil fuel price increase scenario indicates that employment in the green hydrogen sector would peak at about 32,000 in 2032 and then fall to around 15,000 by 2050.

Growth of the Namibian green hydrogen will to a great extent be driven by export demand. The simulations of green hydrogen in Namibia suggest that green hydrogen products will largely remain over-priced for international markets until 2050, due primarily to high transport and storage costs. International trade in green hydrogen products will require a parallel supply chain to be developed and maintained to ensure that the green products received are in fact green. The cost of the extended green hydrogen supply chain is not included in the model but it would most likely be an expensive undertaking with lengthy time lags in implementation. Namibia has the natural resources to become the huge supplier that the Namibian Government and investors envision. What is needed is a policy to stimulate demand for green hydrogen products. In the model scenarios we experimented with an international carbon tax of USD 80/tonne (USD_{2010}). The USD 80 level was inadequate to stimulate international demand for Namibian GH2 products. One possibility would be for green hydrogen producers to be awarded carbon credits for the emissions avoided by using the green hydrogen product instead of the conventional carbon-based product. These credits could then be sold to offset carbon reduction requirements. If an offset ratio greater than one were applied, then net gains in reducing carbon emissions could be made. The sale of the carbon credits would boost the revenue of green hydrogen producers and provide an incentive to expand operations.

Another possibility to consider would be the establishment of a green certificate trading system for green hydrogen products. Under such a system, a government – say the German Government – would impose a requirement that a certain percentage of a climate-damaging product, for example diesel fuel, must be composed of green diesel. For the system to work, the conventional product and the green product must be fully fungible. A certification board would be established to award green certificates to producers of green diesel fuel. The diesel fuel distributor in Germany would buy and issue the green certificates to cover the required percentage of green diesel fuel. In such a system, the same distribution channels could be used for green and conventional products, obviating the need for a segregated supply chain and potentially reducing supply chain costs. The distributor would be able to avoid high shipping costs and the green diesel fuel producer would receive a premium to cover their higher cost of production. Over time the percentage requirement for green diesel fuel could be ramped up and a greater percentage of the diesel fuel supply stream would consist of green diesel. Such green certificate systems are currently being used for sustainable commodities and warrant consideration as a mechanism to reduce cost and increase international demand for GH2 products (Blanco 2012).

Recently, in 2021, a Canadian oil exploration company discovered a large oil deposit in the Okavango region of Namibia. The amount of recoverable oil is uncertain, but some estimates are as high as 120 billion barrels (Richardson 2021). Offshore oil has also been discovered in Namibia. There are discussions that oil exports could double Namibia's GDP by 2040 (Burkhartdt and Cranny, 2022). Such amounts of oil could dwarf Namibia's developing green hydrogen industry and potentially compromise the country's contribution to reducing global carbon emissions through production of green hydrogen. The recent oil discoveries give an added urgency to the need for policies to scale up the green hydrogen industry and establish Namibia as a leading producer of carbon-free energy.

5.6 Technical annex: calibration performance

Refer to the explanation of model statistics under section 3.7.

Table 10 Namibia model calibration statistics

RMSPE	Value (element 1)	Value (element 2)
KPI.population by sex RMSPE[sex]	5.64317E-05	4.45844E-05
KPI.total fertility rate RMSPE	0.000350139	
KPI.life expectancy RMSPE[sex]	0.001165596	0.001168815
KPI.average years of schooling RMSPE[sex]	6.01669E-05	7.85083E-05
KPI.average access to basic health care RMSPE	0.000266113	

