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Green Hydrogen and TVET Employment Prospects: An Assessment in a Context of Ambitious Decarbonisation for South Africa towards 2050

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Table of Contents

ACKNOWLEDGEMENTS	2
TABLE OF CONTENTS	3
FIGURES	6
TABLES	8
ACRONYMS	9
EXECUTIVE SUMMARY	10
BACKGROUND TO THE STUDY	13
2. ESTIMATING EMPLOYMENT AND GHG EMISSION IMPACTS OF A GHE	15
2.1 Overview of modelling methodology.....	15
2.2 Modelling assumptions for a SA domestic Green Hydrogen Economy.....	17
2.3 Scenarios for modelling hydrogen futures for South Africa.....	20
2.4 Modelling TVET employment shares.....	23
3. RESULTS: GROWTH, EMISSIONS AND EMPLOYMENT IMPACTS OF A GHE ...	26
3.1 Introduction.....	26
3.2 Economic growth and sectoral value added.....	26
3.2.1 Overview of GDP outcomes.....	26
3.2.2 Impacts of achieving Net Zero carbon with a domestic-only GHE (Local-H2).....	29
3.2.3 A domestic GHE with a full GHE export portfolio (H2-Export).....	30
3.2.4 Impacts of exporting platinum-based GHE appliances without a GHE (NoH2-Export)	33

3.3 GHE technology dynamics.....	35
3.3.1 Green Hydrogen and Industrial Use.....	35
3.3.2 Power Generation.....	36
3.3.3 Freight Transport	37
3.3.4 Fuel Cell manufacturing.....	39
3.4 GHG emission impacts.....	40
3.5 Employment pathways	42
3.5.1 Total and total TVET employment	42
3.5.2 Scope for a Just Labour Transition towards a GHE	44
3.5.3 PGM and Coal mining, Electricity, and Iron & Steel sectors	46
3.5.4 Refineries, Green Hydrogen and Ammonia, Fuel Cell and Electrolyser manufacturing	49
3.6 Job impacts of selected Green Hydrogen applications	51
3.6.1 Exports.....	51
3.6.2 Domestic use of Fuel Cells.....	53
SUMMARY AND DISCUSSION OF FINDINGS	54
4.1 Introduction	54
4.2 Hydrogen production and demand.....	54
4.3 Economic growth.....	55
4.4 Total employment.....	55
4.5 TVET educated employment	56
4.6 Employment impacts of green hydrogen applications and exports	57
4.7 A Just Labour Transition towards a GHE	59
4.8 Greenhouse gas emission reductions	60

4.9 Limitations	60
CONCLUSION.....	61
APPENDICES	64
A. EXPORT ASSUMPTIONS FOR HYDROGEN	64
A.1 Backgrounds of export assumptions	64
A.2 Hydrogen-based chemicals, fuels and materials demand	67
A.3 Fuel cell and electrolyser demand and supply	68
A.4 PGM Demand and Supply assumptions.....	70
A.5 Assumed SA market shares in global Electrolyser and Fuel Cell markets	73
B ADDITIONAL DETAIL ON RESULTS	74
B.1 Historic trends in SA TVET employment	74
B.2 TVET employment projections by sector.....	77
B.3 Calculation of direct, and indirect and induced H2FC production employment	79
B.4 Capacity at which power plants are run by plant or technology	81

Figures

Figure 2-1: Illustration of the iterative exchange of data between the energy and economic model of SATIMGE	17
Figure 2-2-3: Conceptual representation of the hydrogen sectors in the SATIMGE model.....	19
Figure 2-3: Hydrogen pathways for South Africa towards 2050	20
Figure 3-1: GDP projections to 2050 by scenario in billion ZAR(2012)	28
Figure 3-4: Evolution of the electricity price in R/kWh for Net Zero scenarios	32
Figure 3-5: Real Exchange Rate index to 2050 by scenario, FCU/Rand (2012=100)	32
Figure 3-6: Magnitude of hydrogen demand by application for the scenarios.....	36
Figure 3-7: Electricity consumption by end use category for NZ scenarios.....	36
Figure 3-8: NoH2 power generation capacity 2020-2050 (Left) and Difference in power sector capacity versus NoH2 (Right)	37
Figure 3-9: Evolution of passenger road vehicle technology in SATIMGE.....	37
Figure 3-10: Evolution of freight road vehicle technology in SATMGE. Note: H2FC = Hydrogen Fuel Cell.....	38
Figure 3-11: Portfolio of technology options for heavy class vehicles in category 6 to 9 for Local-H2 scenario	39
Figure 3-12: Scenario projections of South African CO2 emissions from energy use and industrial processes to 2050.....	40
Figure 3-13: Requirement for CO2 capture with CCS and Direct Air Capture (DAC) technology in Net Zero scenarios	41
Figure 3-14: Range of indirect and induced TVET jobs from GHE exports for 2040 to 2050 and their average (red markers)	53
Figure A-1: Historic account of the composition of South African export trade and value.....	64
Figure A-2: Projected gross demand for automotive PGMs for catalytic converters; contrasted with nascent demand for fuel cell vehicles. Source: IEA (2021)	65
Figure A-3: Global consumption of hydrogen (and H2 derived commodities) for net zero GHG Source: IEA (2021)	66

Figure A-4: Key hydrogen deployment milestones for achieving net-zero GHG emissions source: IEA (2021) 67

Figure A-5: Projected global demand for electrolyzers and fuel cells 69

Figure 0-1: Capacity factors for different power plant types and power technologies for Net Zero scenarios 81

Tables

Table 2-1: The potential domestic application of hydrogen along with the archetype alternatives modelled	18
Table 2-2: Key attributes of the scenarios	21
Table 2-3: Commodity export levels assumed	22
Table 2-4: 5-year average share of tertiary employment by sectors of interest (2015/2019) ...	25
Table 2-5: Occupations used on the decomposition analysis	25
Table 3-1: Annual fuel cell capacity (GW) required for HCV 6-9 heavy duty vehicles with platinum demand (tonnes)	39
Table 3-2: TVET employment changes per Just Labour Transition sector-grouping	46
Table 3-3: TVET employment by skill sub-grouping (,000s), for Coal and PGM mining, Power generation, and Iron & Steel	49
Table 3-4: TVET employment in Refineries, Green Hydrogen, Green Ammonia, Fuel Cell and Electrolyser manufacturing	50
Table 3-5: Direct TVET jobs attributed to GHE export commodities ('000s)	51
Table A-1: Estimated projected global demand and SA market export potential for hydrogen and hydrogen-based commodities	68
Table A-2 Estimated potential South African fuel cell and electrolyser export market share for the energy transition. Derived from IEA (2021)	69
Table A-3:Platinum demand ('000 kg, tonnes) by key sector and their market share. Source: Johnson Matthey	70
Table A-4: Estimated platinum demand for automotive catalytic converters for the energy transition with SA market share. Derived from IEA (2021)	71
Table A-5: Mineral demand for the global energy transition Source: IEA (2021)	71
Table A-6: Iridium and platinum loading for PEM electrolyzers with increased performance and material reduction strategies. Source: IRENA 2020	72
Table A-7: Estimated South African platinum demand for the energy transition. Derived from IEA (2021) and IRENA (2020)	73
Table A-8 Estimated potential South African fuel cell and electrolyser export market share for the energy transition. Derived from IEA (2021)	73
Table B-1: TVET employment creation by economic sector (,000s)	77
Table B-2 TVET employment by economic sector relative to no hydrogen usage (,000s)	78
Table B-3 Direct and total TVET job creation associated with domestic use and production of H2FCs for HCVs class 6-9	79

Acronyms

CGE	Computational General Equilibrium (model)
DRI	Direct Reduction Iron
FTE	Full Time Equivalent
GDP	Gross Domestic Product
GHE	Green Hydrogen Economy
GHG	Green House Gas
GVA	Gross Value Added
GVM	Gross Vehicle Mass
GW	Gigawatts
H ₂	Hydrogen
H ₂ FC	Hydrogen Fuel Cell
HCV	Heavy (Duty) Class Vehicle
kt	Kilotonne
LDV	Light Duty Vehicle
Mt	Megatonne
NDC	Nationally Determined Contribution to the Paris Agreement
PGM	Platinum Group Metals
PJ	Petajoule
Pt	Platinum
SAGE	South Africa CGE (model)
SATIM	South Africa TIMES (model)
SATIMGE	SATIM-SAGE (linked model)
SMR	Steam Methane Reforming (of natural gas)
TVET	Technical and Vocational Education and Training
TWh	Terawatt Hours

Executive Summary

Use of green hydrogen – that is, hydrogen produced from renewable energy sources – is an option for energy use which is increasingly identified as being important to achieve Net Zero carbon around the world. One reason is that hydrogen offers possibilities to reduce sectors which would otherwise be difficult or costly to decarbonize, like Iron & Steel production or parts of the transport sector. Within this context, the present study quantifies (1) the extent to which green hydrogen could be utilised competitively within the South African economy, (2) the macro-economic impacts thereof, especially for TVET skilled employment, and (3) green hydrogen's contribution to GHG emission reduction. To this end a full sector representation of the South African economy in a least-cost modelling energy-economy framework, SATIMGE, was used. The Net Zero scenarios explored in this study aimed at Net Zero carbon (greenhouse gas emissions) by 2050 in line with South Africa's commitment to the Paris Agreement. Two dimensions of hydrogen application are considered: Domestic use; and green hydrogen-based commodity and manufacturing export-oriented. The latter scenario is rooted in a global context of future decarbonisation with South Africa being a major producer of platinum and other platinum group metals which are key materials for hydrogen production and use technologies. To quantify the relative impact of introducing green hydrogen results of the two scenarios were compared to a reference scenario in which no green hydrogen is produced at industrial scale. An additional scenario counterfactually explored what could happen if the SA manufacturing sector could develop production of platinum-based fuel cells and electrolyzers for export without a local green hydrogen market.

Based on our analysis, we consider development of a green hydrogen economy an essential element for achieving South Africa's ambition of reaching Net Zero carbon by 2050. The domestic Green Hydrogen Economy studied in the present report consists of development of green hydrogen-based freight transport with hydrogen Fuel Cell trucks, green hydrogen-based production of green Iron & Steel, and applications of hydrogen for industrial heating. Such developments would require a period roughly between 2030 and 2045 of additional energy system investments, especially in power generation capacity and electrolysis, relative to a future in which Net Zero carbon would be achieved without green hydrogen. However, investment in green hydrogen technologies would avoid the need for more costly future investments in different carbon capture & storage technologies, including direct air capture, especially from 2045 onwards. As such, the green hydrogen economy can be accredited to avoid at least between 84 and 93 Megatonnes of cumulative CO₂ emissions in South Africa between 2040 and 2050.

A green hydrogen economy's benefits for climate change mitigation are accompanied by an economic impact which would be as a minimum on average neutral in terms of GDP growth between 2020 and 2050, with the prospect of a better economic outlook from 2050 onwards. The economic benefits of a South African green hydrogen economy could be significantly higher if it paves the way for exports of green hydrogen-based commodities like Green Iron & Steel and the chemical Green Ammonia, as well as platinum-based technologies like Fuel Cells and Electrolyzers components. Establishing considerable shares in global markets for these products could lead to a significant improvement of South Africa's GDP, which is

estimated to be about 11% higher by 2050 in our Green Hydrogen economy Export scenario compared to GDP in a Net Zero future without a hydrogen economy. In conclusion, our study therefore expects only upside risks of establishing a South African green hydrogen economy for the economy, while not developing a green hydrogen economy would entail considerable downside risks for both the economy, especially from the mid-2040's onwards, as well as for achieving Net Zero carbon by 2050.

For employment a similar picture arises as for GDP growth. Developing a domestic green hydrogen economy without GHE exports could have on average a slightly negative impact on employment between 2020 and 2050 compared to a Net Zero future without a green hydrogen economy. The reason is that some crowding out of investment in labour-intensive services takes place. However, once even only moderate green hydrogen economy commodity exports would be added, the employment impacts of a green hydrogen economy become strongly positive. Again, the biggest impacts would be found in the tertiary (services) sectors, due to total GDP growth and these sectors making up the largest part of South African employment.

Zooming in on the sectors considered for a just labour transition from coal mining and refineries to green hydrogen economy-related sectors we observe a small decrease in total TVET employment between 2025 and 2030 in all scenarios due to existing trends for a coal phase out and oil refinery closures. From 2030 onwards this is followed by an increase in total TVET employment in these sectors. TVET job gains are initially concentrated in Power Generation, PGM mining and Iron & Steel, while from 2035 onwards considerable job gains can also be expected for Green Hydrogen and Ammonia production and for Fuel Cell and Electrolyser manufacturing. Again, the employment potentials are much higher if GHE export markets are developed.

Hundreds of TVET graduates can be expected to be needed by green hydrogen economy sectors from 2030 or 2035 onwards, depending on how fast export markets can be developed. However, the scope for a Just Labour Transition from fossil fuel-based sectors towards Green Hydrogen Economy-related sectors is thus found to depend much on timing. I.e., in the period 2025-2030 in a local GHE only future new TVET-educated job opportunities in Power Generation and Iron&steel might be able to absorb about half of the annual TVET educated unemployed being forced to leave coal mining in that same period. Beyond 2030 TVET job creation in Power Generation and Green Iron & Steel are expected to be higher than TVET job losses in coal mining. Similarly, for TVET job losses in Refineries the GHE cannot offer a meaningful alternative yet during the 2025 to 2035 period, but from 2030 to 2035 onwards Green Hydrogen and Green Ammonia production job gains could outpace job losses from Refineries. If achieving considerable exports, the Fuel Cell and Electrolyser manufacturing sectors could add significant numbers of TVET jobs from 2035 onwards. These manufacturing sectors could possibly absorb jobs lost elsewhere in manufacturing, e.g., of catalytic convertors or other automotive vehicle components. Job gains in Green Hydrogen Economy sectors could outpace TVET job losses by far and large from 2035 onwards.

We thus conclude that ample room exists for the TVET college system to both educate and train new students, as well as up- and re-skilling programs to support workers to transition

towards Green Hydrogen Economy jobs, for them to enter the GHE from 2030 to 2035 onwards. This leaves us with a few years to experiment with and develop suitable TVET programs. However more detailed assessments of the requirements for up- or reskilling are still needed. To narrow down uncertainty and to be better able to quantify training requirements, additional research would be needed, beyond current labour statistics.

Background to the study

South Africa's per capita Greenhouse Gas (GHG) emissions are well above the global average. A signatory to the Paris Agreement, the country has committed to reducing its emissions with its first submission of the country's Intended Nationally Determined Contribution (INDC) submitted in 2015.¹ This international pledge is based on the notion of a "peak-plateau-decline" (PPD) emissions trajectory which emphasizes the decarbonisation of the electricity sector owing to its pre-eminence in the national GHG inventory. Subsequent to the formulation of the PPD, as the country embarks on a reassessment of its NDC commitment, technological progress to date presents a compelling case for a more progressive and marked decline in emissions emanating from anthropogenic activity. South Africa's declining Greenhouse Gas (GHG) emission trajectory after 2030 is set to reach Net Zero around 2050 following what is considered a cumulative fair share emission budget for the period 2020-2050² and following the expression of the ambition of South Africa by President Ramaphosa to reach the objective of Net Zero carbon by 2050.³

Although considered an upper middle-income country, a substantial share of the population is still officially regarded as subsisting below the official poverty index.⁴ As such South Africa has prioritised economic growth predicated on affordable and accessible energy services in tandem with a commitment to protecting its natural resources as espoused in the National Development Plan which advocates low carbon development.

Presently, the country's industrial complex is predominately fossil fuel based with coal and crude oil the primary energy sources. Endowed with substantial renewable energy resources, new-energy minerals and an advanced industrial base; a global shift to alternate energy sources therefore presents South Africa with an opportunity to both achieve its GHG emissions reductions and economic growth aspirations by transforming its economy to create new alternative employment in emerging sectors as yester-decade industries decline.

¹ UNFCCC. 'South Africa's Intended Nationally Determined Contribution (INDC)'. Bonn: United Nations Framework Convention on Climate Change (UNFCCC), 2015

² Bruno Merven et al, 'Preliminary work on Net-Zero CO₂ by 2050 for South Africa', Paper submission to the International Energy modelling Workshop (IEW) 2022 (forthcoming); For more information about South Africa's fair share, see , Andrew Marquard, Harald Winkler, Guy Cunliffe, Anthony Dane, 'South Africa's "fair share": mitigation targets in the updated first NDC in an international context' University of Cape Town, 2021. <https://doi.org/10.25375/uct.16691953>

³ President Cyril Ramaphosa, 'South Africa's future is green, but we need a just climate transition', Op-Ed published in Daily Maverick, 11 Oct. 2021; Republic of South Africa, 'Presidency on international partnership to support a just transition to a low carbon economy and a climate resilient society', Media-statement 2 Nov. 2021, available on: <https://www.gov.za/speeches/presidency-international-partnership-support-just-transition-2-nov-2021-0000>, accessed February 2022; Department of Forestry, Fisheries, and the Environment (DFFE), 'South Africa's Low-Emission Development Strategy 2050', version February 2020, available at <https://unfccc.int/documents/253724>, accessed February 2022.

⁴ Thomas H. Roos, 'The cost of production and storage of renewable hydrogen in South Africa and transport to Japan and EU up to 2050 under different scenarios,' International Journal of Hydrogen Energy 46, no.72(2021) <http://hdl.handle.net/10204/12163>. Hereafter: Roos "Costs RE hydrogen SA" IJHE (2021)

Hydrogen is an energy-carrier and industrial feedstock that could be at the basis of a new energy-industrial network based on renewable energy. Global interest in hydrogen⁵ as an energy carrier and industrial feedstock has grown considerably in recent years. The resurgence of interest in the utilisation of hydrogen, notably green hydrogen produced from renewable resources, is also thanks to its potential to help decarbonise sectors for which few alternatives presently exist, e.g., long haul transport, iron & steel production and long-term energy storage. Hydrogen is thus considered a very likely enabler to achieve climate change policy goals - predicated on the notion that GHG emissions resulting from economic activity should be as close to nil as possible as a likely objective for a moment towards the year 2050, which is now becoming the new frontier for climate policy ambition around the world. Global appetite for hydrogen presents further economic opportunities for the country. Its renewable energy resources, mineral endowment, and manufacturing prowess positions it to competitively produce and export hydrogen-derived commodities, such as green ammonia, as well as high value machinery such as fuel-cell components which could mirror South Africa's present export market share of automotive catalytic converters.⁶

The extent to which hydrogen could contribute to employment growth and low carbon development in South Africa has received increasing attention in the last two years.⁷ The present study, as part of the UKPACT South Africa 2021 project on Hydrogen and TVET skills, aims to contribute to this body of literature applying advanced and economy-wide modelling of national energy systems including hydrogen use, and its economic (GDP and employment) and greenhouse gas emission impacts.

This study therefore also aims to support the orientation of South Africa's TVET college system towards the GHE by providing insight in the sectors on which to focus and the timelines by which it could be required to provide its graduates with the skills required in the GHE, as well as the potential for up- or re-skilling given those timelines.

⁵ Below we explain that the present study has a focus on the development of green hydrogen due to its potential for reaching Net Zero Carbon (Net Zero) by 2050. The study makes use of energy modelling which starts from the current energy supply and use in South Africa, and thus implies a shift from grey to green hydrogen. This shift is implicit in the sense that grey hydrogen currently is produced at Sasol's Secunda site and we assume grey hydrogen operations to cease with the retirement of the CTL operations due to ageing by 2034 to 2036. Development of green hydrogen has not been given any geographic restrictions, but this could of course also take place at the Secunda CTL site. Green hydrogen enters South Africa's energy system when the energy systems model considers this a cost-optimal way to respond to energy demand over time on a path to achieving Net Zero carbon by 2050.

⁶ Roos "Costs RE hydrogen SA" IJHE (2021).

⁷ Thomas Roos and Jarrad Wright, 'Powerfuels and Green Hydrogen (summary report)', Council for Scientific and Industrial Research (CSIR), February 2021; Engie and DSI, 'South Africa Hydrogen Valley Final Report'. Engie and Department of Science and Innovation (DSI), Pretoria, October 2021, available at https://www.dst.gov.za/images/2021/Hydrogen_Valley_Feasibility_Study_Report_Final_Version.pdf; IHS Markit, 'Super H2igh Road Scenario for South Africa – Extended Report', June 2021.

2. Estimating employment and GHG emission impacts of a GHE

2.1 Overview of modelling methodology

This study evaluates the economic proposition of utilising hydrogen from renewable sources, so-called green hydrogen, which we assume to be entirely produced through electrolysis technology. Besides green, also grey and blue hydrogen are commonly distinguished, while chemically identical: Grey hydrogen is presently the dominant type of hydrogen and produced from fossil fuels (coal and gas) using either steam reforming, partial oxidation, or gasification. Blue hydrogen is a technology under development in which CO₂ emissions to the atmosphere of the production process are avoided by adding carbon capture and storage (CSS).⁸ The present study's focus is based on the perspective for future cost-competitiveness green of hydrogen and its derived commodities, and for reason of the mentioned context of the Paris Agreement of 2015 and reaching Net Zero Carbon by 2050.^{9,10}

To assess the benefit of establishing a green hydrogen-based economic sector, whether for export or domestic markets, a quantitative framework is used to explore possible hydrogen futures and their resultant impact on economy-wide GHG emissions and employment. In this analysis, the linked energy-economic model SATIMGE, described by Arndt et al. and Merven et al. is used.¹¹ The SATIMGE model provides cost optimal sectoral pathways for technology options and economic activity. These are underpinned by assumptions of the future costs of options and constraints to activity. Constraints to unbridled activity can be either regulatory or policy based (e.g. air quality or GHG emissions), economic (e.g. national growth expectations and capital availability) or physical (e.g. material and labour).

SATIMGE comprises two hard-linked models¹², namely:

⁸ IEA, "Future of Hydrogen" (2019); M. Patel, "Green Hydrogen: A potential export commodity in a new global marketplace", TIPS (2020), hereafter: M. Patel, "Green hydrogen export" (2020); Bambili Advisory, "TVET Skills Gap Analysis report" (SAILA UKPACT, Occasional Research Paper, 2021).

⁹ IEA, "Future of Hydrogen" (2019); M. Patel, "Green hydrogen export" (2020).

¹⁰ As grey hydrogen production in South Africa almost entirely takes place at Secunda's CTL facilities, the facility's expected and modelled retirement by 2034/2036 (due to ageing) ends most of grey hydrogen's production (see footnote 7). Any other small-scale grey hydrogen production is only implicitly assumed to take place in the chemical industry.

¹¹ Arndt, C. Davies, R., Gabriel, S., Makrelov, K., Merven, B., Hartley, F. and Thurlow, J. 2016. A sequential approach to integrated energy modelling in South Africa. *Applied Energy*, 161:591–599. DOI: <https://doi.org/10.1016/j.apenergy.2015.06.053>; and Merven, B., Arndt, C. and Winkler, H. 2017. The development of a linked modelling framework for analysing the socioeconomic impacts of energy and climate policies in South Africa. WIDER Working Paper, No. 2017/40, ISBN 978-92-9256-264-9, The United Nations University World Institute for Development Economics Research (UNU-WIDER), Helsinki.

¹² The term hard-linked refers to distinct models that are programmatically coupled such that a subset of outputs are exchanged in an iterative data input-output loop, until an exit boundary condition is satisfied.

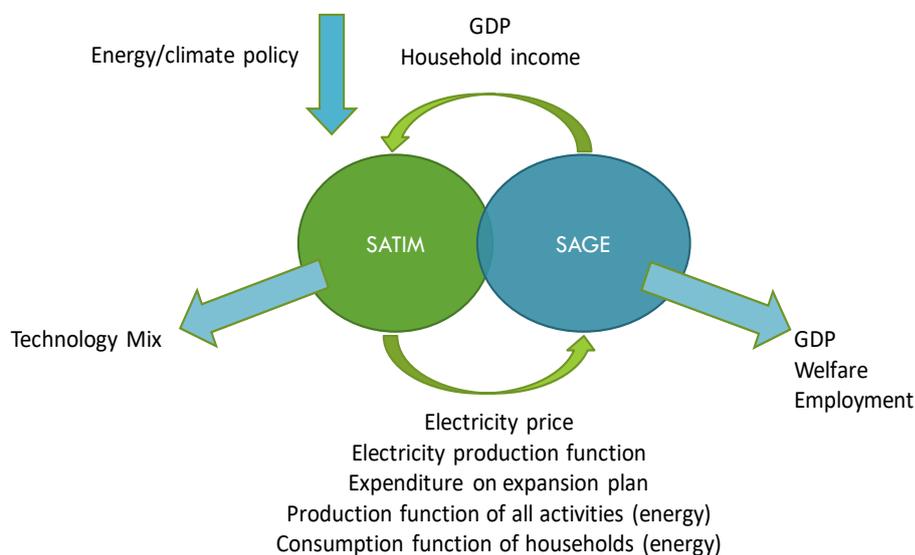
- 1) The South Africa TIMES (SATIM) energy systems model is an instance of the international TIMES modeling platform¹³. TIMES is a so-called partial equilibrium linear optimization modelling platform that facilitates a detailed full-sector representation of supply and demand components of national energy systems from extraction to end-use services (e.g., heating, cooling, lighting, passenger and freight transport, industrial processes). For example, the model includes extraction, transmission and distribution of gas and coal for electricity generation; the transmission and distribution of electricity; and the consumption of electricity by end-use technologies to supply. SATIM tracks flows of energy, materials, emissions, and energy demand services, and determines capital requirements for all technologies embodied in the system, and their full economic costs.
- 2) The South Africa General Equilibrium (SAGE) model is a macro-economic computational general equilibrium (CGE¹⁴) model that describes the national economy not only in monetary flows but also in the physical flow of energy (e.g., measured in PetaJoules), such that these flows match those of the SATIM model's projected energy balances. As a CGE model SAGE is a full sector representation describing production and purchase of intermediate and end-use commodities across the economy. Labour and capital as primary economic drivers are endogenously modelled. Labour is typically modelled through separate labour markets in four groups according to level of education-based skill categories: 1. primary or less, 2. middle-school, 3. completed secondary, and 4. tertiary educated. For the present study additionally the TVET educated employment is analysed (see below). Key outputs of the SAGE model are sectoral growth, employment by educational category, growth in household income and expenditure, and the national balance of payments.

Figure 0-1 schematically depicts the linked models. The SATIM and SAGE models are linked in a way that retains the best features of both models, i.e., one that captures detailed energy investment options, as well as detailed information on economic structure and behaviour. Within our linked framework, SATIM computes a least-cost energy system investment pathway based on forecasted demand and fossil fuel prices from SAGE. SAGE replicates energy investments and the full set of energy prices from SATIM, and then revises its GDP forecast and fuel price forecasts, which are used by SATIM to re-determine future energy demand and run a new least-cost energy system pathway. Iteration is continued until economic growth converges in both models.

¹³ It is developed, promoted and used under the auspices of the International Energy Agency's Energy Technology Systems Analysis Program (IEA-ETSAP), see <http://iea-etsap.org/web/index.asp>

¹⁴ An alternative approach to CGE modelling to arrive at estimates for economic impacts is static Input-Output multiplier analysis, possibly with some exogenously imposed dynamics in value added or cost structures. Though, I-O multiplier analysis ignores several economic trade-offs, especially related to price changes and technology choice dynamics (e.g. see: Acil-Allen Consulting, "Opportunities for Australia from hydrogen exports", Acil-Allen Consulting for ARENA, Australia, August 2018, p.96, Box B.1). Estimates of the job potentials by sector and skill and timing thereof would benefit more from also considering macro-economic adaptive behaviour, e.g., the evolution of domestic and foreign markets for certain goods, and from a complete evaluation of possible energy technology choices.

Figure 0-1: Illustration of the iterative exchange of data between the energy and economic model of SATIMGE



Source: Energy Systems Research Group, University of Cape Town

For the present study SATIMGE was run according to its most recent calibration parametrised for “Existing Policies” and “Reference growth”, as fully described in a recent technical report by UCT¹⁵ prepared for informing the South African government’s process of updating its NDC before the COP26 conference in Glasgow 2021. Compared to the latter, the model version used for the present study includes additional descriptions of hydrogen use technologies in industry and transport, as well as an added description of hydrogen, fuel cell, electrolyser, and ammonia industrial sectors in the economy part of the model. Those additions are described in the next section.

2.2 Modelling assumptions for a SA domestic Green Hydrogen Economy

Table 0-1 summarizes the domestic application of hydrogen that is modelled within the SATIM energy systems model part of the linked model. Following IEA’s outlook for this technology, the platinum-based polymer-electrolyte-membrane (PEM) technology is assumed for both Fuel

¹⁵ Andrew Marquard, Faaiqa Hartley, Bruno Merven, Jesse Burton, et al. ‘Technical Analysis to support the update of South Africa’s First NDC’s mitigation target ranges’. University of Cape Town. Report. <https://doi.org/10.25375/uct.16691950.v2>

Cell and Electrolyser assembly.¹⁶ Water consumption is not presently quantified as a potential limiting factor for the electrolysis. Several studies have concluded that industrial scale hydrogen production would not severely impact water demand, especially when alternate sources to freshwater such as desalination of seawater is used instead.¹⁷ As such, the omission of water in this study is not deemed a critical gap though recommended as a future improvement for local assessments.

Table 0-1: The potential domestic application of hydrogen along with the archetype alternatives modelled

Sector	Hydrogen (H2) option in SATIMGE	Primary alternatives in SATIMGE
Transport	Light Duty Vehicles (passenger & freight)	Battery-electric; Hybrid-ICE; Natural gas, Liquid biofuels
Transport	Heavy Duty Vehicles	Battery-electric ^{#1} ; Natural gas; Liquid biofuels.
Electricity Generation	Fuel-Cell; Gas Turbine	Electric battery; Natural gas turbine with CCS ^{#2}
Industry	Iron production; Process heating.	Coal; Electrification.
Industry	Ammonia production	Natural gas
Manufacturing	Fuel cell production for road vehicles listed for Transport	N/A

Source: Compiled by the Authors

Notes: #1: Restricted to Class 3 vehicles (16,000 kg GVM) at present. As such results represent an optimistic H2 case for which competition from battery-electric vehicles would reduce market share. #2: Carbon Capture and Storage (CCS) via Durban basin.

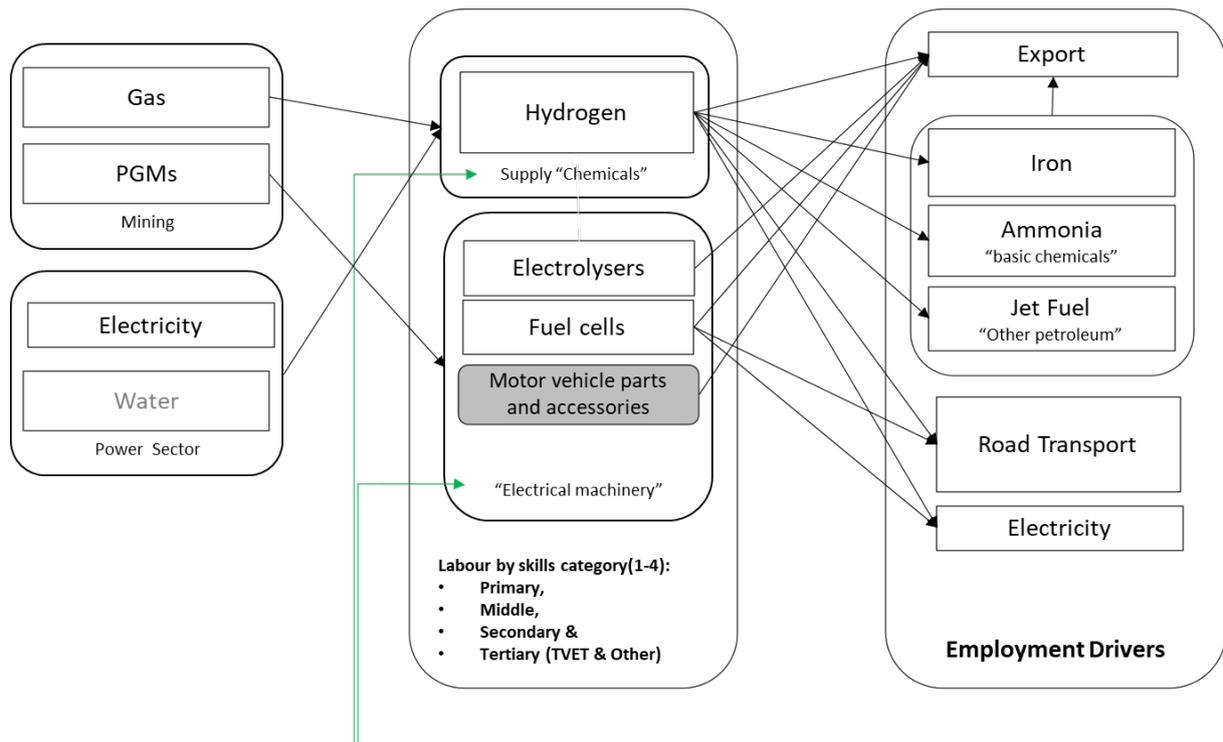
Figure 0-2 illustrates the coverage of hydrogen sectors within the economic part of SATIMGE for the present study. The model is configured such that hydrogen is included as a competing option in the transport and electricity sectors for domestic use. In the electricity sector, utility scale power generation includes hydrogen turbines and fuel cells as options. For transport, fuel cells are presumed as the prime mover technology. However, for modelling hydrogen economy-related sectors data is scarce and typically no data is available for production

¹⁶ IEA, "Future of Hydrogen" (2019)

¹⁷ Acil Allen Consulting, "Opportunities for Australia from hydrogen exports", (Acil Allen Consulting for ARENA, Australia, August 2018); Roos "Costs RE hydrogen SA" IJHE (2021).

facilities at the scale and efficiency which one can expect for the future market for fuel cells.¹⁸ This necessitated at instances the use of proxy sectors to describe the “production recipes” (cost structures) of nascent hydrogen sectors, indicated in Table 2-1 and identified in Schers et al.¹⁹ E.g., the “recipe” for green ammonia production is assumed to mirror “basic chemical industry” in terms of labour intensity and skills as found (calibration) Social Accounts data. However, for the fuel cell and electrolyser sectors, the split between intermediates and value added, as well as for VA’s labour versus capital split, we used inputs from a paper by E4Tech that describes these cost structure breakdowns.²⁰

Figure 0-2: Conceptual representation of the hydrogen sectors in the SATIMGE model



Use of proxy sectors in the absence of empirical data

Source: Compiled by the Authors

¹⁸ For electrolyser technology there might be data, but such industrial “recipes” were not publicly accessible. An interview was held with a South African producer of PEM fuel cell components. Currently their production process still had a high degree of manual and artisanal work which is to be automatized when the process could be scaled-up to satisfy future higher demand. Their current “recipe” is therefore far from representative for future large scale production within a GHE.

¹⁹ Schers, et al. “Green hydrogen and TVET skills” (2021); and: Schers, et al. “Hydrogen economy skills” (2021)

²⁰ E4Tech, “ Study on Value Chain and Manufacturing Competitiveness Analysis for Hydrogen and Fuel Cells Technologies”, (Findings Report for FCH 2 JU, E4tech (UK) Ltd, Ecorys and Strategic Analysis Inc, London (UK), September 2019), <https://www.fch.europa.eu/sites/default/files/Findings%20Report%20v4.pdf>

2.3 Scenarios for modelling hydrogen futures for South Africa

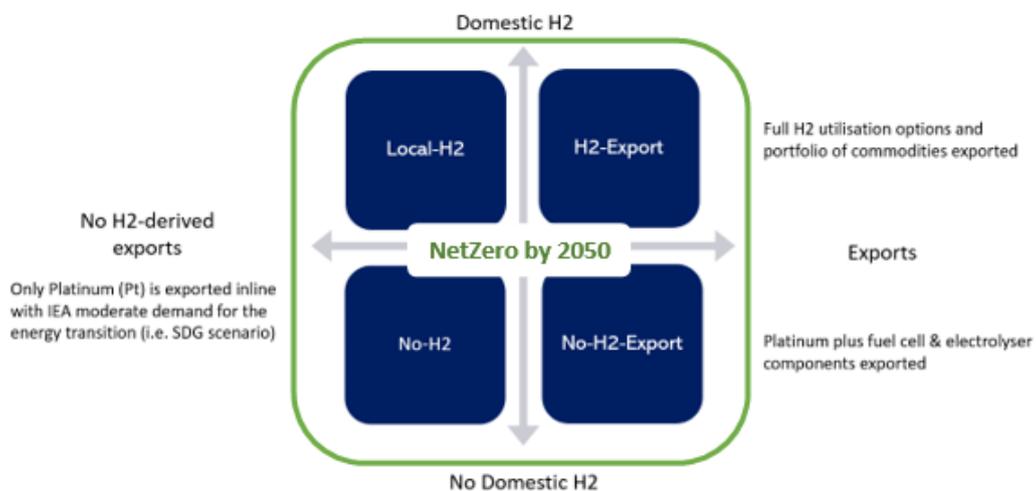
To quantify TVET employment futures, a holistic assessment of the growth of a South African Green Hydrogen Economy (GHE) is required. To estimate implications for growth and for employment associated with developing a green hydrogen economy, this study incorporates two axes that inform future projections of demand as shown in Figure 0-3. The axes form the conceptual framing of the analysis which contrasts domestic utilisation with export-oriented activity, in a context of ambitious climate policy that aligns to the goals of the Paris Agreement 2015, South Africa's NDC and the ambition of Net Zero carbon by 2050. Therefore, a coherent narrative of decarbonisation that includes the 'net-zero'²¹ paradigm across the modelling horizon to the year 2050²² provides the basis to compare the scenarios.

Figure 0-3: Hydrogen pathways for South Africa towards 2050

²¹ 'Net Zero' (NZ) means that globally, we reach a point at which CO₂ sources equal CO₂ sinks. All NZ scenarios aim both at a certain amount of gross emissions by 2050 (which in combination with estimated emission sinks lead to Net zero), and a cumulative GHG emission budget from 2020 to 2050 of 8 Gt CO₂-eq; see Bruno Merven, Andrew Marquard, Bryce McCall, Fadiel Ahjum, et al. 'Preliminary work on Net-Zero CO₂ by 2050 for South Africa' Energy Systems Research Group (ESRG), University of Cape Town (UCT). International Energy modelling Workshop (IEW) 2022 conference paper (forthcoming); 8 Gt cumulative is considered part of South Africa's fair share range to contribute to climate change mitigation efforts. See also: Marquard, Andrew; Winkler, Harald; Cunliffe, Guy; Dane, Anthony. 'South Africa's "fair share": mitigation targets in the updated first NDC in an international context'. University of Cape Town. Report. <https://doi.org/10.25375/uct.16691953>.

²² In 2018 the IPCC produced the Special Report on Global Warming of 1.5°. The Report makes it very clear that a) we are already facing climate impacts; b) that these will be significantly worse at 2° than at 1.5°; and that global CO₂ emissions pathways consistent with keeping global temperature within the 1.5° limit require rapid global emissions reductions – 45% by 2030 (in relation to 2010 levels) and global CO₂ emissions should reach net zero¹ by 2050 (IPCC, 2018).

²² See: Jules Schers et al., "Green hydrogen and TVET skills" (2021).



Source: Compiled by the Authors

Where “No Domestic H2” is assumed green hydrogen and its derived commodities green ammonia and green iron/steel cannot be produced and energy end uses will require use of the renewable primary technology alternatives mentioned in Table 0-1 for moving towards Net Zero carbon. Table 0-2 summarizes the features of the scenarios and Table 0-3 presents export levels assumed for the commodities mentioned in Figure 2-3 (see also Appendix A). In addition to the main scenarios, a *Climate-Lag* scenario is included to examine consequences of delayed climate policy implementation, in which the model also seeks a cost-optimal energy system, but without GHG emission constraints.²³

Table 0-2: Key attributes of the scenarios

Scenario	Domestic hydrogen utilisation	Exports: IEA moderate ^{#2}				
		Platinum ^{#1}	Machinery: Fuel-cells, Electrolysers	Green Ammonia	Green Steel	E-Kerosene (Jet fuel) ^{#3}
No-H2	x	✓	x	x		x

²³ The Climate Lag scenario does not account for possible future carbon-reflective trade tariffs or any other international shift away from fossil-fuel related commodities (e.g. coal and conventional vehicles) and thus ignores certain economic impacts, besides ignoring negative consequences from climate change if delayed action would be a global scenario.

No-H2-Export	x	✓	✓	x		x
Local-H2#4	✓	✓	x	x		x
H2-Export	✓	✓	✓	✓		✓

Source: Compiled by the Authors

Notes: #1 Referring to Appendix A, South African platinum export is estimated for the energy transition in addition to historic exports which is adjusted to account for a projected decline in demand from the ICE automotive sector.

#2 Referring to Appendix A, the IEA moderate projections are used to determine South African export levels.

#3 It is assumed that the Secunda coal liquefaction facility is converted in two phases (per Fischer-Tropsch reactor) to a H2-based facility producing e-kerosene as its primary product (Marchese et al. 2021).

#4 The Climate-Lag scenario which is used to explore hydrogen under a different policy-environment leading to several different technology-choices corresponds to the Local-H2 scenario with the exception that no constraint on greenhouse gas emissions is imposed. The energy model chooses the least-cost energy system for the corresponding economic future without any GHG emission budget or GHG emission target. The Climate-Lag scenario does not account for the possibility of future carbon-reflective tariffs in trade (e.g. carbon border tax adjustment) and a shift away from fossil-fuel based commodities such as coal and conventional vehicles around the world that may otherwise affect the balance of current trade.

Table 0-3: Commodity export levels assumed

Commodity	Units	2030	2035	2040	2045	2050
Export PGMs – Platinum (Pt)	tonne (t)	141	155	170	348	527
Export PGMs – Other Platinum Group Metals	tonne (t)	104	104	104	104	104
Ammonia (energy unit)	PetaJoules (PJ)	2.8	33	63	94	124
- in metric tonnes (mass unit)	Mega-tonnes (Mt)	...	1.5	3	4	5.5
Green Iron/Steel	Mega-tonnes (Mt)	1.0	4.3	7.5	11	14
Green JetFuel (energy unit)	PJ	0	0	5	5	10
- in metric tonnes (mass unit)	Mt	n/a	n/a	0.12	0.12	0.24
PEM Electrolysers (components)	GigaWatt (GW)	0.2	1.3	2.4	12	21
PEM Fuel Cells (components)	GW	0.03	4	8	159	310

Source: Compiled by the Authors (see Appendix A for details of underlying assumptions)

2.4 Modelling TVET employment shares

As discussed in Schers et al.²⁴ our analysis is based on the observation from Post-apartheid Labour Market Series (PALMS) of cross-sectional labour force surveys from 1995-2019.^{25,26} TVET educated shares in employment showed to remain relatively constant over the past decade. On this basis they are projected to remain constant within each sector's labour force, as given by 5-year averages (2015 – 2019) shown in

²⁴ In 2018 the IPCC produced the Special Report on Global Warming of 1.5°. The Report makes it very clear that a) we are already facing climate impacts; b) that these will be significantly worse at 2° than at 1.5°; and that global CO2 emissions pathways consistent with keeping global temperature within the 1.5° limit require rapid global emissions reductions – 45% by 2030 (in relation to 2010 levels) and global CO2 emissions should reach net zero¹ by 2050 (IPCC, 2018).

²⁴ See: Jules Schers et al., "Green hydrogen and TVET skills' role in South Africa's just transition", (SAILA UKPACT and University of Cape Town, Policy Insights, 2021).

²⁵ Kerr, et al. Post-Apartheid Labour Market Series [dataset], Version 2.1, Cape Town: DataFirst [producer and distributor], 2013. [zaf-datafirst-palms-1994-2012-v2.1].

²⁶ The data is weighted using cross-entropy weights created for reliable and consistent data analysis over time. For more info, see: Branson, N., & Wittenberg, M. 'Reweight South African National Household Survey Data to Create a Consistent Series over Time: A Cross-Entropy Estimation Approach', South African Journal of Economics 82, no. (2014):19-38.

Table 0-4. For completeness, the proportion of workers in different tertiary educational categories are also shown.²⁷ There is variation in the proportion of TVET educated workers between different sectors with coal mining having the largest proportion of their workers with a TVET education (10.4%), followed by electricity (7.84%), and Petrochemicals (5.5%).

Further detail about which jobs require what type of TVET education would have been good to have to inform policymaking around TVET education. However, while Labour Force Surveys of Statistics South Africa provide some further disaggregation of sub-categories of TVET-educated labour, these turn out to lead to sample sizes too small for meaningful interpretation. The only exception is the subdivision of the employed in three job-type skill levels, as in Borat et al²⁸, which we use for some of the analysis presented in the present study. The subdivision categorizes employed individuals into skill levels classified as High-skilled, Low-skilled, or Semi-skilled (see Table 0-5). In South Africa most TVET-educated workers are employed in occupations classified as semi-skilled (55% of TVET workers in 2019), followed by high skilled occupations (36% of TVET workers in 2019).²⁹

²⁷ Schers et al, 'Hydrogen economy skills and the just transition' Occasional Research Paper, June 2021 describes the statistical categories in Annex 3. In brief, TVET shares are calculated based on PALMS survey answers about highest education "NTC I to III", and other "Certificates, with or without matric". The Lower Tertiary category consists of education post TVET or post-matric corresponding to "N4-6/NCT4-6", "Diploma's with or without matric" and "Higher Diploma's". Higher Tertiary corresponds to university degrees: "Post Higher Diploma", "Bachelor's Degree", "Honours Degree" and "Higher Degrees".

²⁸ Borat, et al., 2015. "Demographic, employment, and wage trends in South Africa" (Working Paper 2015/141, WIDER, Cape Town, 2015), <https://www.wider.unu.edu/sites/default/files/wp2015-141.pdf>.

²⁹ Schers, et al. "Green hydrogen and TVET skills" Policy Insights (2021).

Table 0-4: 5-year average share of tertiary employment by sectors of interest (2015/2019) ³⁰

Sector	TVET Share	Low Tertiary Share	High Tertiary Share
Coal Mining	10.41%	14.75%	4.43%
Petro Chemical	5.49%	24.02%	18.42%
PGM	4.52%	6.82%	2.72%
Iron and Steel	2.90%	8.70%	4.14%
Land Transport	3.32%	6.81%	3.20%
Electricity	7.84%	31.90%	16.60%
Electric Machinery	3.22%	13.88%	8.44%
Basic Chemicals	4.53%	13.87%	10.90%
Motorised Transport	4.98%	14.74%	5.82%
Total SA Labour Force	3.86%	9.41%	8.93%

Source: Compiled by the Authors calculations based on: Kerr, et al. PALMS v3.3 (2019).

Table 0-5: Occupations used on the decomposition analysis³¹

Broad Task Category	Occupations
High Skilled	1. Legislators, senior officials and managers
	2. Professionals
	3. Technical and associate professionals
Semi-Skilled	4. Clerks
	5. Service workers and shop and market sales workers
	6. Skilled agricultural and fishery workers
	7. Craft and related trades workers
	8. Plant and machine operators and assemblers
Low-Skilled	9. Elementary Occupation
	10. Domestic Worker

Source: Borat et al., "Demographic, employment".

³⁰ Source: Author calculations based on: Kerr, et al. PALMS.

³¹ Borat et al., "Demographic, employment".

³¹ Borat et al., "Demographic, employment".

3. Results: Growth, Emissions and Employment impacts of a GHE

3.1 Introduction

The main finding which this chapter describes are that there are potentially strong economic benefits in terms of growth of GDP and employment if a South African green hydrogen economy (GHE) develops value-generating export markets for green hydrogen-based commodities and appliances. Furthermore, we show that investments for a South African green hydrogen economy reduces the need to rely on costly CCS and Direct Air Capture of greenhouse gas emissions (GHG) technologies closer to the 2050 horizon for Net Zero carbon, as well as thereafter. This finding is based on a comprehensive portfolio of energy technologies that are available currently or in the near future.