TBIAS	Value (element 1)	Value (element 2)
KPI.infrastructure RMSPE[infra]	0.000121179	0.000112919
KPI.employment by sector RMSPE[sector]	0.000217627	2.21052E-05
KPI.Gini coefficient RMSPE	5.51914E-05	
KPI.proportion of population below poverty line RMSPE	0.003029062	
KPI.yield RMSPE[crop]	0.01323259	0.083390484
KPI.livestock production in tonnes per hectare RMSPE[livestock]	0.034758856	
KPI.relative fish capture in tonnes RMSPE[fish]	0.013653448	
KPI.relative fish harvest in tonnes RMSPE[fish]	0.051021347	
KPI.relative forestry production in cubic metres RMSPE[wood]	0.014018806	
KPI.industrial production RMSPE[industry]	0.018227904	
KPI.services production RMSPE[services]	0.020228716	
KPI.private savings RMSPE	0.066908075	
KPI.total export as share of GDP RMSPE	0.003657049	
KPI.agricultural land RMSPE[agriculture]	0.04890527	1.44076E-05
KPI.forested land RMSPE	6.40651E-05	
KPI.access to safely managed water source RMSPE[area]	0.000170676	0
KPI.access to safely managed sanitation facility RMSPE[area]	0.000137615	0.000169148
KPI.total water withdrawal RMSPE	0.000845356	
KPI.soil primary nitrogen balance RMSPE	0.001780698	
KPI.domestic material consumption RMSPE	0.002185543	

TBIAS	Value (element 1)	Value (element 2)
KPI.CO_2 emissions RMSPE	0.00603664	
KPI.fish resources availability share RMSPE	1.94812E-05	
KPI.gross international reserves RMSPE	0.00230551	
KPI.final energy consumption by sector RMSPE[agr, final_energy_with_GH2]	0.00099	0.00921
KPI.final energy consumption by sector RMSPE[ind, final_energy_with_GH2]	0.02311	0
KPI.final energy consumption by sector RMSPE[ser, final_energy_with_GH2]	0.000725	0.01295
KPI.final energy consumption by sector RMSPE[res, final_energy_with_GH2]	0.03528	0.00867
KPI.final energy consumption by sector RMSPE[tra, final_energy_with_GH2]	0.00210	0
KPI.final energy consumption by sector RMSPE[oth, final_energy_with_GH2]	0.000922	0
KPI.population by sex TBIAS[sex]	0.16849919	0.16991366
KPI.total fertility rate TBIAS	0.1482778	
KPI.life expectancy TBIAS[sex]	0.22509123	0.22377512
KPI.average years of schooling TBIAS[sex]	0.15229867	0.1517438
KPI.average access to basic health care TBIAS	0.14911441	
KPI.infrastructure TBIAS[infra]	0.11480127	0.12507452
KPI.employment by sector TBIAS[sector]	0.13414503	0.11504218
KPI.Gini coefficient TBIAS	0.15140866	
KPI.proportion of population below poverty line TBIAS	0.18065426	
KPI.yield TBIAS[crop]	0.01640772	0.05976779

TBIAS	Value (element 1)	Value (element 2)
KPI.livestock production in tonnes per hectare TBIAS[livestock]	0.02150029	
KPI.relative fish capture in tonnes TBIAS[fish]	0.68006579	
KPI.relative fish harvest in tonnes TBIAS[fish]	0.69335361	
KPI.relative forestry production in cubic metres TBIAS[wood]	0.45578123	
KPI.industrial production TBIAS[industry]	0.70168856	
KPI.services production TBIAS[services]	0.87194691	0.007368743
KPI.private savings TBIAS	0.43588006	
KPI.total export as share of GDP TBIAS	0.18290651	
KPI.agricultural land TBIAS[agriculture]	0.1465689	0.12140372
KPI.forested land TBIAS	0.12138387	
KPI.access to safely managed water source TBIAS[area]	0.1357719	0
KPI.access to safely managed sanitation facility TBIAS[area]	0.13822691	0.13740822
KPI.total water withdrawal TBIAS	0.17906061	
KPI.soil primary nitrogen balance TBIAS	0.17073293	
KPI.domestic material consumption TBIAS	0.20543962	
KPI.CO_2 emissions TBIAS	0.28752797	
KPI.fish resources availability share TBIAS	0.631063714	
KPI.gross international reserves TBIAS	0.003156334	
KPI.final energy consumption by sector TBIAS[agr, final_energy_with_GH2]	0.132354	0.212105

TBIAS	Value (element 1)	Value (element 2)
KPI.final energy consumption by sector TBIAS[ind, final_energy_with_GH2]	0.188018	0
KPI.final energy consumption by sector TBIAS[ser, final_energy_with_GH2]	0.13007	0.209906
KPI.final energy consumption by sector TBIAS[res, final_energy_with_GH2]	0.230113	0.201361
KPI.final energy consumption by sector TBIAS[tra, final_energy_with_GH2]	0.128491	0
KPI.final energy consumption by sector TBIAS[oth, final_energy_with_GH2]	0.212715	0