Though only small economic costs and benefits are found of developing a domestic (only) green hydrogen economy for most of the projection horizon, we conclude that a domestic GHE plays a significant role in achieving Net Zero carbon by 2050. The domestic GHE would achieve Net Zero carbon in such a way that it allows more economic prosperity in South Africa by the middle of the century and thereafter compared to a future without green hydrogen development in South Africa, even if exports would not materialize according to our moderate GHE export assumptions.

The discussion in the remainder of this section highlights different aspects of how and to what extend investing in the technologies a green hydrogen economy contributes to GDP growth, emission reductions and employment growth. To make these findings comprehensible this chapter first discusses GDP growth in the different scenarios with a focus at the sectoral level (section 3.2). Sectoral GDP growth outlooks can partially be associated to the differences in the technology profiles of the scenarios, which are discussed next (section 3.3). These technology profiles help explain the greenhouse gas emission impacts of a GHE (section 3.4). Finally, sectoral employment results are discussed (section 3.5) plus estimates of job impacts of specific hydrogen applications (section 3.6).

3.2 Economic growth and sectoral value added

3.2.1 Overview of GDP outcomes

In terms of economic growth³² three out of the four Net Zero scenarios are quite similar (see Figure 2-3 and Figure 3-1): Total growth for 2020 to 2050 in the NoH₂, NoH₂-Exports and Local-H₂ scenarios reflects the reference productivity growth assumption and arrives at an average

³² In SATIMGE we measure economic growth through growth of total Gross Value Added (GVA). Put simply, the more commonly known Gross Domestic Product equates to GVA plus the total value of taxes on products, minus the total value of subsidies on products. As the rate of the value of taxes – subsidies over GVA tends to be quite constant, in the absence of strong policy changes, relative growth in GVA and GDP tends to be very similar.

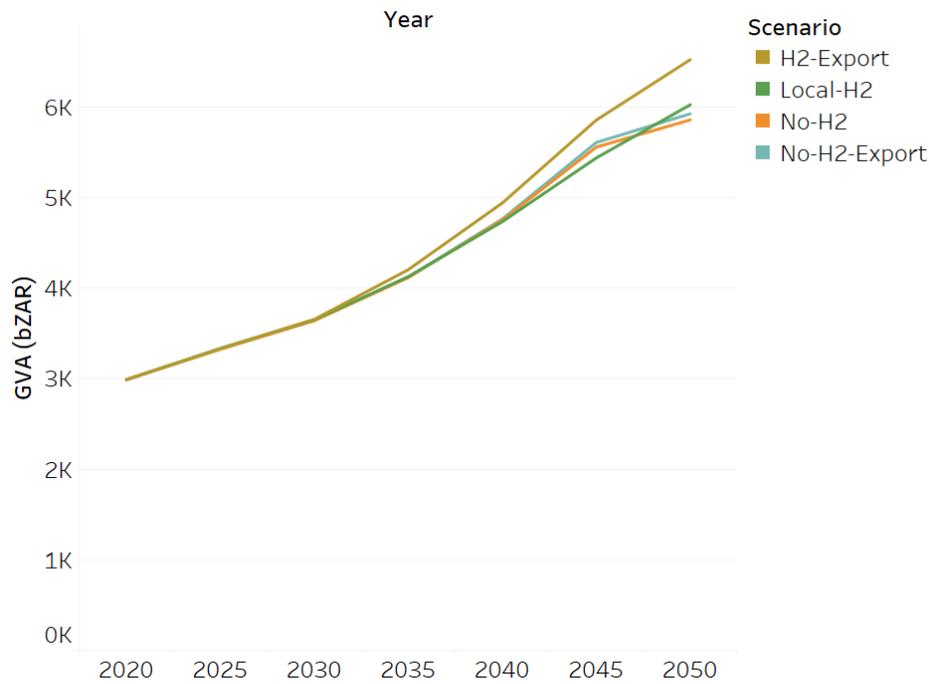
2.3-2.4% growth per year (96% to 102% for the full period). Only the H2-Export scenario shows significantly higher economic growth to 2050 compared to the other three scenarios. This scenario, which has the full exports portfolio of hydrogen-based commodities in combination with a domestic GHE, sees GVA grow on average 0.2-0.3 percentage points more per year between 2020 and 2050 than in the other Net Zero scenarios. This would result by 2050 in the SA economy being about 11% larger than in the case of the NoH2 scenario. Another eye-catching result is that growth in the scenarios without a domestic GHE almost stagnates from the mid 2040's onwards (which is explained below). This means that when heading to Net Zero carbon by the middle of the century the outlook for economic growth is better with a South African GHE than without it, even without GHE commodity exports.

The Climate-Lag scenario has been added for completeness, but its economic outlook cannot be entirely compared to that of the Net Zero scenarios due to the omissions in considering potential negative impacts as discussed previously. However, despite these omissions, the economy in the Climate Lag scenario is by 2050 only marginally bigger than that of the H2-Export scenario, namely 2.5% of 2050 GVA in 2050 (0.08% average annual growth from 2020 to 2050).

In our model these differences for economic growth can all be led back to differences in the country's energy system and to export assumptions. One of the main causes for differences in GDP growth is that the amount of capital for investment is not unlimited.³³ While energy system investments allow for growth of energy supply and energy efficiency to fuel economic growth, its investment requirement also reduces the amount of capital available for investments in the rest of the economy. Therefore, if total costs (capital, fuels, other inputs) of the energy systems are high, growth will be less in other parts of the economy. The main question thus becomes how these investments allow for value creation. This and other reasons for the differences in GDP growth will be discussed in a scenario-to-scenario comparison in the remainder of this subsection.

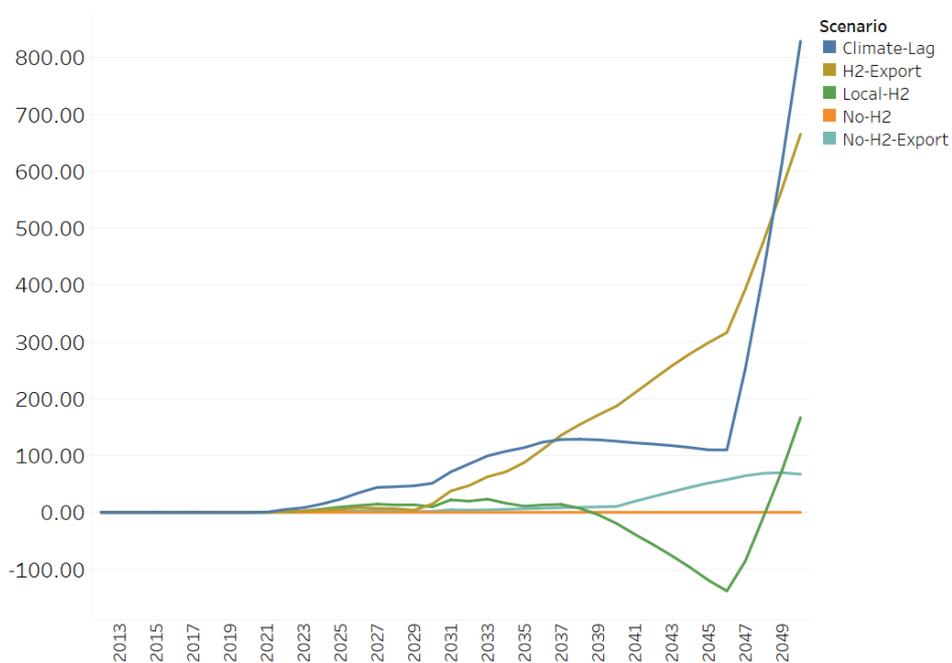
³³ The amount of investment is constrained by the net savings (and saving rates) of South African households, enterprises and government, and an amount of foreign savings (foreign investment) fixed in foreign currency.

Figure 0-1: GDP projections to 2050 by scenario in billion ZAR(2012)



Source: Compiled by the Authors based on own scenario results from SATIMGE model

Figure 0-2: Differences in total GVA to 2050 relative to the NoH2 scenario in billion ZAR(2012)



Source: Compiled by the Authors based on own scenario results from SATIMGE model

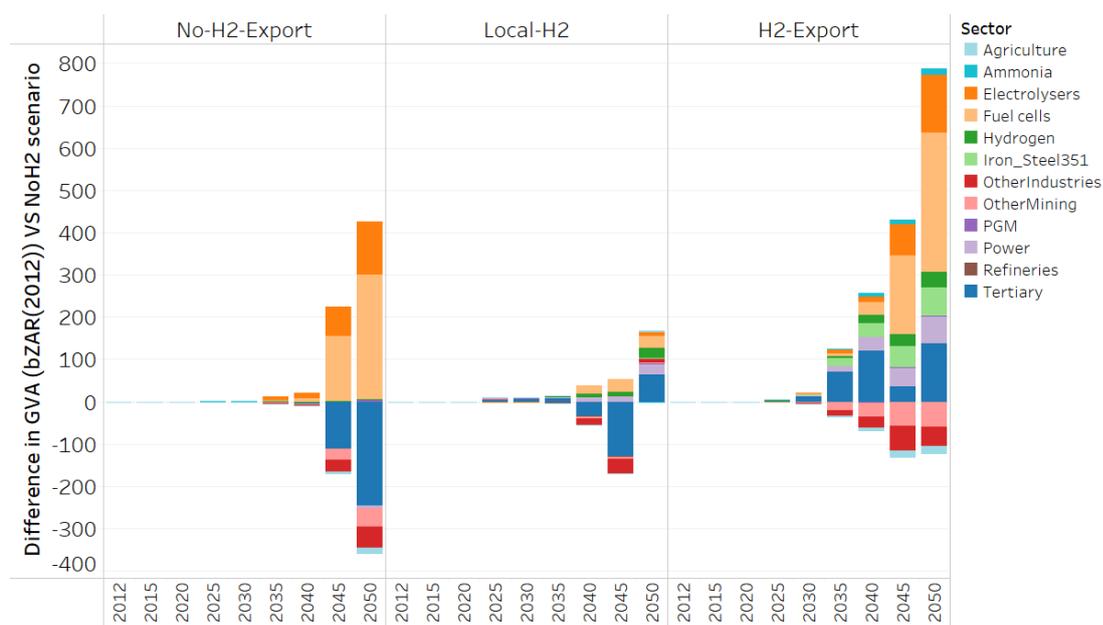
3.2.2 Impacts of achieving Net Zero carbon with a domestic-only GHE (Local-H2)

Growth in Gross Value Added (GVA) is not uniform across sectors and scenarios. All scenarios show differences in terms of composition of GVA, in comparison to the NoH2 scenario (Figure 0-3). These differences are of course related to the introduction of a green hydrogen economy, or of GHE exports. Some are direct consequences of the GHE, while other are indirect – i.e., related to the availability of investment for the economy as a whole.

In the scenario with a local SA Green Hydrogen Economy only (Local-H2) energy system investments in power generation are initially lower than in the NoH2 scenario (see also section 3.3.2). The reason is that in GHE scenarios the future introduction of a GHE is expected to offer room for emission reduction which would not be available without a GHE. In the NoH2 scenario several coal power plants would need to shut down sooner in the period 2024-2037 than in the Local-H2 scenario, to be substituted by earlier additions of renewable power generation capacity than in the Local-H2 scenario (see Appendix B.4).

Later on, between 2033 and 2044, energy system investments become higher in the Local-H2 scenario than in the NoH2 scenario, because of a catch up in replacing coal-based power generation capacity and for additional power generation capacity and other infrastructure, like electrolyzers to prepare for hydrogen production. This explains the small slowdown in economic growth relative to NoH2 scenario between 2035 and 2045. In the Local-H2 scenario this effect of timing of investments means that during this period GVA of Tertiary and Other Industries sectors is lower compared to the NoH2 scenario during those years Figure 3-3. Annual growth in the Local-H2 scenario then overtakes that of the NoH2 scenario again between 2046 and 2050. The reason is that the additional investments for a domestic GHE have reduced the need to rely on Carbon Capture & Storage and especially Direct Air Capture technologies from the mid 2040'ies onwards, as is the case in the NoH2 scenarios (see section 3.4). Those investments are foreseen to be costly and to slow-down economic growth for a long period to come in which these systems would operate to control South African GHG emissions. Developing a Green Hydrogen Economy would thus be an essential ingredient for South African economic growth by the mid-21st century in the context of Net Zero carbon by 2050.

Figure 0-3: : Composition of difference in total GVA compared to No-H2 scenario GVA, in billion ZAR 2012



Source: Compiled by the Authors based on own scenario results from SATIMGE model

3.2.3 A domestic GHE with a full GHE export portfolio (H2-Export)

In the H2-Export scenario, as in the Local-H2 scenario, we observe a similar delay in the need for new power generation capacity investment between the mid 2020'ies and the mid 2030'ies, leading to slightly higher investment and growth in other parts of the economy. The reason is the same as in for the Local-H2 scenario: Several existing coal power plants can operate one or two years longer than in the NoH2 scenario reducing the speed at which additional renewable power generation capacity would be required. However, to make room for the additional economic growth in the H2-Export scenario relative to both the Local-H2 scenario, more greenhouse gas "emission space" is required for industry and transport – sectors which take more time to decarbonise than power generation – which means that several existing coal power plants are still required to shut down a year or two sooner than in the Local-H2 scenario (see Appendix B.4). However, the difference is much smaller than for the Local-H2 scenario and the difference in total GVA between 2025 and 2030 is therefore negligible compared to the NoH2 scenario (see Figure 0-3).

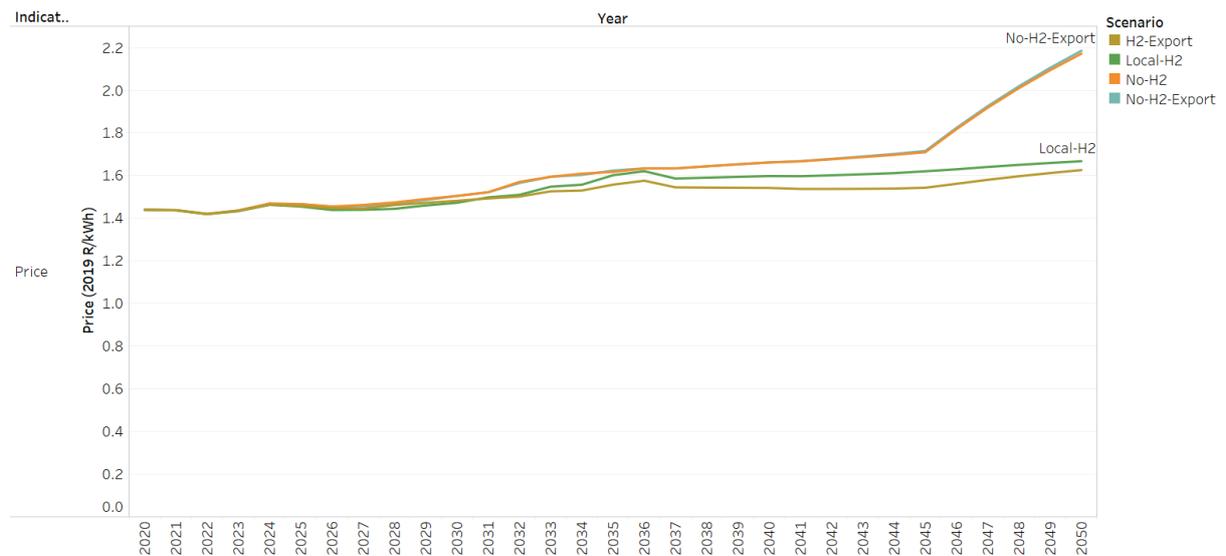
After 2030, exports of Green Iron & Steel and Green Ammonia increase, as well as those of Fuel Cells and Electrolysers. However, from figure 3-1 we also note that exports do not tell the whole story, as the economic benefits of exporting with a domestic green hydrogen economy are much bigger than those of exporting Fuel Cells and Electrolysers without a domestic SA GHE economy (compare H2-Export vs, NoH2-Export scenario). A combination of factors explains why growth is particularly strong in the H2-Export scenario:

1. One reason is that significant exports of green hydrogen-based commodities (Iron & Steel, Ammonia, Jet Fuel) in the H2-Export scenario start much earlier (increasing almost linearly from around 2030 onwards), while exports of platinum-based appliances (PEM Fuel Cells and Electrolysers and their components) in both of the

export scenarios are assumed to only increase strongly from around 2040 onwards (see Table 0-3).

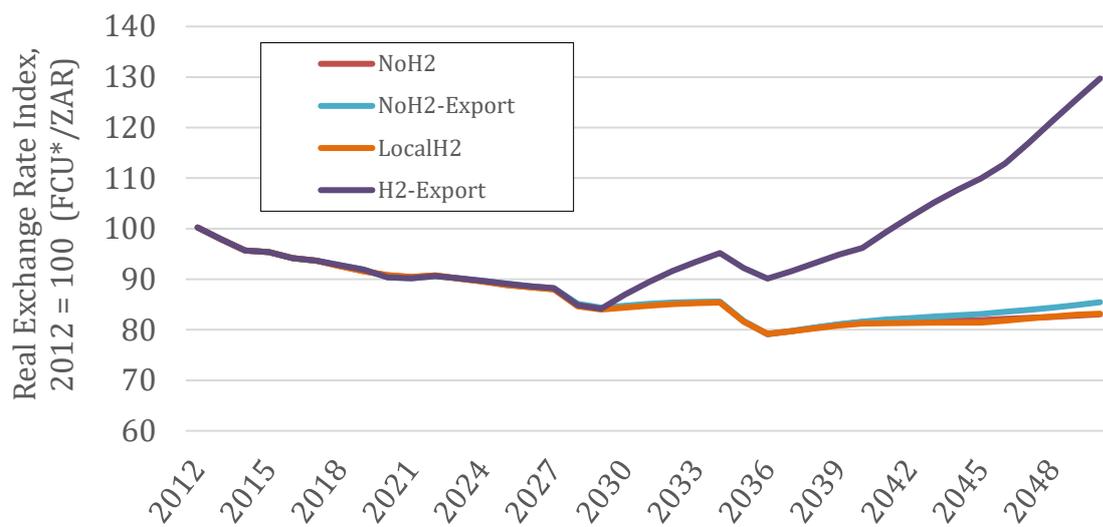
2. Secondly, the Iron & Steel and Ammonia sectors are expected to have more links to the rest of the South African economy by requiring more intermediate inputs per Rand of export value, thus creating more economy-wide GVA relative to the GVA within the sectors themselves.
 - a. This can be observed from comparing the positive change in GDP growth of the H2-Export scenario relative to the NoH2 scenario between 2030 and 2040 (see figure 3-2), with the relatively small share of these sectors in the difference in total GVA between these two scenarios (see figure 3-3).
 - b. Between 2040 and 2050 the Fuel Cell and Electrolyser exports add a lot more GVA than Green Iron & Steel and Green Ammonia exports, but this does not translate into an equivalent increase in growth of total GVA compared to the NoH2 scenario, as more crowding out of investments and thus GVA growth into other sectors (notably of Other industries and Tertiary Sectors (Services)) would take place.
3. Thirdly, the H2-Export scenario benefits from lower electricity prices compared to the other Net Zero scenarios (Figure 0-3). This means South Africa can produce and export more competitively and export similar volumes at a stronger exchange rate (figure 3-4). The reason is that the green hydrogen economy in both the H2-Export and the Local-H2 scenario leads, as mentioned, to a more optimal profile of investment in new power generation capacity thanks to some initial delay for investments and thanks to the strong increase of new capacity later on when renewables and batteries will be even cheaper:
 - a. In the H2-Export scenario cumulative investments in power generation only overtake those of the NoH2 scenarios around 2032 (this happens only in 2034 in the Local H2 scenario), at which point SA's GDP is already about 1% higher than in the NoH2 scenario (a number which increases thereafter), and thus a bigger capacity to support these investments.
 - b. A large part of additional power generation capacity beyond 2030 is meant to power electrolyzers for the GHE (of which a large part within the Iron & Steel sector), which from 2030 onwards increase gradually to about 21 GW by 2050 in the H2-Export scenario (and 10.5 GW in the Local-H2 scenario).
 - c. The hydrogen economy avoids the costly reliance on CCS and Direct Air Capture technologies in the NoH2 and NoH2-Export scenario to reduce remaining emissions of coal and natural gas between 2045 and 2050 and which translate to a steep increase of the electricity price in those scenarios (see Figure 0-3).

Figure 0-2: Evolution of the electricity price in R/kWh for Net Zero scenarios



Source: Authors' scenario results from SATIMGE model

Figure 0-3: Real Exchange Rate index to 2050 by scenario, FCU/Rand (2012=100)



Note: * FCU = Foreign Currency Units, typically we assume US Dollars, but it represents a basket of currencies

Source: Compiled by the Authors based on own scenario results from SATIMGE model

3.2.4 Impacts of exporting platinum-based GHE appliances without a GHE (NoH2-Export)

Lastly, we briefly explain the GDP growth outlook of the NoH2-Export scenario, about which a lot has been said already. While the introduction of Fuel Cell and Electrolyser exports in the 2040'ies in the NoH2-Export scenario leads to growth in GVA for these sectors, we find that between 2035 and 2045 crowding out of GVA of especially the Tertiary sectors (Services) and Other Industries takes place. The main reasons would initially be that a relatively high electricity price (

Figure 0-2) and the capital intensity of the Fuel Cell and Electrolyser industries (estimated respectively at 24% and 20% of the cost structure / producer's price) ³⁴ do not allow for more value creation than in the NoH2 scenario and thus lead to crowding out of investments and growth in other sectors. From 2045 onwards the costs of CCS and Direct Air Capture of CO₂ emissions increase the electricity price and reduce the availability of capital for other sectors thus reducing the potential for export-driven economic growth, though still a small improvement of GDP growth (

³⁴ Schers, et al. "Green hydrogen and TVET skills" Policy Insights (2021).

Figure 0-1) as well as some strengthening of the exchange rate (Figure 0-3) can be observed between 2045 and 2050 for the NoH2-Export scenario compared to the NoH2 scenario.

3.3 GHE technology dynamics

The investment and GDP growth profiles of the scenarios described in the previous section are strongly linked to the technology outlook for different sectors, which this section discusses.

3.3.1 Green Hydrogen and Industrial Use

In the techno-economic trade-off between hydrogen use and the alternative technological options included in the model for the economy-wide assessment (see section 2.2), hydrogen use mainly turns out to be limited to four applications, varying in scale and timing by scenario (Figure 0-4):

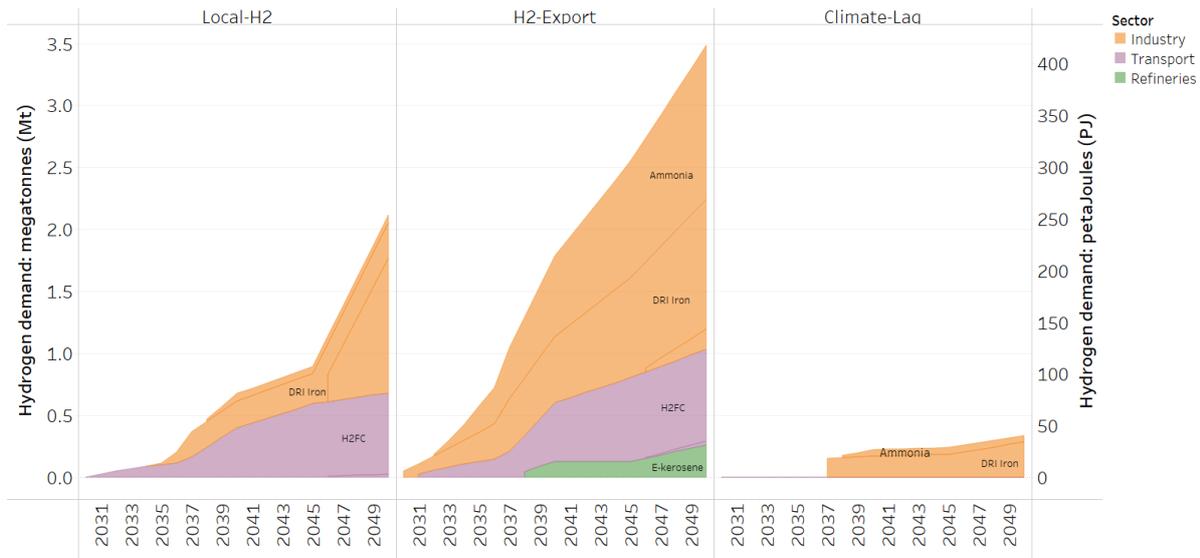
Domestic demand for hydrogen, in the absence of exports (Local-H2 scenario), turns out to be limited to the production of Green Ammonia, Green Iron/Steel and Heavy-duty Vehicles for the domestic markets. In this case the transport sector would dominate hydrogen demand for a long time, with about 0.65 megatonnes (Mt) of the total 2.1 Mt H2 annum in 2050. In freight transport hydrogen is dominantly used by Heavy Cargo Vehicles (HCV, class 6-9), with towards 2050 a niche market for medium-sized HCV2-5 type vehicles. Green hydrogen use for industrial process heat appears in the mid-2040's to become the dominant type of hydrogen demand with 1.1 Mt by 2050. Green Ammonia and Iron/Steel production would require respectively 0.06 Mt and 0.3 Mt hydrogen by 2050.