References

Bhaskar A., Assadi M., Somehsaraei H., 2020. Decarbonization of the iron and steel industry with direct reduction of iron ore with green hydrogen. Energies 2020 13(3) 758. https://www.mdpi.com/1996-1073/13/3/758

Blanca E., 2012. Can commodities be sustainable? Forbes. May 3, 2012. https://www.forbes.com/sites/edgarblanco/2012/05/03/can-commodites-be-sustainable/?sh=39950b2222e9

Burkhartdt P., Cranny M., 2022. 'Jackpot' oil discoveries may help Namibia double GDP by 2040. Bloomberg Markets. https://www.bloomberg.com/news/articles/2022-06-21/-jackpot-oil-discoveries-may-help-namibia-double-gdp-by-2040#xj4y7vzk

Elston L., 2022. Namibia stakes its future on the green hydrogen market. Energy Monitor. June 24, 2022. https://www.energymonitor.ai/tech/hydrogen/namibia-stakes-its-future-on-the-green-hydrogen-market/

Goldthau A., Tagliapietra S., 2022. Energy crisis: five questions that must be answered in 2023. Nature, 16 December, 2022. https://www.nature.com/articles/d41586-022-04467-w

Hamukoshi S.S., Mama N., Shimanda P.P., Shafudah N.H., 2022. An overview of the socio-economic impacts of the green hydrogen value chain in Southern Africa. Journal of Energy in Southern Africa. Aug 2022, vol. 33, no. 3, pp. 12–21. http://www.scielo.org.za/scielo.php?script=sci_arttext&pid=S1021-447X2022000300002

HPPII, 2021. Harambee Prosperity Plan II 2021–2025. Action plan of the Namibian Government Towards Economic Recovery and Inclusive Growth. Republic of Namibia.

Hyphen, 2022. Environmental and social screening study. Proposed green hydrogen export project in the Tsau//Khaeb National Park. May 2022. https://cdn.slrconsulting.com/uploads/2022-05/Hyphen_E%26S%20Screening_BID_10052022.pdf

Hyphen Hydrogen Energy (Pty) Ltd., 2021. Presentation by Marco Raffinetti and Dr Tobia Bischof-Niemz at the 2021 United Nations Climate Change Conference (COP 26). Glasgow. https://www.youtube.com/watch?v=5McAWovwJ6w&t=15852s

Ministry of Mines and Energy Namibia, 2022. Namibia. Green Hydrogen and Derivatives Strategy. Published by Ministry of Mines and Energy Namibia. November 2022.

NGHRI (Namibia Green hydrogen Research Initiative). Ongoing projects at NGHRI. https://nghri.com/projectsocialimpact.html

Owais A., 2022. Green hydrogen for steel production. AZO Cleantech. https://www.azocleantech.com/article.aspx?ArticleID=1606#:~:text=Hydrogen%20as%20a%20reductant%20substitute%20can%20produce%20direct%20reduced%20iron,a%20cheap%20natural%20gas%20supply.

Petersen K., Frank H., Paytan A., Bar-Zeev E., 2018. Impacts of seawater desalination on coastal environments. In: Sustainable desalination handbook, Butterworth-Heinemann, 1 Jan 2018, pp. 437–463

PWC, 2022. Quantifying the opportunity in green hydrogen, Price Waterhouse Coopers https://www.pwc.com/gx/en/industries/energy-utilities-resources/future-energy/green-hydrogen-cost.html

Richardson H., 2021. A big oil project in Africa threatens fragile Okavango region. Yale Environment360. Published at the Yale School of the Environment. https://e360.yale.edu/features/a-big-oil-project-in-africa-threatens-the-fragile-okavango-region

Reuters, 2022. Germany's RWE signs MOU with Hyphen on green ammonia in Namibia. Reuters Markets. 2 December, 2022. https://www.reuters.com/markets/germanys-rwe-signs-mou-with-hyphen-green-ammonia-namibia-2022-12-02/

SASSCAL, 2021. Looking to the future with green hydrogen. Southern African Science Service for Climate Change and Adaptive Land Management. Posted 30 June 2021. https://www.sasscal.org/looking-to-the-future-with-green-hydrogen/

UNEP, 2019. Towards sustainable desalination. United Nations Environment Programme. https://www.unep.org/news-and-stories/story/towards-sustainable-desalination

The Brief, 2022. Namibia targets 12 Mtpa green fuels production by 2050, 6 November 2022. https://thebrief.com.na/index.php/companies/item/1994-namibia-targets-12mtpa-green-fuels-production-by-2050.

World Bank. Proportion of population with access to electricity: https://data.worldbank.org/indicator/EG.ELC.ACCS.ZS?locations=NA.
Accessed: November 2022.

6. Conclusions

For this study, a green hydrogen (GH2) module was developed and connected (through input and output variables) to an existing system dynamics model (the iSDG model) designed to measure a country's performance with regard to the UN's Agenda for Sustainable Development. The main purpose of the study was to test the effects of a potential GH2 market ramp-up on the development of partner countries, measured through their performance on the SDGs.

The GH2 module captures the current status of scientific and technological knowledge regarding GH2 production, transformation, storage and transportation and the expected evolution of technologies and their adoption, mainly expressed as a cost reduction curve. We have set the cost reduction curves linked to the different technological processes involved to meet the expected forecast. Here, uncertainty remains prevalent, as some of these technologies are at a very early stage of development. Model parameters with a higher degree of uncertainty are included in the model interface to enable the user to experiment with alternative parameters under different scenarios.

The results of our simulations show that GH2 technologies and their ramp-up have a high potential to improve sustainable development and progress towards the countries' SDG attainment. The potential for improvement is particularly significant for access to clean energy, employment, material consumption efficiency and the capacity to reduce GHG emissions (SDGs 7, 8, 12 and 13). However, given the complexity of the processes involved, which are often not as efficient as their fossil fuels-based alternatives, GH2 based products should be used for the hard-to-abate sectors only. Therefore, to achieve a just transition, GH2 ramp-up strategies need to be combined with other decarbonisation strategies, such as demand management to improve overall efficiency of the economic system and electrification, where the direct use of a renewable power mix would be more affordable for societies.

This is particularly true in the case of South Africa, where an important share of their GHG emissions originate from coal-fired power plants, which in time will need to be decommissioned and replaced by alternative renewable energy sources. Here GH2 could be considered as a buffer to manage intermittency, but not as the main fuel.

In addition, in South Africa and Namibia, where power is less accessible to the population, GH2 development needs to be accompanied by renewable energy infrastructure development to allow sufficient time to adapt the grid to the energy transition. In Brazil, where electricity is accessible for large parts of the population, GH2 has more potential to bring decarbonisation faster.

Countries where current uses of GH2 already exist are in better positions to start developing the industry, as prices are expected to be affordable for the domestic markets more quickly. Brazil, with its large volume of ammonia-based fertilisers, has a very good opportunity to kick-off the ramp-up. On the other hand, countries such as Namibia that base their strategy mainly on exports may need to wait longer, as prices for export will be difficult to afford for longer periods of time. In this case, there is an added risk of commoditisation, if the industry is not developed in parallel with other developments such as power accessibility. Finally, this should not discourage these initiatives, since new oil discoveries can jeopardise decarbonisation efforts in the region. The moment to act is now.

Annex: Methodology

Structure of the iSDG model

The iSDG model evolved from the Millennium Institute's (MI) experience in developing and using models to evaluate policy impact on sustainable development. Notably, the iSDG builds upon the Threshold 21 model, which focuses on assessing policy impact on the Millennium Development Goals. These models have been developed over the past 35 years as tools to support policy development (Pedercini et al., 2018). The MI has applied these models to over 40 countries and supported governments in using the tools to develop plans for national development, green economy, and sustainable agriculture.

The iSDG is built using the system dynamics (SD) methodology, which excels at deconstructing and analysing complex socio-economic environments and policy systems (Sterman, 2000). Using this method, the model is formulated as a system of ordinary differential equations and includes approximately 3,000 variables organised into 30 sectors. This method of simulation aids in garnering insight into complex inter-relationships (Davis et al., 2007). The system dynamics methodology has a long history of application for analysing social, environmental and economic issues, and these characteristics make it well suited to exploring policies in the complex, interconnected system that is the sustainable development of a country such as Namibia, South Africa or Brazil.