In the export-oriented GHE scenario (H2-Export) Green Hydrogen is produced for production of Green Ammonia, Green Iron/Steel, and E-kerosene (jet-fuel). This demands turns out to require an annual production of almost 3.5 Mt of hydrogen by 2050. Exports hydrogen demand to produce Green ammonia (1.2 Mt) and Green iron/steel (1 Mt) would exceed transport sector demand (0.8 Mt H2) by 2045. For reason of stronger economic growth relative to the Local-H2 scenario, H2 demand for transport is 12 Petajoules (or 0.1 Mt) higher in the H2-Export scenario. This equates to an additional 10,000 HCV class 6 trucks driving 120,000 km per annum.³⁵

Even in the absence of climate policy, in the Climate-Lag scenario, Green Iron & Steel turns out to become a competitive technology with a similar demand for Green Hydrogen as the sector has in the domestic GHE (Local-H2), though only from around 2037 onwards, which is only a few years later than in the GHE scenarios (Local-H2 and H2-Export).

³⁵ A Class 6 heavy-duty vehicle refers to a road vehicle with a gross vehicle mass (GVM) range of 24 to 32 tonnes, See: Adrian Stone et al., 'Providing a foundation for road transport energy demand Analysis: A vehicle parc model for South Africa' *Journal of Energy in Southern Africa* 29, no. 2 (2018): 29–42; Estimated from Dale Hall and Nic Lutsey, 'Estimating the infrastructure needs and costs for the launch of zero-emission trucks', International Council on Clean Transportation (ICCT), 2019, <https://theicct.org/publications/zero-emission-truck-infrastructure>; Jan Havenga, Phillipus le Roux and Zane Simpson, 'A heavy goods vehicle fleet forecast for South Africa', *Journal of Transport and Supply Chain Management* 12, no.0 (2018), <https://doi.org/10.4102/jtscm.v12i0.342>.

Figure 0-4: Magnitude of hydrogen demand by application for the scenarios



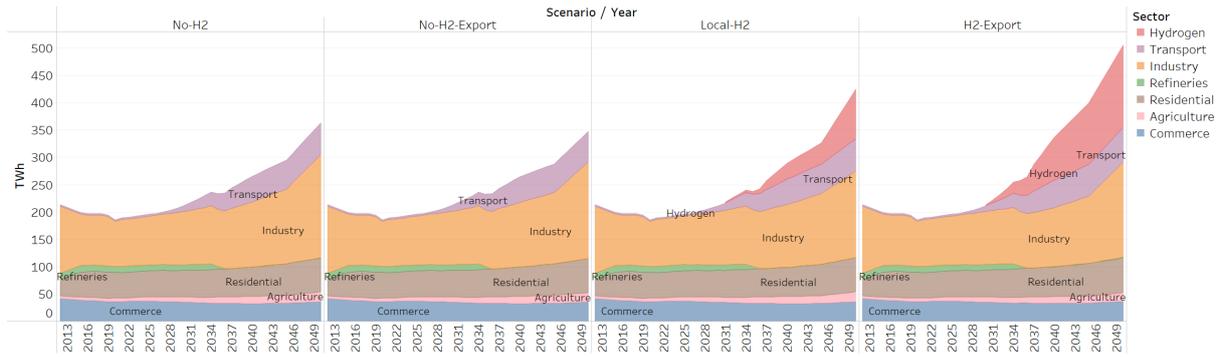
Source: Compiled by the Authors based on own scenario results from SATIMGE model

3.3.2 Power Generation

Both the demand for green hydrogen via electrolysis and economic growth have an impact on power generation. This can be observed from increased electricity consumption compared to the No-H2 scenario in for the Local-H2 and H2-Export scenarios, reaching respectively 70 TWh/year to 150 TWh/year by 2050 (Figure 0-5). In the NoH2 scenario power supply capacity (incl. storage and imports) grows from around 55 GW in 2020 to almost 220 GW by 2050 (Figure 0-6, Left window). Changes over time are a gradual phase-out of coal-fired power generation and gradual introductions of Solar, Wind and Natural Gas-fired power generation until 2032, after which Solar PV and Wind power generation continue to grow steadily. From 2037 onwards batteries are introduced in the power generation system (Figure 0-6, Left window). In comparison, the No-H2-Export scenario requires somewhat less power generation over time (about 6 GW less by 2050) due to Fuel Cell and Electrolyser manufacturing substituting Other Industry and Other Mining activity to some extent, with the former two being less energy-intensive than the latter two sectors.

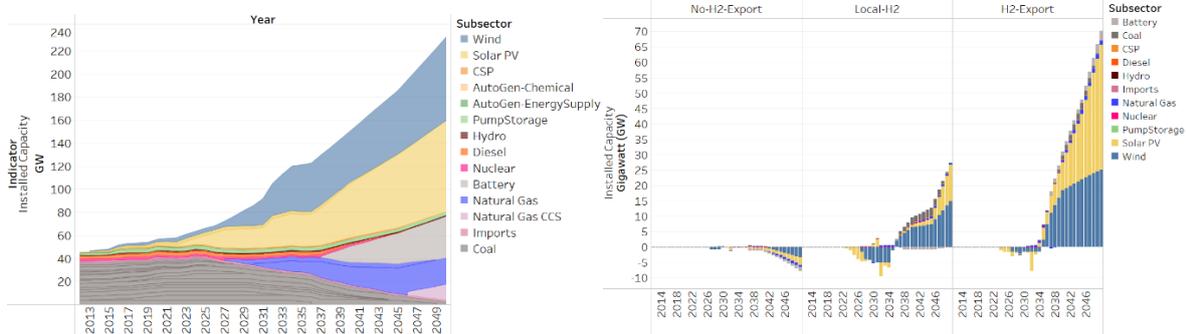
In contrast, the domestic and export GHE scenarios would require substantial additions to the power generation system. The Local-H2 scenario initially requires less capacity than the NoH2 scenario, but by 2035 investments in power generation will have caught up with those for the No-H2 scenario. Growth in demand for hydrogen (see section 3.3.1) after 2035 ultimately leads to 27 GW additional power generation capacity by 2050 compared to the NoH2 scenario, dominated by Wind followed by Solar-PV. The H2-Export scenario would require additional capacity of 7 GW by 2035 increasing up to 70 GW additionally in 2050. Again, additional Capacity relative to the No-H2 scenario are dominated, by Wind (25 GW additionally in 2050) and Solar-PV (41 GW additionally in 2050).

Figure 0-5: Electricity consumption by end use category for NZ scenarios.



Source: Compiled by the Authors based on scenario results from SATIMGE model

Figure 0-6: NoH2 power generation capacity 2020-2050 (Left) and Difference in power sector capacity versus NoH2 (Right)

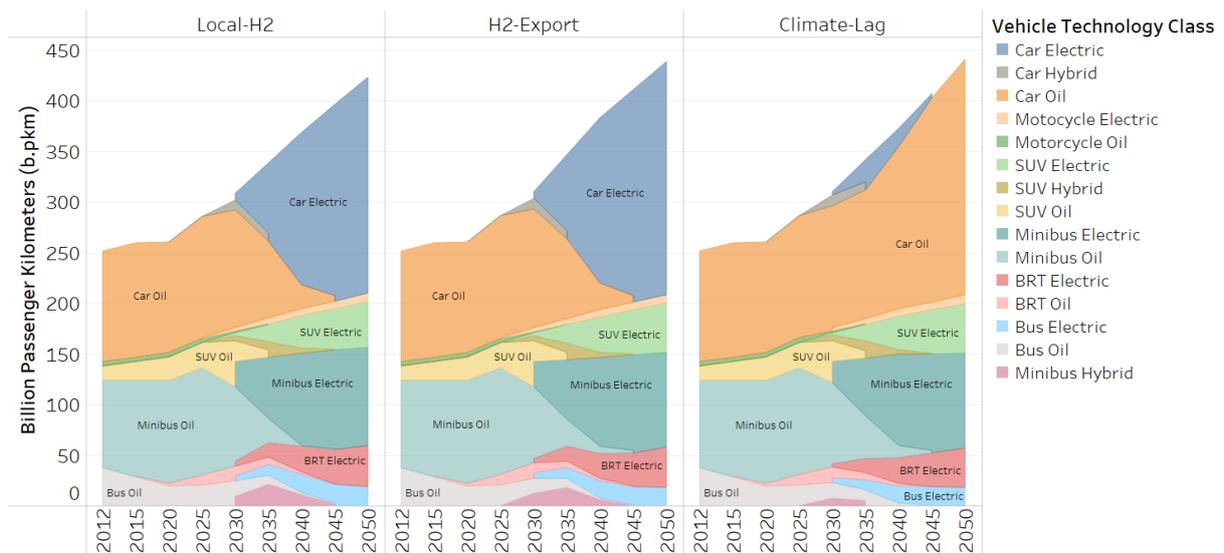


Source: Compiled by the Authors based on scenario results from SATIMGE model

3.3.3 Freight Transport

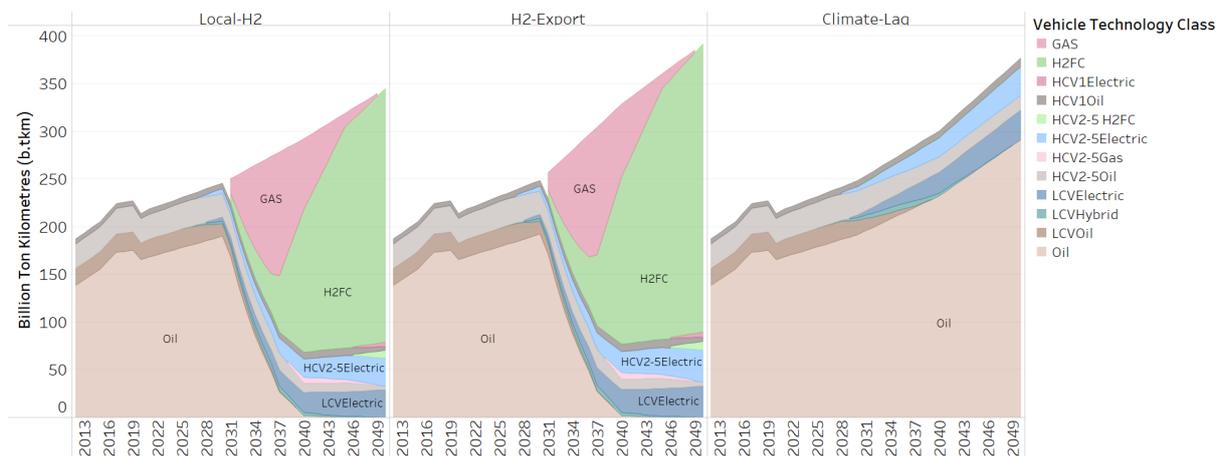
Our transport modelling assumptions assume a convergence of vehicle costs for differing vehicle types and technologies to occur by 2030. The evolution of the *light-duty fleet* towards 2050, for both passenger and freight sectors, is likely to be dominated by battery-electric technology (see Figure 0-7, and LCVs and HCV2-5 categories in Figure 0-8). Hydrogen usage in the road transport sector is restricted to heavy-duty vehicles in the freight sector (HCV6-9) and is therefore the focus of the discussion of the GHE in domestic transport.

Figure 0-7: Evolution of passenger road vehicle technology in SATIMGE



Source: Compiled by the Authors based on scenario results from SATIMGE model

Figure 0-8: Evolution of freight road vehicle technology in SATIMGE. Note: H2FC = Hydrogen Fuel Cell

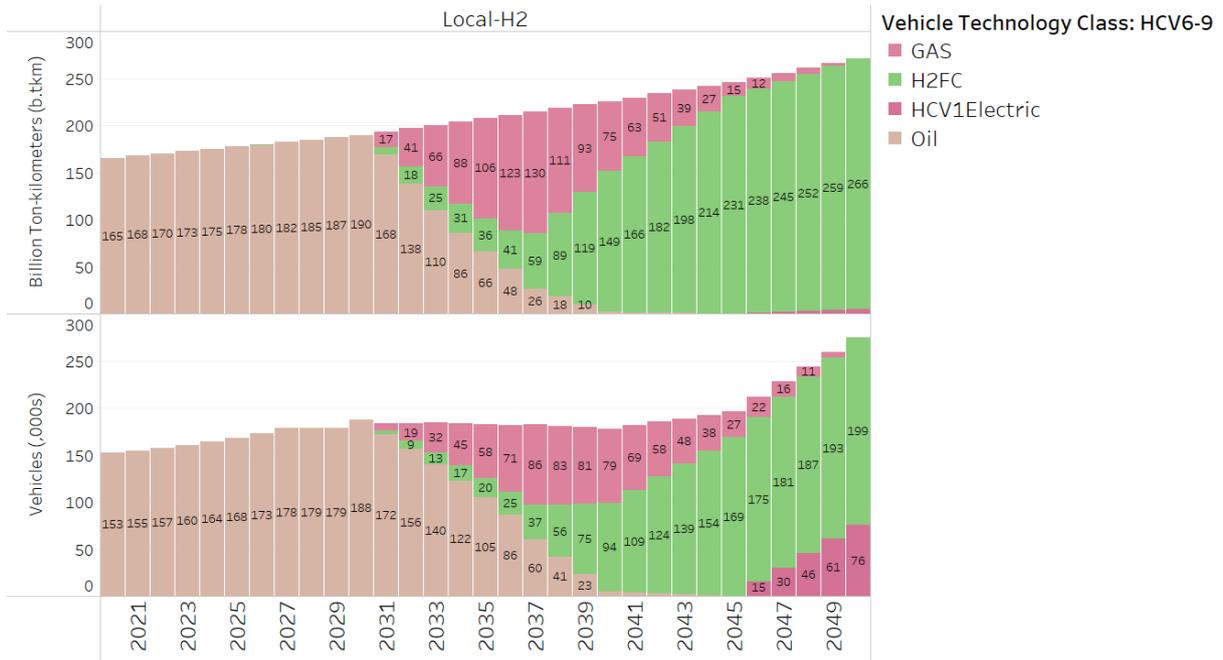


Source: Compiled by the Authors based on own scenario results from SATIMGE model

The vehicle population for Class 6 heavy-duty vehicles grows to to about 200,000 vehicles by 2035, from a present-day estimated 150,000 vehicles (See Figure 0-9). Vehicles using Natural gas in internal combustion engines (ICE) would represent the biggest part of new vehicle sales around 2035 in both the Local-H2 and H2-Export scenarios, with around 13,000 gas ICE vehicles sold per year by then compared to only around 4,000 hydrogen fuel cell (H2FC) vehicles. However, by 2039 H2FC trucks would occupy almost the entire market for new heavy-duty vehicle sales. By 2050 between 199,000 and 226,000 H2FC vehicles could be on the road in respectively the Local-H2 and H2-export scenarios.

Diesel and gasoline fuelled (ICE) heavy duty vehicles will have almost entirely disappeared from this fleet by 2040 in the Local-H2 and H2-Export scenarios, but not in the No-H2 and NoH2-Export scenarios in which only very late, around 2048 sales of gasoline and diesel HCVs stops to be replaced by electric and gas ICE vehicle trucks. This requires additional Direct Air Capture in these scenarios to achieve Net Zero carbon by 2050.

Figure 0-9: Portfolio of technology options for heavy class vehicles in category 6 to 9 for Local-H2 scenario



Source: Compiled by the Authors based on own scenario results from SATIMGE model

3.3.4 Fuel Cell manufacturing

In addition to upstream hydrogen demand, a domestic H2FC heavy duty transport fleet would require supply of fuel cells. Model results for fuel cell capacity requirement for a domestic fleet of HCV 6-9 H2FC vehicles project new vehicle sales of 3.7 to 5.6 thousand H2FC heavy duty cargo vehicles (class 6-9) in 2035, which would necessitate an annual fuel cell production of 1.5– 2.1 GW in 2035 (Table 0-1). By 2050 these numbers are 28 to 32 thousand new H2FC HCV6-9 vehicles and 14.7 to 16.7 GW of Fuel Cell capacity (Table 0-1). Annual platinum demand for fuel cells would range between 0.23 tonne and 0.32 tonne for a case of medium material use efficiency in 2035, and 1.65 to 1.88 tonne in 2050.³⁶ This demand would add to the assumed export volumes (see section 2.2).

Table 0-1: Annual fuel cell capacity (GW) required for HCV 6-9 heavy duty vehicles with platinum demand (tonnes)

Local-H2		H2-Export	
2035	2050	2035	2050
1.5 – 2.1	14.7 – 16.7	1.5 – 2.1	14.7 – 16.7
0.23 – 0.32	1.65 – 1.88	0.23 – 0.32	1.65 – 1.88

³⁶ Appendix A provides further information on assumptions regarding future material loading for PEM FCs.

H2FC Vehicle Sales ('000s)	3.7	28	5.6	32
Fuel cells (GW)	1.5	14.7	2.1	16.7
Platinum – Low (t)	0.17	0.60	0.24	0.69
Platinum – Medium (t)	0.23	1.65	0.32	1.88
Platinum – High (tonne, t)	0.25	2.05	0.34	2.34

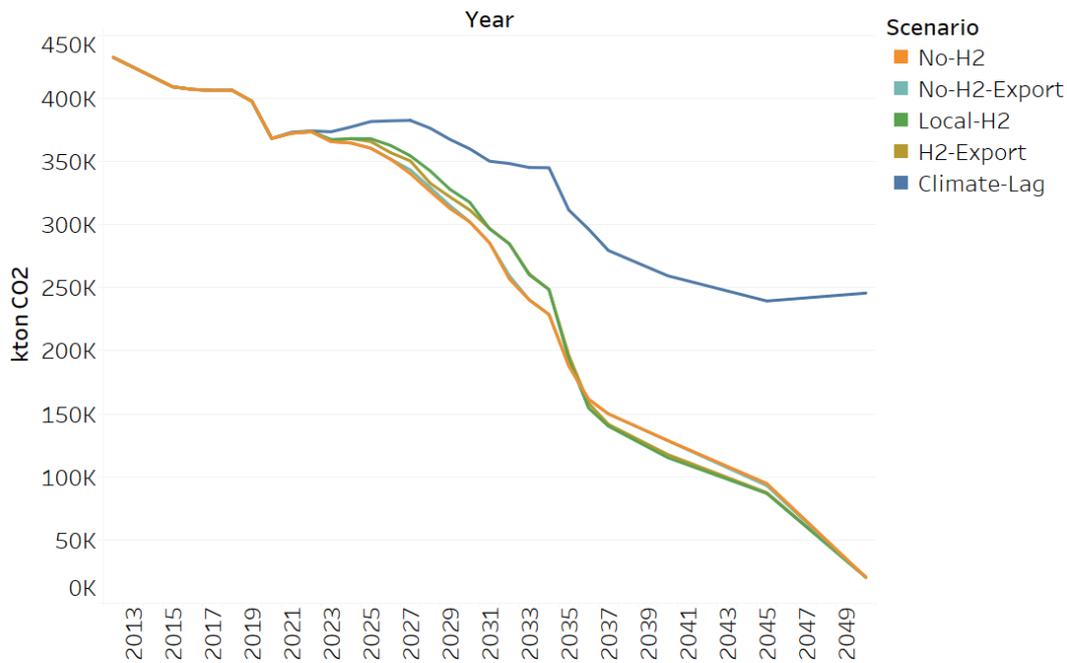
Source: Compiled by the Authors based on own scenario results from SATIMGE model

3.4 GHG emission impacts

The net-zero context of this study unsurprisingly results in similar CO₂ emissions trajectories across the scenarios except for the delayed climate response case (*Climate-Lag*). The similar emissions trajectories are largely a result of the cost-optimal pathway required to satisfy the net-zero goal in 2050. This objective requires CO₂ emissions to decline steeply in all Net Zero scenarios, from about 360 Megatonne (Mt) CO₂/year by 2025 to about 150 Mt CO₂/year by 2036 (Figure 0-10). The steepest decline by 2034-2036 is due to retirement of South Africa's CTL facilities, while decarbonisation of power generation continues. After 2036 a larger share of emissions is in industry sectors which are less easy to decarbonise. From 2045 onwards emission reductions are increased again to reach the goal of Net Zero GHG emissions. In the *Climate Lag* scenario emission reductions would then largely halt and remain around 250 Mt CO₂ in the 2040'ies (Figure 0-10). Differences in the timing between the Net Zero scenarios are related to cost-optimal planning of energy system investments between 2020 and 2050, but all scenarios lead to the assumed same cumulative greenhouse gas emission budget of 8 Gt CO₂-equivalent.

A large part of the emission reductions to arrive at Net Zero carbon can be achieved with presently feasible technologies and limited lifestyle changes (e.g. some switching from road to rail in transport). However, the last stretch of emission reductions to arrive at Net Zero seems (for the time being) only achievable with processes that combine with Carbon Capture & Storage (CCS) or with expensive Direct Air Capture technology (DAC). Without the availability of hydrogen-based technology in the NoH₂ and NoH₂-Export scenarios this amounts to over 50 Mt CO₂ per year by 2050, against 35-40 Mt CO₂/yr in the LocalH₂ and H₂-Export scenarios (Figure 0-11). While in the latter two scenarios CCS technologies are the dominant type of carbon capture, in the NoH₂ scenarios DAC is responsible for capturing of about 22-23 Mt CO₂/year by 2050, against only 5-6 Mt CO₂/year in the Green Hydrogen Economy scenarios.

Figure 0-10: Scenario projections of South African CO₂ emissions from energy use and industrial processes to 2050



Source: Compiled by the Authors based on own scenario results from SATIMGE model

The technologies of the Green Hydrogen Economy can be said to substitute for many fossil-fuel based CO₂ emitting technologies in many applications (see the previous section). However, alternative technologies are possible too. The benefit of the Green Hydrogen Economy lies in the fact that it allows to reach Net Zero in a more economical way. As a minimum the local Green Hydrogen Economy described above can thus be said to avoid capture of CO₂ emissions. The different carbon capture technologies Cumulatively absorb 242 Mt until 2050 in the NoH₂ scenario, and similarly 237 Mtonne in the NoH₂-Export scenario. In the Local-H₂ scenario this becomes 149 Mt CO₂, and in the H₂-Export scenario 152 Mt CO₂. The green hydrogen economy would thus avoid at least 84 to 93 Mtonne of CO₂ emissions between 2040 and 2050.

Figure 0-11: Requirement for CO₂ capture with CCS and Direct Air Capture (DAC) technology in Net Zero scenarios



Source: Compiled by the Authors based on own scenario results from SATIMGE model

3.5 Employment pathways

The first sub-section presents total job gains or losses for all and for TVET employment by scenario. TVET employment creation for key sectors of the GHE is then discussed in further detail in the next sub-sections.³⁷

3.5.1 Total and total TVET employment

In all scenarios total employment in South Africa more than doubles from about 15,6 million full time equivalent (FTE)³⁸ jobs in 2020 (down from 17 million jobs in 2019) to about 32 million jobs by 2050 in all 4 scenarios. Nevertheless, the GDP impacts and technology dynamics described above are accompanied by differences in job creation. To assess the employment impacts of a Green Hydrogen Economy we compare results of the LocalH2 and H2-Export scenarios to those of the No-H2 scenario.