The iSDG model focuses on representing the concepts that drive attainment of the Sustainable Development Goals (SDG), put forward by United Nations (UN) working committees around 2012 to follow up on the Millennium Development Goals (MDG) that were about to expire (Griggs et al., 2013). While the MDGs were more focused on alleviating poverty and promoting socio-economic development, the SDGs brought in additional focus on environmental impacts in combination with social and economic development. The iSDG model has adapted these relationships to MI's historical work with the Threshold 21 model.

Model sectors

The iSDG model structure includes all 17 SDGs and 78 of the indicators associated with them. The model includes 30 social, economic, and environmental modules (Figure 57). Relationships are represented both within and between sectors in order to capture the interconnected nature of development. The sectors of the iSDG are categorised into environmental (green), social (red) and economic (blue) modules.

Each module operates as a sub-model and includes the factors that influence SDGs within the sector. The arrows connecting the sectors in Figure 58 show how the model also integrates the sectors by modelling the cross-sectoral impacts. As the model simulates, the modules interact with each other based on the calculations done within and between the modules. This interaction between modules enables the integration of cross-sectoral effects, which must be considered when assessing sustainable development policies.

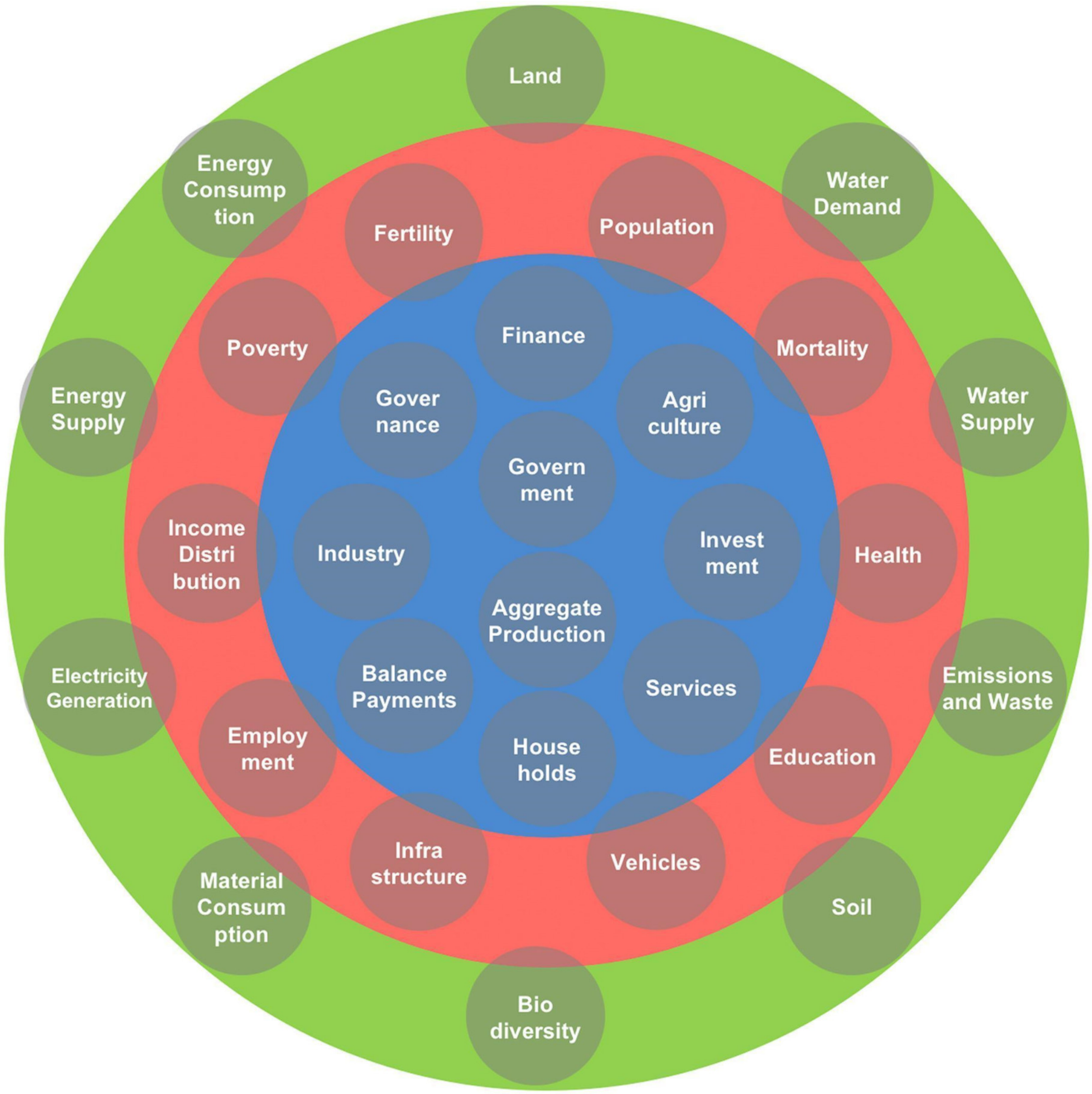

Figure 58. iSDG: the 30 modules included in the model structure

SDG indicators

The global framework of indicators adopted by the United Nations Statistical Commission consists of 169 indicators that can be used to monitor the progress made by countries on an internationally comparable scale. However, the same indicators are not necessarily applicable to all national contexts because of the characteristics specific to each country and the availability of the data required for their calculation.

The iSDG tracks 64 unique SDG indicators, 78 if counting multiple times those that appear in more than one SDG. The 78 indicators are part of 51 targets. All SDGs are represented by at least one target. The complete list can be found under SDG Indicators in the iSDG Model Annex. The targets included were selected based on the criteria of quantifiability and data availability.