Just adding the platinum beneficiating fuel cell and electrolyser exports to the NoH2 economy does not lead to an advantage in terms of jobs without a local green hydrogen economy due to similar substitution effects as for the Local-H2 case vs the No-H2 case (see full scenario employment projections in Appendix B.2).

³⁷ TVET employment impacts of a GHE have also been discussed in the context of the scope for a just labour transition in Schers, et al. "Green hydrogen and TVET skills" Policy Insights (2021); Full TVET employment results are furthermore presented in Appendix B.

³⁸ Full time equivalent (FTE) employment is implied in this study.

For the Local-H2 scenario the application of green hydrogen technologies without GHE exports has different impacts over time. It would result in 98 thousand jobs more than in the NoH2 scenario by 2035, of which a thousand at the TVET level. However, by 2050 the Local-H2 scenario would count 288 thousand FTE jobs less than the NoH2 scenario, of which approximately 11 thousand jobs (4%) would be TVET educated. Yet, total TVET employment within energy sectors and the for the green hydrogen economy relevant mining and industry/manufacturing sectors remains the same as in the NoH2 scenario, both in 2035 and 2050 (see Appendix B.2 for all employment results).

The relatively smaller number of jobs created in the Local-H2 scenario versus the NoH2 scenario is primarily a consequence of having little additional Gross Value Added (GVA) in the predominantly employment-intensive tertiary sector which comprises of all services, from high-educated ones to services with low educated workers. Recall from section 3.2 that this is partly a consequence of economic substitution between manufacturing and services: The economy has about the same size in the LocalH2 and NoH2 scenarios, but in the LocalH2 scenario economic growth is still catching up with that of the NoH2 scenario after a period (which lasts till about 2045) of somewhat higher investment needs for the energy system. In the very long run (after 2050) these investments will allow energy system costs to be lower for the LocalH2 scenario, and growth of GDP and of employment will very likely be higher in the LocalH2 case compared to the NoH2 case. However, this has not been quantified as it was beyond the scope of our economic modelling.

However, the combination of a domestic GHE with the full GHE exports portfolio (in the H2-Export scenario) leads to strong additional growth in employment: 732 Thousand more jobs are created than in the No-H2 scenario by 2035, while by 2050 this number amounts to 3.2 million additional jobs. For TVET educated workers this translates respectively into 26.5 thousand and 114 thousand additional jobs. As with the No-H2-Export scenario, the manufacturing sector producing fuel cells and electrolyzers for export features as the main sector generating more value added than in the NoH2 scenario (see figure 3-3 in section 3.2). However, in terms of employment the tertiary sectors and *Iron and Steel* industry would provide the bulk of additional jobs. The tertiary sector alone would generate more than half of the new employment with 2 million additional jobs by 2050, followed by the (green) *Iron and Steel* industry producing about 700 thousand additional jobs by 2050 compared to the No-H2 scenario. The Fuel Cell and Electrolyser manufacturing sectors would produce 584 thousand additional jobs by 2050 compared to the NoH2 case. Green ammonia and green hydrogen production would respectively add 61 and 52 thousand additional jobs, and the power sector would generate additional of 46 thousand jobs.

The reason that the tertiary sector dominates the additional job gains is because services (both public and private, formal, and non-formal) make up a large part (the majority) of the South African economy. The 11% additional Gross Value Added of the H2-Export scenario compared to the NoH2 scenario in 2050 necessarily consists of a large amount of additional value added for services, which is a labour- rather than a capital-intensive sector. This means that it generates relatively many additional jobs. Finally, growth in GHE derived exports (section 0) explain job gains in *Iron & Steel*, *Fuel Cell* and *Electrolyser* manufacturing, and *Green Ammonia*. The job gains in the *Green Hydrogen* production and the *Power* generation sectors

are due to the growth in demand for their outputs from the other mentioned sectors (relative to the NoH2 case).

3.5.2 Scope for a Just Labour Transition towards a GHE

To describe employment creation per sector in the context of a Just Labour Transition we consider totals TVET jobs per group of sectors which are considered closely affiliated in terms of the skill sets required in their labour forces (

Table 0-2).³⁹ In this sub-section we first present an overview of the results of the two green hydrogen economy scenarios, namely without (Local-H2) and with exports of GHE commodities and appliances (H2-Export). More detailed results are discussed below. The scenario results show that post-COVID19 economic recovery should lead to recovery in TVET employment by 2025 relative to 2020. However, expected changes in coal mining output (due to retirements) and in refinery capacity (for a large part due to international market pressure) unrelated to the green hydrogen economy will lead to net reductions in TVET employment in the second half of the present decade.

Depending on the extent to which export markets can be developed early on, net TVET job losses within the Refineries-Hydrogen-Ammonia sector can only be compensated by a growing green hydrogen economy from 2030 (for the H2-Exports scenario) to 2035 (for the Local-H2 scenario) onwards.

Within the Coal mining and PGM mining category this moment of net TVET job gains due to GHE-related growth of PGM mining output is realized even later (only from 2040 onwards), as PGM mining itself will likely pass through a period of low growth due to the time it takes between a phase-out of Internal Combustion Engines (ICEs) around the world (between 2025 and 2035) and the increasing PGM demand for use in green hydrogen-based PEM Fuel Cells and PEM Electrolysers technology (see Appendix A.4). To provide a job transition from existing labour in coal mining to green hydrogen economy-related sectors than more distant job transitions should be considered, e.g. by aiming labour to change from coal mining to the Iron & Steel industry or to Power Generation. (see the discussion next).

³⁹ See: Bambili Advisory, "TVET Skills Gap Analysis report" (SAILA UKPACT, Occasional Research Paper, 2021); Schers, et al. "Green hydrogen and TVET skills" Policy Insights (2021); and: Schers, et al. "Hydrogen economy skills" (2021).

Table 0-2: TVET employment changes per Just Labour Transition sector-grouping

	Local-H2 scenario						H2-Export scenario					
	2025	2030	2035	2040	2045	2050	2025	2030	2035	2040	2045	2050
TVET jobs appearing/disappearing, relative to 2020 (cumulative)												
Refineries, Hydrogen, Ammonia	438	-829	-1 003	-860	-779	116	438	-783	84	1 224	2 447	3 828
Fuel Cells and Electrolysers	0	0	32	580	934	1 492	39	64	676	1 868	10 401	18 816
Iron & Steel	370	790	1 242	1 693	2 055	2 306	366	2 356	7 655	12 713	17 891	22 479
Coal and PGM mining	2 400	146	-1 059	-1 495	7 293	14 116	1 825	-3	-1 074	-1 572	9 616	20 270
Power generation	46	619	2 501	4 147	5 950	8 400	91	776	2 971	5 323	7 754	10 575
Average annual TVET employment change over preceding 5-yr period												
Refineries, Hydrogen, Ammonia	88	-253	-35	29	16	179	88	-244	174	228	245	276
Fuel Cells and Electrolysers	0	0	6	109	71	112	8	5	122	238	1 707	1 683
Iron & Steel	74	84	90	90	72	50	73	398	1 060	1 012	1 036	918
Coal and PGM mining	480	-451	-241	-87	1 758	1 365	365	-366	-214	-99	2 238	2 131
Power generation	9	115	376	329	361	490	18	137	439	470	486	564

Source: Compiled by the Authors based on own scenario results from SATIMGE model

3.5.3 PGM and Coal mining, Electricity, and Iron & Steel sectors

As part of a just labour transition to a Green Hydrogen Economy there is opportunity for workers from the coal mining industry to be deployed to the platinum group metals mining.⁴⁰ Across the scenarios for which PGMs are exported to satisfy global demand for the energy transition, the employment gains could in theory compensate the losses associated with a decline in coal mining (domestic and export markets). However, when looking more detailed into the year-by-year timing of these job gains our analysis shows that this would only be possible from about 2030 onwards, when growth in PGM mining TVET employment can be expected to outperform decreases in coal mining TVET employment (

⁴⁰ See Schers, et al. "Green hydrogen and TVET skills" Policy Insights (2021).

Table 0-3).

For the nearer future it would be interesting to consider a just labour transition to industries which require skill sets which are slightly more distant to those expected for coal mining, but which nevertheless could require strong mechanical, teamwork, and logistics skills. For this reason we also analyse the evolution of jobs by TVET skill-subtype of the Power Generation and Iron&Steel sectors (). We observe that the total of power generation and Iron & Steel could make use of a large part of the necessary medium- and high-skill TVET-educated staff which could be lost in coal mining already in the period up to 2030. This is especially the case in the H2-Export scenario of a domestic Green Hydrogen Economy with a strong export orientation (see lower-right panel in

Table 0-3 below). Beyond 2030 there would be even more room for such a job transition. Nevertheless, more detailed analysis of the requirements for up-skilling or re-skilling would be needed, plus a careful analysis of the age profiles of these labour forces and the willingness to move among workers.

Table 0-3: TVET employment by skill sub-grouping (,000s), for Coal and PGM mining, Power generation, and Iron & Steel

SA GHE ?	Sector	TVET Jobs by type x1000 by sector	PGM Exports only					PGM, Fuel Cell, and Electrolyser Exports						
			2019	2030	2035	2040	2045	2050	2019	2030	2035	2040	2045	2050
No SA GHE	Coal	TVET low skilled	0,3	0,2	0,1	0,1	0,1	0,0	0,3	0,2	0,1	0,1	0,1	0,0
	Coal	TVET semi skilled	6,7	4,5	2,9	2,3	1,7	1,0	6,7	4,5	2,9	2,3	1,7	1,0
	Coal	TVET high skilled	0,8	0,5	0,4	0,3	0,2	0,1	0,8	0,5	0,4	0,3	0,2	0,1
	Coal	TVET total	7,8	5,2	3,4	2,6	2,0	1,2	7,8	5,2	3,4	2,6	2,0	1,2
	PGM	TVET low skilled	1,5	1,3	1,4	1,5	3,2	5,3	1,5	1,3	1,4	1,5	3,4	6,4
	PGM	TVET semi skilled	5,9	5,2	5,7	6,2	12,8	21,3	5,9	5,2	5,7	6,2	13,9	25,9
	PGM	TVET high skilled	0,9	0,8	0,9	0,9	2,0	3,3	0,9	0,8	0,9	0,9	2,1	4,0
	PGM	TVET total	8,3	7,3	8,0	8,6	18,0	29,9	8,3	7,3	8,0	8,6	19,4	36,2
	Power	TVET low skilled	0,1	0,1	0,1	0,1	0,2	0,2	0,1	0,1	0,1	0,1	0,1	0,2
	Power	TVET semi skilled	4,2	4,9	6,1	6,9	8,1	9,2	4,2	4,9	6,1	6,9	8,0	9,0
	Power	TVET high skilled	1,6	1,9	2,4	2,7	3,2	3,6	1,6	1,9	2,4	2,7	3,1	3,5
	Power	TVET total	5,9	6,9	8,6	9,8	11,4	13,0	5,9	6,9	8,6	9,8	11,2	12,6
	Iron & Steel	TVET low skilled	0,3	0,4	0,4	0,5	0,5	0,5	0,3	0,4	0,4	0,5	0,5	0,5
	Iron & Steel	TVET semi skilled	3,2	4,0	4,4	4,9	5,3	5,1	3,2	4,0	4,4	4,9	5,4	5,3
	Iron & Steel	TVET high skilled	0,5	0,6	0,6	0,7	0,8	0,7	0,5	0,6	0,6	0,7	0,8	0,8
Iron & Steel	TVET total	3,9	4,9	5,4	6,1	6,5	6,3	3,9	4,9	5,4	6,1	6,7	6,6	
All 4	TVET low skilled	2,1	1,9	2,1	2,2	3,9	6,0	2,1	1,9	2,1	2,2	4,1	7,1	
All 4	TVET semi skilled	20,1	18,6	19,1	20,3	27,9	36,7	20,1	18,6	19,2	20,2	29,0	41,2	
All 4	TVET high skilled	3,8	3,8	4,2	4,6	6,1	7,7	3,8	3,8	4,2	4,6	6,2	8,4	
All 4	TVET total	26,0	24,4	25,4	27,1	37,9	50,4	26,0	24,4	25,4	27,1	39,4	56,7	

SA GHE ?	Sector	TVET Jobs by type x1000 by sector	PGM Exports only					Full Exports (PGM,FC,ELT,Ammonia, and I&S)						
			2019	2030	2035	2040	2045	2050	2019	2030	2035	2040	2045	2050
Yes, with a SA GHE	Coal	TVET low skilled	0,3	0,2	0,1	0,1	0,1	0,0	0,3	0,2	0,1	0,1	0,1	0,0
	Coal	TVET semi skilled	6,7	4,7	3,0	2,2	1,7	0,9	6,7	4,6	3,1	2,2	1,6	0,9
	Coal	TVET high skilled	0,8	0,6	0,4	0,3	0,2	0,1	0,8	0,6	0,4	0,3	0,2	0,1
	Coal	TVET total	7,8	5,5	3,5	2,5	1,9	1,0	7,8	5,3	3,6	2,6	1,9	1,0
	PGM	TVET low skilled	1,5	1,3	1,4	1,5	3,2	4,5	1,5	1,3	1,4	1,5	3,6	5,6
	PGM	TVET semi skilled	5,9	5,2	5,7	6,1	12,8	18,4	5,9	5,2	5,7	6,1	14,5	22,8
	PGM	TVET high skilled	0,9	0,8	0,9	0,9	2,0	2,8	0,9	0,8	0,9	0,9	2,2	3,5
	PGM	TVET total	8,3	7,3	8,0	8,6	18,0	25,7	8,3	7,3	8,0	8,5	20,3	31,9
	Power	TVET low skilled	0,1	0,1	0,1	0,1	0,2	0,2	0,1	0,1	0,1	0,2	0,2	0,2
	Power	TVET semi skilled	4,2	4,8	6,1	7,3	8,5	10,3	4,2	4,9	6,4	8,1	9,8	11,8
	Power	TVET high skilled	1,6	1,9	2,4	2,8	3,3	4,0	1,6	1,9	2,5	3,2	3,8	4,6
	Power	TVET total	5,9	6,7	8,6	10,2	12,0	14,5	5,9	6,9	9,1	11,4	13,8	16,6
	Iron & Steel	TVET low skilled	0,3	0,4	0,4	0,4	0,5	0,5	0,3	0,5	0,9	1,3	1,7	2,0
	Iron & Steel	TVET semi skilled	3,2	4,0	4,4	4,7	5,0	5,2	3,2	5,3	9,5	13,6	17,8	21,5
	Iron & Steel	TVET high skilled	0,5	0,6	0,6	0,7	0,7	0,8	0,5	0,8	1,4	2,0	2,6	3,1
Iron & Steel	TVET total	3,9	4,9	5,4	5,8	6,2	6,5	3,9	6,5	11,8	16,9	22,1	26,7	
All 4	TVET low skilled	2,1	1,9	2,1	2,2	3,9	5,3	2,1	2,0	2,5	3,0	5,5	7,9	
All 4	TVET semi skilled	20,1	18,7	19,2	20,3	28,1	34,7	20,1	19,9	24,7	30,0	43,8	56,9	
All 4	TVET high skilled	3,8	3,8	4,3	4,7	6,2	7,7	3,8	4,0	5,1	6,3	8,8	11,3	
All 4	TVET total	26,0	24,4	25,5	27,2	38,1	47,6	26,0	26,0	32,4	39,3	58,1	76,1	

Source: Compiled by the Authors based on own scenario results from SATIMGE model

3.5.4 Refineries, Green Hydrogen and Ammonia, Fuel Cell and Electrolyser manufacturing

For the refineries and chemicals sectors job transitions are expected to largely remain within similar sectors.⁴¹ The estimated 39 thousand workers in refineries in 2019 could thus potentially find new jobs in emerging hydrogen production and processing, and its downstream sectors like green chemicals (e.g. Ammonia).⁴²

⁴¹ It should be noted the storage and distribution of liquid fuels are implicitly part of the tertiary sector in the model includes, like it is done in national accounts as a trade service. The same would be true for the storage and distribution of hydrogen. These jobs could therefore not be specifically measured and reported.

⁴² See Schers, et al. "Green hydrogen and TVET skills" Policy Insights (2021).

Green hydrogen production could result in employment gains compared to 2019 of 2 thousand (in 2035) to 31 thousand jobs (by 2050) in our Local-H2 scenario (see Appendix B.2). Of these jobs, close to 100 (2035) to 1.4 thousand (2050) are estimated to comprise the TVET category (Table 0-4). Total job numbers increase to respectively 9 thousand (2035) to 52 thousand (by 2050) in the H2-Export scenario (see Appendix B.2). Of those jobs, between 400 (2035) to 2.3 thousand (2050) would comprise TVET educated jobs (Table 0-4).

In almost all scenarios employment in the Ammonia sector (part of South Africa's chemicals sector) would fluctuate between 4 and 5 thousand jobs between now and 2050. Only in the H2-Export scenario international demand for SA Green ammonia would lead to an increase in employment from about 5 thousand jobs in 2030 to 21 thousand jobs by 2035, and 66 thousand by 2050. Of those jobs, respectively 230, 950 and 3 thousand jobs would be TVET educated (Table 0-4).

However, from our analysis we however observe that the petrochemical sector might already suffer output decreases (mainly due to market forces) before 2030 (see Appendix B.2 and Table 0-4). This is sooner than the current expectation for the development of the chemicals-side of the Green Hydrogen Economy through green hydrogen and green ammonia production, which starts to develop somewhere between 2030 and 2035. More distant sectors in terms of the skills profile would be the Fuel Cell and Electrolyser (component) manufacturing sectors. These sectors unfortunately also only provide significant TVET job opportunities from 2035 onwards in the case of successful entering of export markets for such SA producers (H2-Export scenario), or from 2040 onwards for domestic use in the Local-H2 scenario. A question for policymakers would therefore be whether there is room to speed-up the development of a Green Hydrogen Economy, to bridge the skills from the SA petrochemical industry to a growing green hydrogen economy.

Table 0-4: TVET employment in Refineries, Green Hydrogen, Green Ammonia, Fuel Cell and Electrolyser manufacturing

SA GHE ?	TVET jobs (x1000) by sector	No-H2 / PGM Exports only							NoH2-Exports / PGM, FC, and ELT exports						
		2019	2025	2030	2035	2040	2045	2050	2019	2025	2030	2035	2040	2045	2050
	Selected sectors subtotal	2,4	2,0	0,8	0,5	0,3	0,3	0,4	2,4	2,0	0,8	1,1	1,5	9,5	17,5
	Refineries (incl.CTL)	2,14	1,76	0,55	0,33	0,11	0,11	0,12	2,14	1,76	0,55	0,33	0,11	0,11	0,12
No SA	Hydrogen	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0	0	0	0	0	0	0
GHE	Ammonia	0,23	0,23	0,23	0,18	0,18	0,23	0,23	0,23	0,23	0,23	0,18	0,18	0,23	0,23
	FuelCells	0	0	0	0	0	0	0	0	0	0	0,10	0,23	4,51	8,77
	Electrolysers	0	0	0	0	0	0	0	0	0,04	0,06	0,52	0,93	4,64	8,35
SA GHE ?	TVET jobs (x1000) by sector	Local-H2 / PGM Exports only							H2-Exports / Full GHE exports (PGM,FC,ELT, Ammonia, and I&S)						
		2019	2025	2030	2035	2040	2045	2050	2019	2025	2030	2035	2040	2045	2050
	selected sectors subtotal	2,4	2,0	0,7	0,6	1,3	1,7	3,2	2,4	2,0	0,8	2,3	4,6	14,4	24,2
	Refineries (incl.CTL)	2,14	1,76	0,49	0,27	0,05	0,00	0,03	2,14	1,76	0,49	0,27	0,05	0,05	0,05
Yes, with a local SA GHE	Hydrogen	0	0	0	0,09	0,45	0,59	1,42	0	0	0,05	0,41	1,18	1,72	2,34
	Ammonia	0,23	0,23	0,23	0,18	0,18	0,18	0,22	0,23	0,23	0,23	0,95	1,54	2,22	2,99
	FuelCells	0	0	0	0,03	0,58	0,93	0,83	0	0	0	0,16	0,90	5,54	9,71
	Electrolysers	0	0	0	0	0	0	0,66	0	0,04	0,06	0,52	0,97	4,86	9,11

Source: Compiled by the Authors based on own scenario results from SATIMGE model

3.6 Job impacts of selected Green Hydrogen applications

3.6.1 Exports

We estimate both the direct number of jobs related to the exports of commodities (and technology) related to the production and use of Green Hydrogen and the number of jobs induced in the entire economy by these exports. To estimate the difference in terms of *direct* jobs we compare the H2-Export scenario with the Local-H2 scenario, and the NoH2-Export scenario with the NoH2 scenario. In the Local-H2 scenario these jobs are all contributing to production of Fuel Cells for the domestic market. Fuel cell jobs in H2-Export scenario are caused by local demand and export demand. The difference is not exactly the number of jobs linked to production for the export market, due to the stimulus impact of GDP growth in the H2-Export scenario resulting in an increase in local fuel cell demand as well. However, for simplicity and given the probably small difference for our objective to present direct jobs per GW of fuel cells we allocate the additional jobs in the H2-Export scenario to the increase of Fuel Cell exports. Table 0-5 thus lists the direct employment attributed to export commodities, except for green jet fuel.^{43, 44, 45}

Table 0-5: Direct TVET jobs attributed to GHE export commodities ('000s)

Commodity by Measure	Units \ Scenario	No-H2		Additional in NoH2-Export		Local-H2		Additional in H2-Export	
		2035	2050	2035	2050	2035	2050	2035	2050
TVET Jobs by sector									
(Green) Ammonia		n/a	n/a	n/a	n/a	0,18	0,22	0,8	2,8
Fuel Cells	TVET Jobs ('000s)	0	0	0,1	8,8	0,03	0,83	0,1	8,9
Electrolysers		0	0	0,5	8,4	0	0,7	0,5	8,4
(Green) Iron & Steel		n/a	n/a	n/a	n/a	5,4	6,5	6,4	20,2
Volumes for Domestic use (Local-H2) and Exports									
(Green) Ammonia	PetaJoules (PJ)			n/a	n/a	12	22	33	124
Fuel Cells	GigaWatt (GW)	n/a	n/a	3,9	310	1,5	14,7	4,5	312
Electrolysers	GigaWatt (GW)			1,3	21	0,0	1,0	1,3	21
(Green) Iron & Steel	Megatonnes (Mt)			n/a	n/a	3,7	4,4	4,3	14
Direct TVET jobs per physical unit produced									
(Green) Ammonia	TVET Jobs / PJ			n/a	n/a	15	10	23	22
Fuel Cells	TVET Jobs / GW	n/a	n/a	25	28	21	57	29	28
Electrolysers	TVET Jobs / GW			396	398	n/a	653	396	402
(Green) Iron & Steel	TVET Jobs / Mt			n/a	n/a	1466	1466	1491	1441

Source: Compiled by the Authors based on own calculations based on scenario results from SATIMGE model

To estimate the number of indirect and induced jobs per unit of GHE commodity exported (including Fuel Cell and Electrolyser products) we study the same scenario – scenario

⁴³ Jet fuel can be distinguished as a separate activity in the energy model, but not in the economic-part of SATIMGE.

⁴⁴ Due to slightly variations in the economic equilibrium direct jobs per export unit may also vary somewhat between scenarios and years.

⁴⁵ Due to the different types of physical units used to measure volumes and due to product-specific characteristics like the typical volumes produced and consumed, the number of jobs per unit are not comparable between different products. They are only meant to provide a link between day-to-day measures used in policymaking and investment decisions and our estimates of TVET job creation.

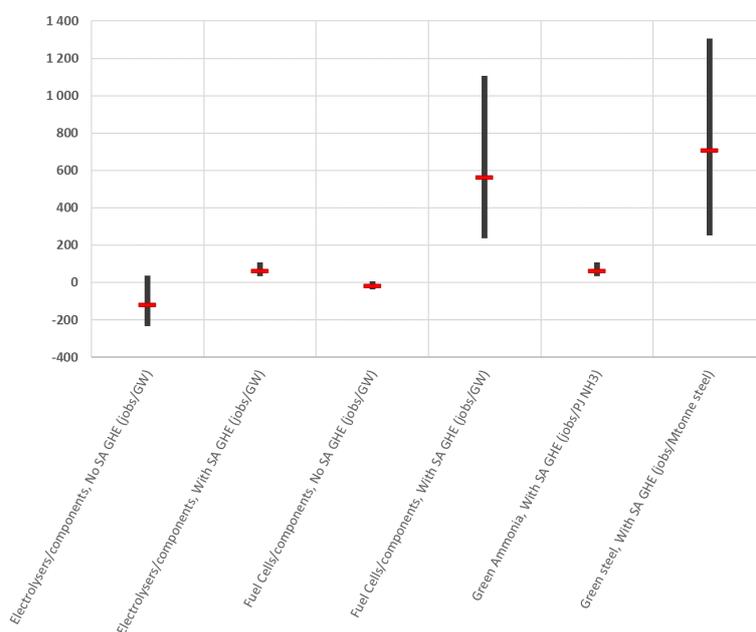
comparison where possible and allocate economy-wide job gains based on a pro-rata of these exports in additional Gross Value Added. Due to changing economic circumstances, e.g., the exchange rate, the impact of these exports on the whole economy changes from year-to-year. We present the range and the average of multiple projection years (2040, 2045, and 2050) in Figure 0-12.⁴⁶

For Green Ammonia we find an average of about 60 TVET jobs/GW (33-109), meaning that its indirect and induced job impact on the SA economy would be 2 to 3 times bigger than its direct job impact. For Green Iron/Steel we find about 700 indirect and induced TVET jobs per Megatonne (253-1307), which means that its indirect and induced jobs impact is smaller than its direct TVET jobs impact, meaning that TVET jobs from Iron & Steel exports come for a small part at a loss of TVET jobs elsewhere in the economy, though the net TVET job impact of green iron/steel remains positive.

For Fuel Cells and Electrolysers the picture is more complex, as there were two scenarios in which these exports were studied. One scenario with a SA GHE (H2-Export), and one scenario without an SA GHE (NoH2-Export). The establishment of the SA green hydrogen economy allows the SA economy to decarbonise in a cheaper way than in the NoH2 scenarios and thus contributes to SA's exports being more competitively priced, with benefits for the trade balance and/or the exchange rate (see section 3.2). In the case with a SA GHE the indirect and induced job impact of Fuel Cell and Electrolyser exports is therefore positive, respectively 561 and 62 jobs per GW. This would imply that the indirect and induced job impact of Fuel Cells is many times its direct job impact, whereas that of Electrolysers is only small compared to its direct job impact. However, if the SA economy would need to reach Net Zero without a domestic GHE, the economic benefits of these exports are also suddenly less, with for Fuel Cells -19 and for Electrolysers -119 TVET jobs per GW on average. The introduction of the GHE economy therefore turns out to stimulate the economic benefits for SA of some of selling some of the GHE's products on world markets.

⁴⁶ Typically, the induced job impact of exports is bigger in earlier years when exports are smaller rather than in later years. One reason could be that when exports increase to a considerable size their impact on the exchange rate starts to be felt, which could reduce their macro-economic benefits (for example, strengthening of the exchange rate discourages exports in other sectors).

Figure 0-12: Range of indirect and induced TVET jobs from GHE exports for 2040 to 2050 and their average (red markers)



Source: Compiled by the Authors based on own calculations based on scenario results from SATIMGE model

3.6.2 Domestic use of Fuel Cells

In Table 0-4 we reported that in the Local-H2 scenario Fuel Cell manufacturing would employ an increasing number of TVET educated workers, going from about 30 workers by 2035 to about 830 workers by 2050. In the H2-Export scenario the Fuel Cell employment difference with the NoH2-Export scenario ranges from 64 TVET jobs in 2035 to 945 jobs by 2050. These employment numbers correspond to an annual supply of respectively 1,5 to 2,1 GW in 2035 to 14,7 to 16,7 GW in 2050. This corresponds to on average 76 direct TVET jobs per GW of Fuel Cell manufactured (see Appendix B.3 for details). When assuming 350 kW of Hydrogen Fuel Cell per Heavy Cargo Vehicle (truck), in class 6, this means that for each 37 fuel cell trucks one TVET educated full-time job is created.

Hydrogen fuel cell truck sales for the domestic market are projected to grow from between 3,7 to 5,6 thousand trucks per year in the first half of the 2030'ies to 28 to 32 thousand per year in 2050 in the Local-H2 and H2-Export scenarios. The indirect and induced jobs created by the development of a domestic hydrogen fuel cell use in transport depends strongly on the economic circumstances. On average about 60 TVET jobs per GW of H2FC could be created between 2035 and 2050, but this is surrounded by strong uncertainty as the number varies strongly depending on the economic circumstances given by each scenario.

As mentioned, in the Local-H2 scenario the introduction of a green hydrogen economy has temporarily, between 2035 and 2045/2050, small negative impacts on GDP and employment compared to a future in which Net Zero would be reached without a green hydrogen (see

section 3.2). Recall, that this was for reason of crowding out of investment for other economic activities, but that this would come with higher economic growth and cheaper greenhouse gas emission reductions for 2050 and thereafter relative to the NoH2 scenario. In the H2-Export scenario the indirect and induced job impact of developing a domestic market for H2FC trucks (HCVs) is always positive, but also varies due to the timing of impacts. As an indication of the uncertainty margin, we find the weighted average of induced jobs per GW of H2FC produced for the domestic market for the period 2035 - 2050 to range from – 1,8 thousand (Local-H2) to +1,9 thousand (H2-Export) TVET jobs per GW of H2FC (see Appendix B.3 for details).

Summary and Discussion of Findings

4.1 Introduction

Use of green hydrogen – that is, hydrogen produced from renewable energy sources – is an option for energy use identified as important to achieve Net Zero carbon around the world. Within this context, the present study quantifies (1) the extent to which green hydrogen could be utilised competitively within the South African economy, (2) the macro-economic impacts thereof, especially for TVET skilled employment, and (3) green hydrogen's contribution to GHG emission reduction. To this end, SATIMGE, a full sector representation of the South African economy in a least-cost modelling energy-economy framework was utilised.

The Net Zero scenarios explored in this study aimed at Net Zero greenhouse gas emissions by 2050, and for a cumulative GHG emission budget in line with South Africa's commitment to the Paris Agreement. Two dimensions of hydrogen application were considered, namely: (A) domestic use (*Local-H2 scenario*); and (B) green hydrogen-based commodity and manufacturing export-oriented (*H2-Export scenario*). The latter scenario was rooted in a global context of future decarbonisation and South Africa being a major producer of Platinum and other PGMs - key materials for hydrogen technology. To quantify the relative impact of introducing green hydrogen results of the two scenarios were compared to a reference scenario (*No-H2*) in which no green hydrogen is produced at industrial scale. An additional scenario (*No-H2-Export*) counterfactually explored what could happen if the SA manufacturing sector could develop (SA platinum-based) production of fuel cells and electrolyzers for export without a local green hydrogen market.

4.2 Hydrogen production and demand

In the case of the domestic scenario for industrial-scale hydrogen usage (*Local-H2*), starting around 2035, the transport sector would dominate hydrogen demand for a long time at a larger scale with about 0.65 Megatonnes (Mt) of the total 2.1 Mt H2 annum in 2050. In freight transport, hydrogen is expected to be dominantly used by Heavy Cargo Vehicles (HCVs). Green hydrogen use for industrial process heat appears in the mid-2040'ies to become the dominant type of hydrogen demand with 1.1 Mt by 2050. Green Ammonia and Iron/Steel production would require respectively 0.06 Mt and 0.3 Mt hydrogen by 2050. In the export-oriented GHE scenario (*H2-Export*) by 2050 almost 3.5 Mt of Green Hydrogen would be

produced for production of Green Ammonia, Green Iron/Steel, and E-kerosene (jet-fuel), and this export demand would exceed demand for domestic freight transport (0.8 Mt H₂) from 2045 onwards. Transport demand for hydrogen would be 12 Petajoules (or 0.1 Mt) higher in the H₂-Export scenario than in the Local-H₂ scenario. This would equate to an additional 10 thousand HCV class 6 trucks driving 120 thousand kilometres per year.

4.3 Economic growth

In our *NoH₂* Net Zero reference scenario the South African economy would grow by about 2.3% per year, meaning that it almost doubles between 2020 and 2050. A domestic green hydrogen economy (Local-H₂ scenario) would increase average annual GDP growth by about 0.1% compared to the *NoH₂* scenario, and thus lead to a 2.8% higher GDP in 2050. This positive impact comes after a bit more than a decade (2034-2045) in which growth would be slightly lower than in the *NoH₂* scenario due to a temporarily increased need for (up-front) investments in the hydrogen-economy's energy system. However, those investments pay off through lower investment needs and lower energy costs by the middle of the 21st century, when a *NoH₂* future would be required to invest additionally in CCS and especially costly Direct Air Capture technology to reach the 2050 Net Zero carbon goal. The means that a domestic-only green hydrogen economy would lead to net economic benefits for the middle and the second half of the 21st century.

Moreover, the economic outlook of a green hydrogen economy improves considerably if the green hydrogen economy would lead to large-scale green hydrogen-based exports of green ammonia, green iron & steel, and green jet fuel, and of platinum-based electrolyzers and fuel cells appliances and their components. In this H₂-Export scenario GDP would grow 118% until 2050 (2.6% per year) and add 3.5 trillion Rand (ZAR 2012) to the economy between 2020, meaning GDP would be about 11% higher by 2050 than in the *NoH₂* scenario. The positive impact of these exports can be explained from a combination of relatively low energy (system) costs thanks to the domestic green hydrogen-economy, and most-of-all the demand for green hydrogen-based exports translating into increased value added and an improved exchange rate for the Rand.

4.4 Total employment

Employment increases more than GDP in all scenarios. In the *NoH₂* reference case employment would grow 105% between 2020 and 2050, to reach slightly more than 32 million full-time equivalent jobs, with the Local-H₂ and *NoH₂*-Export scenarios obtaining quite similar employment results by 2050. As with GDP, the biggest growth in employment takes place in the H₂-Export scenario, where it reaches 35,2 million jobs by 2050. The economic importance of developing the green hydrogen export markets is underlined by the difference with the Local-H₂ scenario, in which only PGM exports increase for the global green hydrogen economy, and in which there is no further beneficiation of PGMs. In that case employment creation turns out a little bit lower than for the Local-H₂ scenario than for the *NoH₂* scenario, with 31,8 million jobs in 2050.

This relatively lower growth of employment is related to higher investment requirements for the domestic Green Hydrogen Economy during the period 2034-2045. Green hydrogen economy investments only start to pay off in terms of lower energy costs and future investment needs from 2045 onwards in comparison to a NoH2 future. As the Local-H2 scenario does not imply changes for the economy's Total Factor Productivity or in export-based value generation energy system costs become determinant for the potential for growth and model results thus show some extend of competition for economic resources, i.e., investment.⁴⁷ This competition for resources turns out positive for employment creation in industrial and manufacturing sectors but slows down job creation a bit in the labour-intensive tertiary sector. However, post 2050 the perspective for growth of the economy and employment is better for the Local-H2 scenario than in the No-H2 scenario, due to its relatively lower energy system costs as the green hydrogen economy avoids reliance on expensive CCS and Direct Air Capture technologies. This should also translate to more employment in the tertiary sector post 2050.

4.5 TVET educated employment

For growth in TVET-educated employment the picture is similar to that of all employment, with only small deviations from growth rates for total employment due to differences in TVET intensity of sectoral labour forces (see

⁴⁷ Model results show that labour is mostly in ample supply for the 4 skill levels defined (uneducated, primary, secondary, and tertiary/post-secondary category), and the evaluation of the requirement for TVET skills is performed ex-post by disaggregating the tertiary/post-secondary labour category.

Table 0-4 in section 2.4). In the NoH2 reference scenario the total employment of TVET educated workers would increase from an estimated 610 thousand in 2020 to 868 thousand by 2035, and to 1.25 million by 2050. Compared to those numbers the domestic green hydrogen economy scenario sees TVET job gains that are slightly higher by 2035 (4 thousand TVET jobs more) and finally slightly lower by 2050 (11 thousand jobs). The reason is again difference in the growth of the tertiary sector in the preceding periods due to either relative abundance or relative constraints on investment for future growth of activity. Total TVET employment within energy and for the green hydrogen economy relevant mining and industry/manufacturing sectors is however about the same or slightly higher in the Local-H2 scenario compared to the NoH2 scenario (see Appendix B.2).

Out of the sectors involved in the development of a green hydrogen economy TVET skills the three sectors with the highest employment levels in the Local-H2 scenario would be Power generation, PGM mining, and Iron & Steel by 2035; and PGM mining, Power generation, and Green Hydrogen production by 2050. However, relative to the NoH2 scenario, growth in TVET employment would be highest in Green Hydrogen production and Power generation (both 1.4 thousand additional TVET jobs), with Fuel Cell and Electrolyser manufacturing sectors following closely (together adding 1.5 thousand TVET jobs, see Appendix B.2).

A successful development of GHE export markets (in our H2-Export scenario) would see PGM mining, Iron & Steel industry, and Power generation as the biggest GHE-related TVET employers. However, relative to the NoH2 scenario, additional growth in GHE-related TVET employment by 2050 would be highest in Iron & Steel industry (20 thousand TVET jobs), Fuel Cell (10 thousand TVET jobs) and Electrolyser production (9 thousand TVET jobs).

These results reflect the relative direct TVET intensity of Gross Value Added in the different sectors: Green Iron & Steel and Green Ammonia production are estimated to respectively generate about 172 and 313 TVET jobs per billion ZAR(2012) of gross value added, while for Power generation, Hydrogen production, and Fuel Cell and Electrolyser manufacturing these numbers vary between 29 and 67 TVET jobs per billion ZAR(2012).

4.6 Employment impacts of green hydrogen applications and exports

The discussion of employment results thus far shows that developing export markets is favourable for TVET job generation. This is also reflected in the job impacts per hydrogen-application, especially when looking at the induced job impact on the entire economy. In terms of direct job creation there are little differences between production of Fuel Cells and its components for domestic or foreign markets: Fuel cell production is estimated to create between 21 and 57 direct TVET Jobs per GW of fuel cells produced per annum, both for domestic use and exports. For electrolyzers this is estimated to be between 396 and 653 direct TVET jobs per GW produced per annum. For Green Ammonia we estimate that this would be between 10 and 23 direct TVET jobs per *PetaJoule* produced per annum, and for Green Iron

& Steel we estimate this number to be between 1441 and 1491 direct TVET jobs *per Megatonne* produced per year.⁴⁸

The green hydrogen economy would create additional demand for electricity for hydrogen production for its various end uses (transport, ammonia production, iron & steel production). A green hydrogen economy would require additional renewable energy power generation capacity of between 27 GW (in the Local-H2 scenario) and 70 GW (in the H2-Export scenario). This would result in respectively 1.5 thousand and 3.6 thousand additional direct TVET jobs, which implies between 51 and 55 TVET educated jobs per GW of additional power generation.

The number of jobs which the production of GHE technologies and commodities would create in the whole economy (*induce*) has been estimated too. Scenario comparison of model results shows the impact of a combination of a few economic changes, in our case the introduction of different green hydrogen economy technologies and/or exports of hydrogen-based commodities.⁴⁹ Allocating job gains on the basis of Fuel Cell production's share in additional GVA of the GHE leads to estimate of the amount of induced jobs due to the introduction of this technology.

For domestic use of Fuel Cells, we estimate on average a net positive effect of about 60 induced TVET jobs per GW of Fuel Cell appliances or components manufactured per annum for the period 2035-2050, but the estimate varies strongly with the macro-economic conditions in which the fuel cells are produced. If additional investments lead to crowding out of other activities during the period 2034-2045, and if there would be zero development of export markets, then an average net loss could be induced of on average 1,7 thousand TVET jobs per GW manufactured per annum between 2035 and 2050. On the contrary, the domestic production and use of fuel cells within South Africa is estimated to induce on average 1,9 thousand TVET jobs per GW of Fuel Cell appliances produced per annum, if demand from GHE export markets increases economic growth and domestic (and foreign) investment.

Export-oriented production of green hydrogen economy application leads to a more favourable outlook for additional job creation by the green hydrogen economy. In the case of having developed both export markets and a domestic South African green hydrogen economy, Fuel Cell exports could induce on average - between 2040 and 2050 - around 560 TVET jobs per GW manufactured per annum. Yet, beneficiating platinum to produce Fuel Cell appliances or components for export markets without a domestic GHE (NoH2-Export scenario) would lead to an induced loss of almost 20 TVET jobs per GW manufactured per annum due to the same economic crowding out effects. For Electrolysers or their components these numbers would respectively be 62 to -119 induced TVET jobs per GW produced per annum. However, exports of Green Ammonia and of Green Iron/Steel are necessarily rooted in having domestic green hydrogen production. These exports have therefore only been explored under the H2-Export scenario and they are estimated to induce on average (between 2040 and

⁴⁸ Due to the different physical units used to measure volumes and due to product-specific characteristics like the typical volumes produced and consumed, the number of jobs per unit are not comparable between different products. These numbers are only meant to provide a link between day-to-day measures used in policymaking and investment decisions and our estimates of TVET job creation.

⁴⁹ These are often called "shocks" in macro-economic modelling terminology.

2050) 62 TVET jobs per PetaJoule of green ammonia, and 706 TVET jobs per Megatonne of green Iron/Steel.

4.7 A Just Labour Transition towards a GHE

The scope for a Just Labour Transition from fossil fuel-based sectors to a Green Hydrogen Economy depends on the timing. In the period 2025-2030 a GHE without green-hydrogen-based exports in our Local-H2 scenario sees new TVET-educated job opportunities arise in Power Generation and Iron&steel that are about equal to about half of the 400 annual TVET job losses in coal mining in that period. Beyond 2030 TVET job creation in Power Generation (between 300 and 500 new TVET-educated jobs per year) and Iron&Steel (about 70 TVET jobs per year in the Local-H2 scenario to about a 1000 TVET jobs/year in the H2-Export scenario) would be higher than TVET job losses in coal mining (between 100 and 400 TVET jobs lost per year).

However, for TVET job losses in Refineries the GHE cannot yet offer a meaningful alternative during the 2025-2030 period, with about 250 TVET jobs lost per year. Job gains in Green Hydrogen and Green Ammonia production could outpace job losses from Refineries between from 2035 onwards in a Local-H2 (only) scenario with about 70 TVET jobs created per year in the 2035-2040 period versus a bit more than 40 TVET jobs lost per year in Refineries in the same period. Though, this transition possibility could already be available from 2030 onwards if development of exports of green hydrogen-based commodities is successful, leading to over 200 new TVET jobs per year in green hydrogen and green ammonia production between 2030 and 2035.

Depending on being able to export or not, also the Fuel Cell and Electrolyser manufacturing sectors could lead to significant TVET job creation from 2030 onwards (about a 100 TVET jobs per year in the H2-Export scenario), or from 2035 onwards (about a 100 to 200 TVET jobs in the 2030'ies and around 1700 TVET jobs in the 2040'ies in the Local-H2 scenario). The Fuel Cell and Electrolyser manufacturing sectors could possibly absorb jobs lost in manufacturing of catalytic converters or other automotive vehicles manufacturing sectors – though these sectors were out-of-scope of the present analysis.

More detailed studies of the requirements for up- or re-skilling are still needed. Also, the scale and nature of coal mining job losses still requires further study, especially concerning the age and education profile of these workers, as well as of the willingness and ability to move among workers. Possibly solutions to consider to avoid a part of forced job losses for younger workers could be offering 10 years earlier retirement to all the coal mining's labour force.⁵⁰ Nevertheless, given differences in geographical location of different sectoral activities and the observed difference in timing of different energy transitions, an urgent need remains for alternative economic development in coal mining areas between now and 2030. One TVET-education related solution could be to prioritize pilots for up- or re-skilling in coal mining

⁵⁰ Jules Schers and Jesse Burton, 'Managing the coal transition for workers in South Africa: A scenario analysis of age & education profiles'. Presented at the online conference "Energy, COVID, and Climate Change," International Association of Energy Economists (IAEE), 8 June 2021. See <https://www.iaee.org/proceedings/article/17459>, accessed February 2022

communities, and to envision new careers, outside a green hydrogen economy, e.g., through improved TVET teaching of mathematics and digital literacy.⁵¹

4.8 Greenhouse gas emission reductions

Several Green Hydrogen economy technologies are still in their market introduction-stage, but the general expectation is that they will become economically viable from around 2030 onwards. This means that their contribution to achieving South Africa's NDC objectives for 2030 can be considered negligible. However South Africa's NDC, envisions an emission decline trajectory post 2030, for which the present study assumed that the country's aspiration to achieve Net Zero carbon emissions by 2050 will be determinant. For achieving Net Zero carbon by 2050 green hydrogen-based commodities and technologies are now seen as a crucial element, especially for the last steps in otherwise difficult to decarbonise sectors like industry. In the present study all scenarios reaching Net Zero by 2050. However, the scenarios in which a hydrogen economy was excluded as an option required other, more expensive technologies to reach net zero. In our scenarios the GHE could avoid the need to reduce Greenhouse gas emissions through Carbon Capture & Storage (CCS) and Direct Air Capture (DAC) technologies, which are expected to remain quite expensive (if not only due to their own energy and material needs). Our scenarios show that a green hydrogen economy could therefore avoid about 17 Megatonnes of annual CO₂ emissions by 2050.⁵²

4.9 Limitations

Obviously, the results presented in this study have been obtained within the limitations of the methodology applied. Modelling is an exercise which by definition tries to simplify our complex reality, which also means that models are necessarily constrained in the extent to which they can represent that reality. For instance, the intertemporal "central planner" perspective of our energy-systems modelling methodology means that the timing of new technologies might be a few years different from how various public or private actors would decide to invest in new capacity. This means that impacts for the period beyond 2035, when new capital starts to get a more significant role in shaping the energy system in comparison to its well-described present-day capital stock, could take place a few years earlier or later. This is inherent methodological uncertainty.

Other limitations are that due to how technology choice operates in the energy systems model the heavy-duty class hydrogen fuel cell (H₂FC) vehicles were assumed dominant for class 6-9 HCVs, with little competition from other technologies. However, battery electric vehicles (BEVs) could be a future option within this category too to some extent, while on the other hand the penetration of H₂FC vehicle technologies in lower (smaller) vehicle classes, like HCV2-5 might possibly be bigger than our model predicts, e.g., depending on local circumstances (grid

⁵¹ See: Bambili Advisory, "TVET Skills Gap Analysis report" (SALLA UKPACT, Occasional Research Paper, 2021); Schers, et al. "Green hydrogen and TVET skills" Policy Insights (2021); and: Schers, et al. "Hydrogen economy skills" (2021).

⁵² In reality the contribution to decarbonisation will be higher, because GHE technologies will also substitute electrification with renewable power generation to some extent in some sectors, like transport and industry. This however could not be quantified.

access etc). These opposite model biases hopefully cancel each other out in respect to the future need for H₂FCs. We also assumed, in line with International Energy Agency forecasts, that Platinum-based PEM Fuel Cells and PEM Electrolysers would remain the dominant technologies in their fields. However, these fields could still experience strong technological developments, while also the future metal prices of the diverse mineral resources necessary for competing technologies are uncertain.