Table 11 SDG indicators quantified in the iSDG model

Indicator	Description
SDG 1	**End poverty in all its forms everywhere**
1.1.1	Proportion of population below the international poverty line, by sex, age, employment status and geographical location (urban/rural)
1.2.1	Proportion of population living below the national poverty line, by sex and age
1.4.1	Proportion of population living in households with access to basic services
1.5.1	Number of deaths, missing persons and directly affected persons attributed to disasters per 100,000 population
1.5.2	Direct economic loss attributed to disasters in relation to global GDP
SDG 2	**End hunger, achieve food security and improved nutrition and promote sustainable agriculture**
2.1.1	Prevalence of undernourishment
2.2.1	Prevalence of stunting among children under 5 years of age
2.2.2	Prevalence of malnutrition among children under 5 years of age, by type (wasting and overweight)
2.3.1	Volume of production per labour unit by classes of farming/pastoral/forestry enterprise size

2.4.1	Proportion of agricultural area under productive and sustainable agriculture
SDG 3	**Ensure healthy lives and promote well-being for all at all ages**
3.1.1	Maternal mortality ratio
3.1.2	Proportion of births attended by skilled health personnel
3.2.1	Under-five mortality rate
3.2.2	Neonatal mortality rate
3.4.1	Mortality rate attributed to cardiovascular disease, cancer, diabetes or chronic respiratory disease
3.6.1	Death rate due to road traffic injuries
3.7.1	Proportion of women of reproductive age who have their need for family planning satisfied with modern methods
3.7.2	Adolescent birth rate per 1,000 women in that age group
3.8.1	Coverage of essential health services
SDG 4	**Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all**
4.1.1	Proportion of children and young people achieving at least a minimum proficiency level in reading and mathematics, by sex
4.1.2	Completion rate (primary education, lower secondary education, upper secondary education)
4.3.1	Participation rate of youth and adults in formal and non-formal education and training in the previous 12 months, by sex
4.5.1	Parity indices (female/male, rural/urban, bottom/top wealth quintile and others such as disability status, indigenous peoples and conflict-affected, as data become available)
4.6.1	Percentage of population in a given age group achieving at least a fixed level of proficiency in functional (a) literacy and (b) numeracy skills, by sex