Finally, we assumed TVET shares in sectoral labour forces remain constant. This is a reasonable assumption in view of the trend of the TVET labour share in South Africa's labour force over the last decade. However, we do not know the reason behind the trend: (A) It might be possible that there is a constant outflow from this category to the lower and higher tertiary education categories if people who initially had TVET-education as their highest degree decide to continue their education and become employed at the level of higher diplomas or degrees. (B) More importantly, the fact that someone has a certain type of education does not guarantee that the job the person occupies requires specifically that level of education. It could both be higher (with possibly some on-the-job training), or lower if well educated people crowd out less educated workers on the labour market. Our results for future TVET employment should therefore rather be considered indicative of future trends in terms of growth or decline within a sector, rather than precise predictions. To narrow down uncertainty or to be able to better quantify training requirements, additional research would be needed, e.g., through detailed surveys of sectoral or company labour forces or with detailed enquiries with Human Resources managers of leading companies in each sector.

Conclusion

Based on our analysis, we consider development of a green hydrogen economy an essential element for achieving South Africa's ambition of reaching Net Zero carbon by 2050. The domestic Green Hydrogen Economy studied in the present report consisted of development of green hydrogen-based freight transport with hydrogen Fuel Cell (H₂FC) Heavy Cargo Vehicles (HCVs), green hydrogen-based production of green Iron & Steel, and applications of hydrogen for industrial heating. Such developments would require a period (between 2030 and 2045) of additional energy system investments, especially in power generation capacity for electrolysis, relative to a future in which Net Zero carbon would be achieved without green hydrogen. However, investment in green hydrogen technologies would avoid the need for more costly investments in different carbon capture & storage technologies, including direct air capture, towards 2045 and onwards. As such, the green hydrogen economy can be accredited to avoid at least 84 to 93 Megatonnes (Mt) of cumulative CO₂ emissions between 2040 and 2050, or about 17 Mt annually by 2050.

These benefits for climate change mitigation are accompanied by an overall economic impact until 2050 of a green hydrogen economy which would be as a minimum be as a minimum on average neutral in terms of GDP growth, with the prospect of a better economic outlook from 2050 onwards. The economic benefits of a South African green hydrogen economy could furthermore be significantly higher if it paves the way for exports of platinum-based technologies like manufacturing of Fuel Cells and Electrolysers components, and for exports of green hydrogen-based commodities like Green Iron & Steel and the fuel/ basic chemical Green Ammonia. Establishing considerable shares in global markets for these products is expected to lead to a significant improvement of South Africa's GDP, estimated at about 11% higher by 2050 (in our H2-Export scenario) compared to GDP in a future without a hydrogen economy (in our NoH2 scenario). In conclusion, our study therefore expects only upside risks of establishing a South African green hydrogen economy for the economy, while not developing a green hydrogen economy would entail considerable downside risks for both the economy, post-2045, as well as for achieving global climate change mitigation goals as set out in the Paris Agreement of 2015 and in South Africa's own climate policy.

For employment a similar picture arises as for GDP growth. Developing a domestic green hydrogen economy has, as a minimum, a relatively neutral impact on employment: the impacts for employment of developing a domestic green hydrogen economy without GHE exports are slightly positive up to 2035 and post 2050, with between 2035 and 2050 a small net negative impact on employment growth. However, once green hydrogen economy commodity exports are added (in the H2-Export scenario), the employment impacts of a GHE become strongly positive. The biggest impacts are found in the tertiary (services) sectors, due to total GDP growth and these sectors making up the largest part of South African employment.

Zooming in on the sectors considered for a just labour transition from coal mining and refineries to green hydrogen economy-related sectors⁵³ we observe a small decrease in total TVET employment between 2025 and 2030 in all scenarios due to existing trends for a coal phase out and oil refinery closures. From 2030 onwards this is followed by an increase in total TVET employment in these sectors. TVET job gains are initially concentrated in Power Generation, PGM mining and Iron & Steel, while from 2035 onwards considerable job gains can also be expected for Green Hydrogen and Ammonia production and for Fuel Cell and Electrolyser manufacturing. Again, the employment potentials are much higher if GHE export markets are developed.

The scope for a Just Labour Transition from fossil fuel-based sectors towards Green Hydrogen Economy-related sectors is thus found to depend much on timing. I.e., in the period 2025-2030 in a local GHE only future new TVET-educated job opportunities in Power Generation and Iron & steel might be able to absorb about half of the 400 annual TVET educated unemployed being forced to leave coal mining in that same period. Beyond 2030 TVET job creation in Power Generation and Green Iron & Steel are expected to be higher than TVET job losses in coal

⁵³ Hydrogen production, Green Iron & Steel industry, Fuel Cell (component) and Electrolyser (component) manufacturing, Green Ammonia (chemicals) production, and important associated input-industries: Power generation and PGM mining.

mining. Similarly, for TVET job losses in Refineries the GHE cannot offer a meaningful alternative yet during the 2025-2030/2035 period, but from as soon as 2030 (with GHE exports) or 2035 (without GHE exports) onwards Green Hydrogen and Green Ammonia production job gains could outpace job losses from Refineries. Depending on being able to export or not, also the Fuel Cell and Electrolyser manufacturing sectors could add significant TVET job creation from 2030 or from 2035 onwards. These manufacturing sectors could possibly absorb jobs lost elsewhere in manufacturing, e.g., of catalytic converters or other automotive vehicle components. Job gains in GHE sectors could outpace TVET job losses by far and large from 2035 onwards.

We thus conclude that ample room exists for the TVET college system to both educate and train new students, as well as up- and re-skilling programs to support workers to transition towards Green Hydrogen Economy jobs, for them to enter the GHE from 2030-2035 onwards. This leaves us with a few years to experiment with and develop suitable TVET programs. However more detailed assessments of the requirements for up- or reskilling are still needed. To narrow down uncertainty and to be better able to quantify training requirements, additional research would be needed, beyond current labour statistics, e.g., through detailed surveys of sectoral or company labour forces or with detailed enquiries with Human Resources managers of leading companies in each sector. Careful analysis of the age and education profiles of the various labour forces would also be needed, besides a survey of the possibility and willingness among workers to move between regions. A strong and urgent need remains for alternative economic development in coal mining areas between now and 2030 in view of differences in timing of a coal phase-out and the emergence of a green hydrogen economy. TVET education of mathematics and digital literacy could play a role.

In summary, the main lessons of the present and its preceding studies within the UKPACT South Africa 2021 project on a green hydrogen economy and TVET skills is that the provision of green hydrogen-related skills through the TVET college system are:

- Hundreds of TVET graduates can be expected to be needed by green hydrogen economy sectors from 2030 or 2035 onwards, depending on how fast export markets can be developed.
- TVET graduates will require skills to work with the volatile hydrogen gas and green ammonia, to work with hydrogen-related equipment (fuel cells), to work in platinum beneficiation and fuel cell and electrolyser component manufacturing, or to work in production of green iron & steel.
- A labour transition from coal mining to both renewable power generation and a potentially emerging green iron & steel industry post-2025, and to PGM mining post-2030, possibly requires up- or re-skilling programs.
- Difference in timing between the closure (under economic pressure) of South Africa's oil refineries in the 2020'ies and the emergence of a green hydrogen and ammonia industry in the 2030'ies leads to the recommendation to study options to advance the emergence of a green chemicals industry to safeguard skills currently existing within the labour forces of refineries.
- To narrow down uncertainty and to quantify training requirements for up- or reskilling, additional research would be needed, e.g., through detailed surveys of sectoral or company labour forces or with detailed enquiries with Human Resources managers of leading companies in each sector.

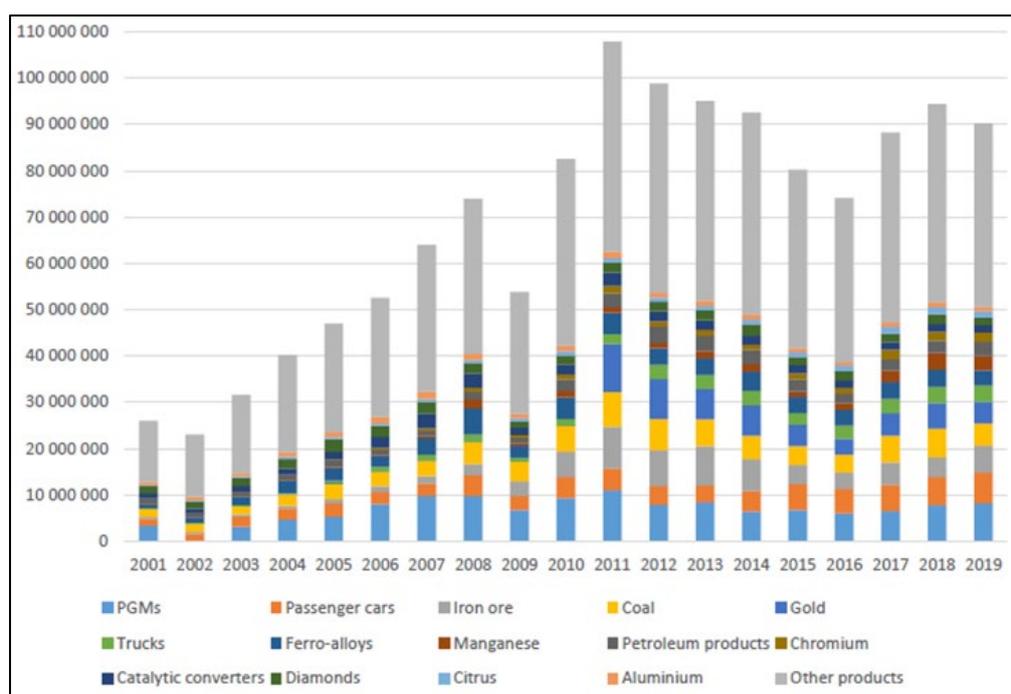
Appendices

A. Export assumptions for hydrogen

A.1 Backgrounds of export assumptions

The carbon intensive South African economy is also reflected in the country's international trade. Export revenue is predominantly derived from the direct trade in fossil fuel commodities (e.g. coal) or indirectly via goods such as, for example, platinum (including palladium and rhodium) that underpin fossil fuel use such as catalytic converters in conventional ICE⁵⁴ vehicles, and iron-ore which relies on fossil fuel feedstocks for processing. As illustrated in Figure A-1 a sizeable share of export trade is concentrated in the fossil fuel value chain. Furthermore, almost half of existing export trade⁵⁵ is with countries or regions (i.e. EU, UK, USA) that have committed to decarbonising their economies in accordance with the Paris Agreement.

Figure A-1: Historic account of the composition of South African export trade and value



Source: Montmasson-Clair (2020)⁵⁶

⁵⁴ ICE= internal combustion engine

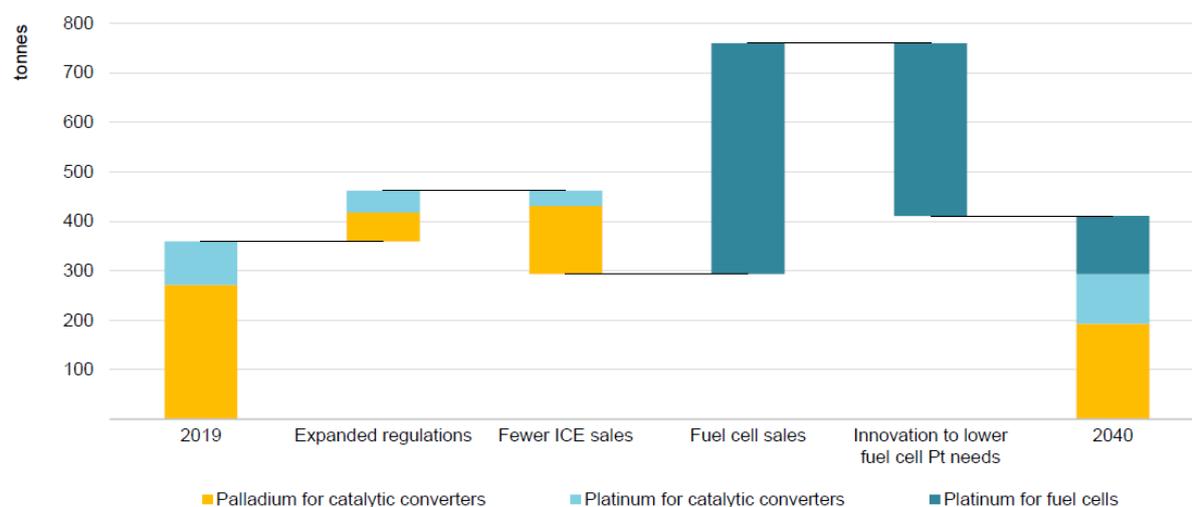
⁵⁵ OEC - The Observatory of Economic Complexity, <https://oec.world/en/subnational/#subnational-country-block-zaf> Accessed 10 June 2021

⁵⁶ Gaylor Montmasson-Clair, *The global climate change regime and its impacts on South Africa's trade and competitiveness: A data note on South Africa's exports*, TIPS, (2020) <https://www.tips.org.za/research-archive/>.

Presently, aside from the export of conventional internal combustion engine (ICE) vehicles for which South Africa's global share averaged 0.67%⁵⁷, catalytic converters are the highest value vehicle component exported, typically accounting for nearly half of the component export market which in 2019 generated R53.7 billion in revenue. For a Net-Zero GHG emissions pathway, the IEA's assessment of metals required for the transition, suggests a net decline in demand for catalytic converters and concomitantly the PGM metals which they utilise (Figure A-2).

It is anticipated that in the near to medium term that demand associated with ICE vehicles will increase due to stricter environmental regulations (or enforcement). Approaching 2040 it is anticipated that gains will be offset by declines in ICE sales as alternative drivetrains are adopted. Fuel-cell vehicle sales are expected to contribute to a sharp increase in demand for platinum due to their higher material loading compared to conventional vehicles^{58,59}. Future gross demand for the metal is however expected to be ~25% of present-day material usage⁵⁸. Therefore in 2040, despite declining sales, ICE vehicles, as hybrids, would still stimulate platinum demand comparable to fuel-cell vehicles. By 2050, in accordance with the Paris Agreement, platinum demand associated with ICE vehicles is expected to be to nil⁶².

Figure A-2: Projected gross demand for automotive PGMs for catalytic converters; contrasted with nascent demand for fuel cell vehicles. Source: IEA (2021)⁶⁰



Source: IEA, *The Role of Critical Minerals in Clean Energy Transitions* (Paris, IEA, 2021)

Since South Africa is reported to export a quarter of its GHG emissions⁶¹, the implications of carbon border adjustment taxes is a compelling imperative to restructure the economy to

⁵⁷ Norman Lamprecht, *Automotive Export Manual – 2020 – South Africa* (Automotive Industry Export Council, 2020)

⁵⁸ US DoE, *Fuel Cell Technical Team Roadmap* (USDoE, 2017)

⁵⁹ McKinsey, *Reboost: A comprehensive view on the changing powertrain component market and how suppliers can succeed* (McKinsey & Company, 2019) <https://www.mckinsey.com/industries/automotive-and-assembly/our-insights>.

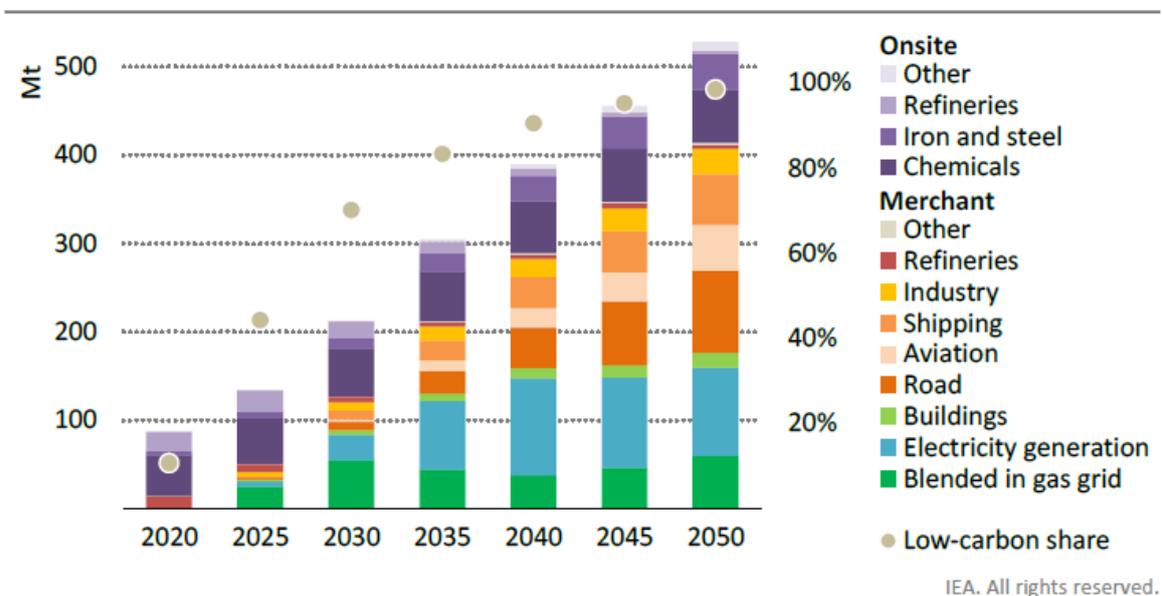
⁶⁰ IEA, *The Role of Critical Minerals in Clean Energy Transitions* (Paris, IEA, 2021)

⁶¹ Gaylor Montmasson-Clair, *The global climate change regime*.

facilitate trade in low, ideally neutral, carbon commodities either directly such as hydrogen or indirectly via enabling technologies such as fuel cells and electrolyzers or their components or the raw minerals required such as the platinum group metals (PGMs).

To gauge the scale of the potential global demand, the IEA's global net-zero⁶² pathway indicates that by 2030 demand for hydrogen would need to double from present day consumption to ~ 200Mt/a and increase to ~500 Mt/a by 2050 (Figure A-3) of which 414 Mt would be merchant supplied (Figure A-4). Future demand would be driven primarily by utilisation in electricity generation for balancing, transportation (notably international shipping and aviation) and industrial feedstocks.

Figure A-3: Global consumption of hydrogen (and H2 derived commodities) for net zero GHG Source: IEA (2021)



The initial focus for hydrogen is to convert existing uses to low-carbon hydrogen; hydrogen and hydrogen-based fuels then expand across all end-uses

Note: Includes hydrogen and hydrogen contained in ammonia and synthetic fuels.

Source: IEA, Net Zero by 2050 (2021)

⁶² IEA, Net Zero by 2050, (Paris, 2021)

Figure A-4: Key hydrogen deployment milestones for achieving net-zero GHG emissions source: IEA (2021)

Sector	2020	2030	2050
Total production hydrogen-based fuels (Mt)	87	212	528
Low-carbon hydrogen production	9	150	520
<i>share of fossil-based with CCUS</i>	95%	46%	38%
<i>share of electrolysis-based</i>	5%	54%	62%
Merchant production	15	127	414
Onsite production	73	85	114
Total consumption hydrogen-based fuels (Mt)	87	212	528
Electricity	0	52	102
of which hydrogen	0	43	88
of which ammonia	0	8	13
Refineries	36	25	8
Buildings and agriculture	0	17	23
Transport	0	25	207
of which hydrogen	0	11	106
of which ammonia	0	5	56
of which synthetic fuels	0	8	44
Industry	51	93	187

Note: Hydrogen-based fuels are reported in million tonnes of hydrogen required to produce them.

Source: IEA, *Net Zero by 2050 (2021)*

A.2 Hydrogen-based chemicals, fuels and materials demand

South Africa's RE endowment positions the country as a competitive global supplier of hydrogen commodities. Recent IHS Markit⁶³ analysis indicates that South Africa could competitively supply hydrogen to European and Japanese markets against Australia and Morocco respectively if supply via ammonia as a carrier is adopted. Optimistic and moderate projections for South African trade in the global hydrogen economy is provided in Table A-1.

⁶³ IHS Markit, *Super High Road Scenario for South Africa*, 2021

Table A-1: Estimated projected global demand and SA market export potential for hydrogen and hydrogen-based commodities

2050		Ammonia: Fertiliser	Ammonia: Shipping fuel	Ammonia: Electricity	Jet Fuel	Iron/Steel
SA export market share		10%	10%	10%	10%	5%
Enertrag- High ⁶⁴	Global (Mt/a)	170	500	13	400	2000
IEA- Moderate ^{65,69}	Global (Mt/a)	20	56	13	44	80

Source: Compiled by the Authors based on own assumptions, and calculations based Bischof-Niemz, (ENERTRAG AG, 2021), IEA, Net Zero by 2050 (2021), and Michael Liebreich (2020)

A.3 Fuel cell and electrolyser demand and supply

The EU's *Strategy for Energy System Integration*⁶⁶ and *Hydrogen Strategy*⁶⁷ proclaims a key role for green hydrogen as an energy carrier and industrial feedstock in the transition to a European climate-neutral economy. It is reported that by 2030 and 2050 46 GW and 500 GW, respectively, of renewable energy. Powered electrolysers would be required, which would by then be similar to Europe's present peak demand of 546 GW⁶⁸.

The ascent of intermittent Solar PV and Wind generation has resulted in Platinum (and Iridium) based PEM electrolysers overtaking alkaline technology as the preferred option for the production of green H₂ from variable RE with 80% of installed electrolyser capacity in 2019 being PEM technology⁶⁹.

The recent IEA⁷⁰ (2021) study of critical metals for the global energy transition contrasted two scenarios: Stated Policies Scenario (STEPS) and Sustainable Development Scenario (SDS). The SDS conforms to a global vision that aligns with the Paris Agreement with an accelerated transition to carbon-neutral energy systems. Figure A-5 contrasts the projected global demand

⁶⁴ Tobias Bischof-Niemz, *Green Hydrogen Export Opportunity for South Africa* (ENERTRAG AG, 2021)

⁶⁵ IEA, *Net Zero*.

⁶⁶ European Commission, *Powering a climate-neutral economy - An EU Strategy for Energy System Integration*, (2020) <https://ec.europa.eu/energy/>.

⁶⁷ European Commission, *A hydrogen strategy for a climate-neutral Europe 2020*, <https://ec.europa.eu/energy/>.

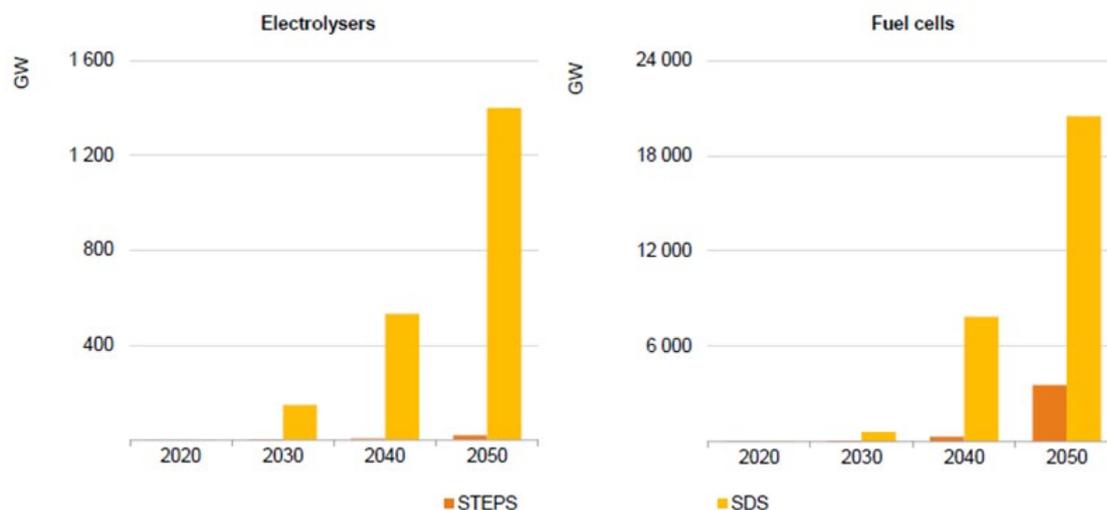
⁶⁸ Michael Liebreich, *Separating Hype from Hydrogen – Part One: The Supply Side 2020*,

⁶⁹ IEA, *The Future of Hydrogen*, 2019

⁷⁰ IEA, *The Role of Critical Minerals*.

for electrolyzers and fuel cells for the IEA scenarios. The table below estimates the export of electrolyzers and fuel-cells (or their components) for scenarios of domestic beneficiation of the PGM sector.