SDG 5	**Achieve gender equality and empower all women and girls**
5.5.2	Proportion of women in managerial positions
5.6.1	Proportion of women aged 15–49 years who make their own informed decisions regarding sexual relations, contraceptive use and reproductive health care
SDG 6	**Ensure availability and sustainable management of water and sanitation for all**
6.1.1	Proportion of population using safely managed drinking water services
6.2.1	Proportion of population using safely managed sanitation services, including a handwashing facility with soap and water
6.4.1	Change in water-use efficiency over time
6.4.2	Level of water stress: freshwater withdrawal as a proportion of available freshwater resources
SDG 7	**Ensure access to affordable, reliable, sustainable and modern energy for all**
7.1.1	Proportion of population with access to electricity
7.2.1	Renewable energy share in the total final energy consumption
7.3.1	Energy intensity measured in terms of primary energy and gross domestic product
SDG 8	**Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all**
8.1.1	Annual growth rate of real GDP per capita
8.2.1	Annual growth rate of real GDP per employed person
8.4.1	Material footprint (MF),MF per capita, and MF per GDP
8.4.2	Domestic material consumption (DMC),DMC per capita, and DMC per GDP
8.5.2	Unemployment rate, by sex, age and persons with disabilities
8.6.1	Proportion of youth (aged 15–24) not in education, employment or training
SDG 9	**Build resilient infrastructure, promote inclusive and sustainable industrialisation and foster innovation**
9.1.1	Proportion of the rural population who live within 2 km of an all-season road

9.2.1	Manufacturing value added as a proportion of GDP and per capita
9.2.2	Manufacturing employment as a proportion of total employment
9.4.1	CO_2 emission per unit of value added
SDG 10	**Reduce inequality within and among countries**
10.1.1	Growth rates of household expenditure or income per capita among the bottom 40 per cent of the population and the total population
10.2.1	Proportion of people living below 50 per cent of median income, by age, sex and persons with disabilities
10.4.1	Labour share of GDP, comprising wages and social protection transfers
10.4.2	Redistributive impact of fiscal policy
SDG 11	**Make cities and human settlements inclusive, safe, resilient and sustainable**
11.5.1	Number of deaths, missing persons and directly affected persons attributed to disasters per 100,000 population
11.5.2	Direct economic loss attributed to disasters in relation to global GDP, including damage to critical infrastructure and disruptions to basic services attributed to disasters
11.6.1	Proportion of urban solid waste regularly collected and with adequate final discharge out of total urban solid waste generated, by cities
11.6.2	Annual mean levels of fine particulate matter (e.g. PM2.5 and PM10) in cities (population weighted)
SDG 12	**Ensure sustainable consumption and production patterns**
12.2.1	Material footprint (MF), MF per capita, and MF per GDP
12.2.2	Domestic material consumption (DMC), DMC per capita, and DMC per GDP
SDG 13	**Take urgent action to combat climate change and its impacts**
13.1.1	Number of deaths, missing persons and directly affected persons attributed to disasters per 100,000 population
13.2.2	Total greenhouse gas emissions per year

SDG 14	**Conserve and sustainably use the oceans, seas and marine resources for sustainable development**
14.4.1	Proportion of fish stocks within biologically sustainable levels
14.5.1	Coverage of protected areas in relation to marine areas
SDG 15	**Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss**
15.1.1	Forest area as a proportion of total land area
15.1.2	Proportion of important sites for terrestrial and freshwater biodiversity that are covered by protected areas, by ecosystem type
15.5.1	Red List Index
SDG 16	**Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels**
16.1.1	Number of victims of intentional homicide per 100,000 population, by sex and age
16.6.2	Proportion of the population satisfied with their last experience of public services
SDG 17	**Strengthen the means of implementation and revitalise the Global Partnership for Sustainable Development**
17.1.1	Total government revenue as a proportion of GDP, by source
17.1.2	Proportion of domestic budget funded by domestic taxes
17.3.1	Foreign direct investments (FDI), official development assistance and South-South cooperation as a proportion of total domestic budget
17.4.1	Debt service as a proportion of exports of goods and services

Model validation

The iSDG is structured to analyse medium to long-term development issues at the national level in order to provide practical policy insights. Specifically, the model provides policymakers and other users with the means to analyse the consequences of planned and alternative policies. Such estimates are not to be taken as forecasts, since no model can accurately forecast long-term development trends, but as potential outcomes based on a set of clear and well-grounded assumptions.

The model's results inherently embed a high degree of uncertainty over the time horizon considered in the simulation. A variety of unforeseeable changes can take place during the period and they may occur in social, economic, or environmental systems. To address the uncertainty inherent to modelling the complex interactions in sustainable development, the iSDG validation process focuses on strengthening the underlying assumptions based on currently available data and research. The goal of validation is to improve the model's ability to provide insights into the key questions being addressed (Forrester, 1961).

Validation is embedded in the broader model implementation and includes structural and behavioural validation tests (Barlas, 1996). Structural validation tests involve direct verification of the assumptions made in the model structure and parameters. Behavioural validation tests involve assessment of the model's ability to replicate the historical behaviour of the main indicators for the historical period of the simulation. Structural and behavioural validation techniques are discussed at a general level in the following section.

Structural validation

Testing the structural robustness of the model consists of five steps (Forrester & Senge, 1980; Richardson & Alexander L Pugh, 1981; Sterman, 2000). The key purpose of validating the model structure is to determine how suitable the model is for evaluating the questions asked in the analysis. This can be done by addressing the following questions:

1. Is the model structure consistent with qualitative knowledge?
2. Are the model equations dimensionally consistent?
3. Are concepts for addressing the questions represented in the model?
4. Are parameters consistent with descriptive and numerical knowledge?
5. Does the simulation result make sense when inputs take on extreme values?

These questions are addressed by MI during model development as well as throughout the implementation stages of the project. The iSDG model is maintained and updated on the basis of leading research and modelling techniques. Equations are evaluated throughout the model development phase and project applications in order to ensure model consistency. The analytical direction is set based on the country's needs and the model can be adjusted as a means to accurately address these questions.

During calibration of the model to the national context, parameter values are assessed both qualitatively and quantitatively to evaluate model fit. Furthermore, extreme conditions are tested during simulation to evaluate the robustness of the calibrated model. These considerations are necessary to verify that the model represents the national context both qualitatively and quantitatively. The approach increases the rigour of the model application and ensures that the model will be useful for analysing the policy impacts.

Behavioural validation

Behaviour validation is a significant step in the model application. In the context of the model, behaviour describes the simulation results of the variables in the model. The purpose of the iSDG model is to test policy impacts on the evolution of medium to long-term trends in sustainable development. The model calibration aims to accurately reflect medium-term to long-term behaviour in historical data. This approach places less emphasis on short-term cycles.

Statistical summaries are used to validate the behaviour of the model. The statistics used are standard econometric techniques for quantitatively assessing the degree to which the model replicates the trends and patterns found in historical data. The calibration report evaluates the goodness-of-fit for the model application. This analysis guides further calibration towards the reduction of error in order to continually refine the behavioural validity of the model application.

Model database

Data is collected from both international and national data sources. A comprehensive list of data sources for the inputs into the model and the data used to calibrate the model can be found in the data sources annex. When available, national data sources were prioritised and international data filled gaps where national data was not available for model variables. If data was not available from national or international sources and if that data is necessary for calibration, interpolations and assumptions were made. Data was verified for internal consistency and was confirmed with government officials.

Model calibration

The model is calibrated to the historical data incrementally, module by module. The calibration process estimates parameters of the model in order to minimise residual error between the simulated variables and historical data. The partial-model testing method is used to minimise confounding effects between sectors and improve the robustness of calibration (Homer, 2012). In practice, the sectors of the model are broken down into the smallest relevant structures and calibrated step by step. The modules are then integrated and the final adjustments are made based on cross-sectoral effects. This process can be broken down into four steps: (1) isolate each partial-model, (2) estimate parameters, (3) integrate partial-models, and (4) assess and revise.

The calibration process was designed considering best practices used for developing structural models like the iSDG. By following this process, the method adheres to the three heuristics for model testing (Oliva, 2003): it allows the calibration to (1) include all knowledge available about system parameters in calibration, (2) apply calibration to the smallest possible problems, and (3) use calibration to test the model's ability to explain behaviour. This approach reduces the risk of fitting the model to data, increases estimation efficiency, and concentrates the error in the model's structure generating the behaviour, thereby increasing the robustness of the application.