Figure A-5: Projected global demand for electrolyzers and fuel cells



Source: IEA, *The Role of Critical Minerals*. (2021)

Table A-2 Estimated potential South African fuel cell and electrolyser export market share for the energy transition. Derived from IEA (2021)⁶⁶

GW	Electrolyser			Fuel cell		
	2030	2040	2050	2030	2040	2050
Low	0.2	0.4	1.0	0.01	0.02	0.04
Moderate	0.2	2	21	0.03	8	310
High	1	9	56	4	124	818

Note: Assumes South Africa supplies IEA projected quantities at a global market share of 1% in 2030; 2% in 2040 and 5% in 2050⁷¹; PEM technology maintains 80% share.

Source: Compiled by the authors based on IEA 2021

⁷¹ Tobias Bischof-Niemz, *Green Hydrogen Export*.

A.4 PGM Demand and Supply assumptions

Presently, in terms of material use by market, platinum usage in the automotive sector via catalytic convertors comprise approximately a third (32% in 2019) of gross demand with industrial use, jewellery, and investments comprising the remainder (see Table A-3). Future demand for platinum in catalytic convertors is expected to decline due to the phase-out of ICE vehicles when moving to a Net Zero carbon world (Table A-4). This reduction in platinum demand is expected to be offset by demand for Platinum and other PGMs for fuel cells and electrolyzers:

The IEA expects the primary demand for metals to be for fuel-cell vehicles rather than electrolyzers. PGM (by extension platinum) usage accounts for ~99% of demand by 2040 or 117 tonnes. Presently fuel cells, by capacity rather than units, are predominately found in the transport sector with vehicles accounting for 80% of the 1.1 GW shipped in 2019, compared to the 40% market share in 2014⁷². PEM fuel cells dominate the technology portfolio with a market share of 900 MW (~80%). Below estimates follow of ranges for the future demand of PGMs (platinum).

Table A-3: Platinum demand ('000 kg, tonnes) by key sector and their market share. Source: Johnson Matthey⁷³

Sector	2018	2019	2020		2018	2019	2020
Autocatalyst	93.8	88.9	69.2		38%	34%	32%
Jewellery	70.2	63.9	49.2		28%	24%	23%
Industrial	80.4	75.1	68.9		33%	29%	32%
Investment	2.1	35.2	28.0		1%	13%	13%
Total gross demand	246.6	263.1	215.2		100%	100%	100%
Recycling	- 64.3	- 64.8	- 51.1		-26%	-25%	-24%
Total net demand	182.3	198.4	164.2				

Source: Johnson Matthey (2021)⁷⁴

⁷² E4tech, *The Fuel Cell Industry Review 2019*, (UK, E4tech, 2019) <http://www.fuelcellindustryreview.com>.

⁷³ Johnson Matthey, *PGM market report February 2021*, (Johnson Matthey, 2021)

⁷⁴ Johnson Matthey, *PGM market report February 2021*, (Johnson Matthey, 2021)

Table A-4: Estimated platinum demand for automotive catalytic converters for the energy transition with SA market share. Derived from IEA (2021)⁸⁸

Net platinum demand (tonnes)	2030	2040	2050
Global gross demand Pt-ICE ^{#1}	133 ^{#2}	101	0
SA Market share ^{75,76}	10%	10%	-
SA supply Pt-ICE ^{#3}	10	7.6	0

Note: ^{#1}Pt-ICE= Platinum for ICE vehicles";^{#2}Additional demand due to increased environmental regulations; ^{#3}Assumes constant recycling rate of 25%.

Source: IEA, *The Role of Critical Minerals*. (2021), and authors own calculations and assumptions based on Andreas Künne,(2013)⁷⁷, and CCIG, *AUTO CATALYSTS REPORT* (Catalytic Converter Interest Group, n.d)

Table A-5: Mineral demand for the global energy transition Source: IEA (2021)

Demand	Stated Policies Scenario			Demand	Sustainable Development Scenario		
	2020	2030	2040		2020	2030	2040
(tonnes, t)				(tonnes, t)			
Hydrogen	1	13	18	Hydrogen	1	36	118
Electrolyser	0.001	0.012	0.017	Electrolyser	0.00	0.97	1.51
Iridium	0.0007	0.008	0.013	Iridium	0.001	0.60	1.20
Platinum	0.00032	0.004	0.003	Platinum	0.0003	0.37	0.30
FCEV	1	13	18	FCEV	1	35	117
PGM	0.8	12.6	18.3	PGM	0.8	35.5	116.9

Source IEA, *The Role of Critical Minerals*. (2021)

Recycling can supply a part of the outlook for demand, but recycling rates of platinum stock remain relatively stagnant at ~25% having shown signs of a marginal decrease over the last three years. Improvements in the platinum value chain suggest higher rates of recycling are possible, especially with regard to the automotive sector, although with its own set of challenges^{78,79}. Recovery rates of 30% (EU present day best practice) to 80% are proposed for scrapped vehicles⁷⁹. However, in absolute terms, an increase in recycling automotive components (i.e. catalytic converters) would be

⁷⁵ Andreas Künne, *Beneficiation in SA: Perspective of German-South African Industry*, (German Embassy Pretoria, 2013)

⁷⁶ CCIG, *AUTO CATALYSTS REPORT*(Catalytic Converter Interest Group, n.d).

⁷⁷ Andreas Künne, *Beneficiation in SA: Perspective of German-South African Industry*, (German Embassy Pretoria, 2013)

⁷⁸ Han Hao et al.*Securing Platinum-Group Metals for Transport Low-Carbon Transition*(One Earth, 2019)

<https://doi.org/10.1016/j.oneear.2019.08.012>.

⁷⁹ Rikka Wittstock, Alexandra Pehken and Michael Wark, *Challenges in Automotive Fuel Cells Recycling* (Recycling, 2016), <https://doi.org/10.3390/recycling1030343>.

offset by the larger material use required for fuel cells. For example a Toyota Mirais, ~0.25g/kW of platinum compared to a comparative conventional ICE vehicle (0.05 g/kW for a Euro VI gasoline)⁷⁸. However much lower platinum loading is also reported at 0.125 g/kW (80 kW system) with a target value of ~0.1 g/kW for the near term⁸⁰.

Another influence on demand for mining PGMs is material use intensity. For both PEM electrolyzers and fuel cells trends suggest a decline in material requirements as capacity scales and the state of the art improves material efficiency: McKinsey⁸¹ reports that for the period 2005-2019 an 80% reduction in the use of platinum to produce fuel cells for automotive use has been achieved; and the future material requirements for electrolyzers are also expected to decline (Table A-6).

Table A-6: Iridium and platinum loading for PEM electrolyzers with increased performance and material reduction strategies. Source: IRENA 2020⁸²

	TODAY	FUTURE
Current density (A/cm ²)	2	5
Electrode area (cm ²)	1200	5000
Iridium loading (mg/cm ²)	5	0.2
Iridium loading (g/kW)	1.3	0.4
Platinum loading (mg/cm ²)	2	0.05
Platinum loading (g/kW)	0.5	0.1

Source: IRENA 2020⁸³

Combining the above trends in demand, recycling and material intensity, Table A-7 estimates future platinum demand for the energy transition for platinum-based PEM electrolyzers and fuel-cells based on the literature review and assumptions derived thereof. To maintain consistency with the scenarios outlined metal demand is estimated net of the presumed domestic beneficiation that would occur with the export of components. Values shown in brackets denote the tonnage that is beneficiated domestically for the component value chain.

As stated previously, it is presumed, that the production of fuel cells (and electrolyzers) are of the PEM technology which currently accounts for 80% of global market share of fuel cells deployed.⁸⁴ PEM technology would increase demand for the Platinum Group Metals (PGM) for which South Africa is the primary supplier. This study considers platinum demand as a proxy for PGM demand, cognisant of the suite of additional minerals (e.g. Iridium) that would complement demand for minerals for the energy transition, whilst offsetting a potential decline in demand linked to fossil-fuel consumption; notably catalytic converters (e.g. platinum, rhodium and palladium).

The underlying assumption regarding PGM activity, as indicated in Table 0-2, is that the extraction and export of commodities are subject to global demand and intransigent to the evolving domestic

⁸⁰ US DoE, *Fuel Cell*.://www.energy.gov/sites/default/files/2017/11/f46/FCTT_Roadmap_Nov_2017_FINAL.pdf

⁸¹ McKinsey, *Reboost: A comprehensive view*.

⁸² IRENA, *Green Hydrogen Cost Reduction: Scaling up Electrolyzers to Meet the 1.5°C Climate Goal* (Abu Dhabi, IEA, 2020)

⁸³ IRENA, *Green Hydrogen Cost Reduction: Scaling up Electrolyzers to Meet the 1.5°C Climate GOAL* (Abu Dhabi, IEA, 2020)

⁸⁴ See Appendix A.

application of hydrogen. Therefore, all scenarios, including the scenario of no expansion of domestic usage at industrial scale⁸⁵ (No-H2), has PGMs – specifically platinum – exported in a context of global demand for the energy transition and the consequent demand for “new-energy” minerals. The myriad of applications outside of the energy paradigm is itself a complex task to project future demand and therefore for this study the historical activity is assumed until 2050 with additional demand included and attributed to the energy transition. Additional demand consists of mineral exports and domestic demand for beneficiation associated with the manufacture of fuel cells and electrolyzers. A potential future decline in demand from automotive applications (i.e. catalytic converters) are also accounted for.

Table A-7: Estimated South African platinum demand for the energy transition. Derived from IEA (2021)⁸⁶ and IRENA (2020)⁸⁷

Net platinum demand (tonnes)	2030	2040	2050
Low	4	1	1
Moderate	4 [0.1]	33 [1]	436 [15]
High	60 [1]	542 [15]	1373 [98]
<p>Note: Assumes South Africa supplies IEA⁸⁸ projected quantities at its current global market share of 65%⁸⁹; Material use efficiency as described above is reached in 2050; Recycling of platinum stock is constant at 25% of gross demand; PEM technology maintains 80% share^{90,91}. Total demand inclusive of material for electrolyzers and fuel cells; The IRENA project pipeline for the period 2020-2030 provides the basis for the low platinum export scenario⁹¹; This denotes net demand exclusive of other sectors list;</p> <p>Values shown in brackets denote the tonnage that is beneficiated domestically for the component value chain.</p>			

Source: Derived from IEA (2021)⁹² and IRENA (2020)⁹³

A.5 Assumed SA market shares in global Electrolyser and Fuel Cell markets

The Moderate assumption in Table A-8 has been used for the H2-Export and NoH2-Export scenarios in the present study.

Table A-8 Estimated potential South African fuel cell and electrolyser export market share for the energy transition. Derived from IEA (2021)⁸⁶

⁸⁵ That is, outside of present-day usage in the petrochemical sector.

⁸⁶ IEA, The Role of Critical Minerals.

⁸⁷ IRENA Green Hydrogen.

⁸⁸ IEA, The Role of Critical Minerals.

⁸⁹ Johnson Matthey, PGM market repor.

⁹⁰ E4tech, The Fuel Cell Industry.

⁹¹ IRENA, Green Hydrogen.

⁹² IEA, The Role of Critical Minerals.(2021)

⁹³ IRENA Green Hydrogen.

GW	Electrolyser			Fuel cell		
	2030	2040	2050	2030	2040	2050
Low	0.2	0.4	1.0	0.01	0.02	0.04
Moderate	0.2	2	21	0.03	8	310
High	1	9	56	4	124	818

Note: Assumes South Africa supplies IEA projected quantities at a global market share of 1% in 2030; 2% in 2040 and 5% in 2050⁹⁴; PEM technology maintains 80% share.

Source: Derived from IEA (2021)⁸⁶

B Additional detail on results

B.1 Historic trends in SA TVET employment

The number of workers employed in the South African economy was increasing at a steady pace from 2009 to 2019

⁹⁴ Tobias Bischof-Niemz, "Green Hydrogen Export Opportunity for South Africa" ENERTRAG AG, 2021

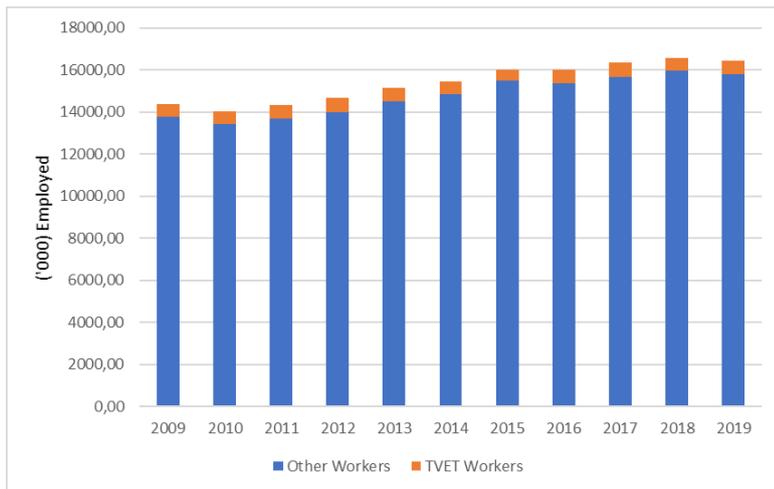
Figure B-1). Figure B-2 shows the smoothed trend in educational makeup of the South African labour force from 2000,⁹⁵ based on the Post-apartheid Labour Market Series (PALMS) which is a series of cross-sectional labour force surveys from 1995-2019.^{96,97} The trend shows that there has been a significant increase in the proportion of matric and secondary educated individuals as well as a slight increase in lower and tertiary educated individuals while the proportion of TVET educated worked in the labour force remains relatively constant, increasing slightly between 2005 and 2010 before levelling at between 3% to 4% for the last 10 years.

⁹⁵ To smooth the movement in the level of education within each industry we generate graphs using the `ipoly` command on the Stata program. This performs a kernel-weighted local polynomial regression of mean education level on years.

⁹⁶ Kerr, et al. *Post-Apartheid Labour Market Series* [dataset], Version 2.1, Cape Town: DataFirst [producer and distributor], 2013. [zaf-datafirst-palms-1994-2012-v2.1]

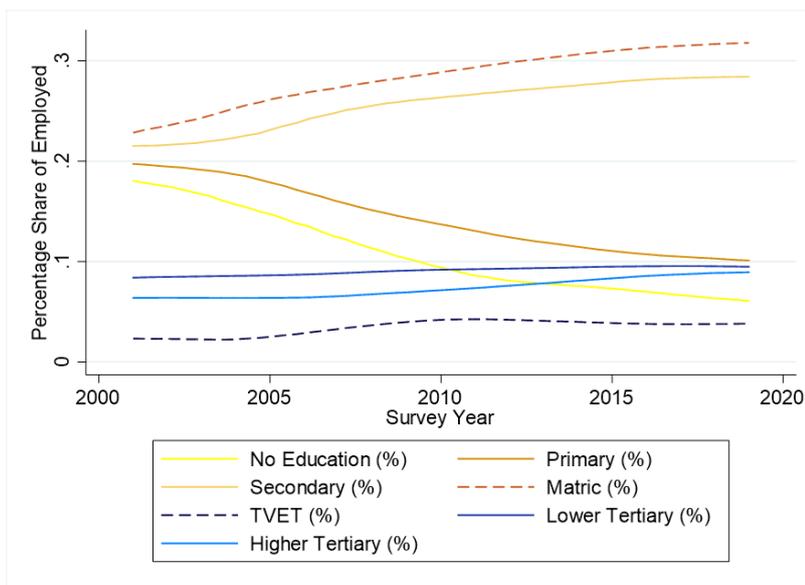
⁹⁷ The data is weighted using cross-entropy weights created for reliable and consistent data analysis over time. For more info, see: Branson, N., & Wittenberg, M. 'Reweighting South African National Household Survey Data to Create a Consistent Series over Time: A Cross-Entropy Estimation Approach', *South African Journal of Economics* 82, no. (2014):19-38.

Figure B-1: Employment trends in South African Labour Force⁹⁸



Source: Compiled by authors based on Kerr, et al. PALMS [dataset v3.3] (2019).

Figure B-2: Smoothed proportion of education categories (2000 – 2019)⁹⁹



Source: Compiled by authors calculations based on: Kerr, et al. PALMS. v3.3 (2019)

⁹⁸ Kerr, et al. PALMS [dataset v3.3] (2019).

⁹⁹ Source: Author calculations based on: Kerr, et al. PALMS.

B.2 TVET employment projections by sector

Table B-1: TVET employment creation by economic sector (,000s)

SA		PGM Exports only						PGM,Fuel Cell , and Electrolyser Exports				
GHE ?	TVET jobs (x1000) by sector	2020	2030	2035	2040	2045	2050	2030	2035	2040	2045	2050
	Total	610	772	868	989	1 150	1 247	772	869	989	1 144	1 230
	Selected sectors subtotal	24,5	25,2	26,0	27,4	38,3	50,8	25,3	26,6	28,6	48,9	74,2
	Refineries (incl.CTL)	1,3	0,5	0,3	0,1	0,1	0,1	0,5	0,3	0,1	0,1	0,1
	Hydrogen	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
	Ammonia	0,2	0,2	0,2	0,2	0,2	0,2	0,2	0,2	0,2	0,2	0,2
	FuelCells	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,1	0,2	4,5	8,8
	Electrolysers	0,0	0,0	0,0	0,0	0,0	0,0	0,1	0,5	0,9	4,6	8,4
No SA	Iron & Steel	4,1	4,9	5,4	6,1	6,5	6,3	4,9	5,4	6,1	6,7	6,6
GHE	PGM mining	5,2	7,3	8,0	8,6	18,0	29,9	7,3	8,0	8,6	19,4	36,3
	Coal mining	7,5	5,2	3,4	2,6	2,0	1,2	5,2	3,4	2,6	2,0	1,2
	Power Gen, and T&D	6,1	7,0	8,6	9,8	11,4	13,1	7,0	8,6	9,8	11,3	12,7
	Agriculture	29,2	37,5	41,5	44,8	49,2	51,5	37,5	41,4	44,6	46,3	46,2
	Other Mining	6,5	7,8	8,3	8,6	9,1	9,0	7,8	8,2	8,6	8,2	7,7
	Other Industries	142	174	192	210	236	241	174	192	210	230	229
	Tertiary sector	407	527	600	697	818	895	527	601	697	810	873
SA		PGM Exports only						Full Exports (PGM,FC,ELT,Ammonia, and I&S)				
GHE ?	TVET jobs (x1000) by sector	2020	2030	2035	2040	2045	2050	2030	2035	2040	2045	2050
	Total	610	773	872	978	1 110	1 236	774	895	1 035	1 211	1 361
	selected sectors subtotal	24,5	25,2	26,2	28,5	39,9	50,9	26,9	34,8	44,0	72,6	100,4
	Refineries (incl.CTL)	1,3	0,5	0,3	0,1	0,0	0,0	0,5	0,3	0,1	0,1	0,1
	Hydrogen	0,0	0,0	0,1	0,5	0,6	1,4	0,0	0,4	1,2	1,7	2,3
	Ammonia	0,2	0,2	0,2	0,2	0,2	0,2	0,2	1,0	1,5	2,2	3,0
	FuelCells	0,0	0,0	0,0	0,6	0,9	0,8	0,0	0,2	0,9	5,5	9,7
	Electrolysers	0,0	0,0	0,0	0,0	0,0	0,7	0,1	0,5	1,0	4,9	9,1
Yes,	Iron & Steel	4,1	4,9	5,4	5,8	6,2	6,5	6,5	11,8	16,9	22,0	26,6
with a	PGM mining	5,2	7,3	8,0	8,6	18,0	25,7	7,3	8,0	8,5	20,3	31,9
SA	Coal mining	7,5	5,5	3,5	2,5	1,9	1,0	5,3	3,6	2,6	1,9	1,0
GHE	Power Gen, and T&D	6,1	6,7	8,6	10,3	12,1	14,5	6,9	9,1	11,4	13,9	16,7
	Agriculture	29,2	37,5	41,8	44,7	47,9	50,9	36,5	39,1	41,7	43,5	45,5
	Other Mining	6,5	7,7	8,2	8,6	8,9	9,2	7,6	7,6	8,1	8,1	8,5
	Other Industries	142	175	192	205	225	242	172	188	205	223	232
	Tertiary sector	407	528	604	691	789	883	531	625	736	864	975

Source: Compiled by authors based on own scenario results from SATIMGE model

Table B-2 TVET employment by economic sector relative to no hydrogen usage (.000s)

Comparing ...		NoH2 with FC+ELT exports vs. NoH2-PGM exports only									
TVET jobs (x1000) by sector		2030	2035	2040	2045	2050					
	Total	0,3	0,5	0,1	-6,2	-16,6					
	Selected sectors subtotal	0,1	0,6	1,1	10,6	23,4					
	Refineries (incl.CTL)	0,0	0,0	0,0	0,0	0,0					
	Hydrogen	0,0	0,0	0,0	0,0	0,0					
	Ammonia	0,0	0,0	0,0	0,0	0,0					
	FuelCells	0,0	0,1	0,2	4,5	8,8					
"Yes, with a SA GHE" vs. "No SA GHE"	Electrolysers	0,1	0,5	0,9	4,6	8,4					
	Iron & Steel	0,0	0,0	0,0	0,2	0,3					
	PGM mining	0,0	0,0	0,0	1,4	6,3					
	Coal mining	0,0	0,0	0,0	0,0	0,0					
	Power Gen, and T&D	0,0	0,0	0,0	-0,2	-0,4					
	Agriculture	0,0	-0,2	-0,2	-3,0	-5,3					
	Other Mining	0,0	0,0	-0,1	-0,8	-1,3					
	Other Industries	0,0	-0,2	-0,3	-5,4	-12,2					
	Tertiary sector	0,2	0,3	-0,4	-7,6	-21,3					
Comparing ...		PGM Exports only vs PGM Exports only					Full Exports (PGM,FC,ELT,Ammonia, and I&S) vs. NoH2-PGM exports only				
TVET jobs (x1000) by sector		2030	2035	2040	2045	2050	2030	2035	2040	2045	2050
	Total	1,1	3,9	-10,6	-40,4	-11,3	1,9	26,5	46,3	60,5	114,2
	Selected sectors subtotal	0,0	0,2	1,1	1,6	0,1	1,6	8,8	16,6	34,2	49,6
	Refineries (incl.CTL)	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1
	Hydrogen	0,0	0,1	0,5	0,6	1,4	0,0	0,4	1,2	1,7	2,3
	Ammonia	0,0	0,0	0,0	0,0	0,0	0,0	0,8	1,4	2,0	2,8
	FuelCells	0,0	0,032	0,6	0,9	0,8	0,0	0,161	0,9	5,5	9,7
With SA GHE & Full exports vs NoH2&NoExports	Electrolysers	0,0	0,0	0,0	0,0	0,7	0,1	0,5	1,0	4,9	9,1
	Iron & Steel	0,0	0,0	-0,2	-0,3	0,2	1,6	6,4	10,8	15,5	20,3
	PGM mining	0,0	0,0	0,0	0,0	-4,2	0,0	0,0	-0,1	2,4	2,0
	Coal mining	0,2	0,1	-0,1	-0,1	-0,2	0,1	0,2	-0,1	-0,1	-0,2
	Power Gen, and T&D	-0,2	0,0	0,5	0,6	1,4	-0,1	0,5	1,6	2,4	3,6
	Agriculture	0,0	0,3	-0,1	-1,3	-0,6	-1,0	-2,5	-3,0	-5,7	-6,1
	Other Mining	0,0	0,0	0,0	-0,1	0,2	-0,2	-0,6	-0,6	-1,0	-0,5
	Other Industries	0,1	-0,2	-5,1	-11,2	1,2	-2,0	-4,0	-5,5	-12,6	-8,8
	Tertiary sector	1,1	3,7	-6,5	-29,4	-12,1	3,4	24,8	38,9	45,6	80,1

Source: Compiled by authors based on own scenario results from SATIMGE model

B.3 Calculation of direct, and indirect and induced H2FC production employment

Direct employment impacts of domestic use of hydrogen-Fuel Cells (H2FCs) have been calculated by dividing the number of TVET employees in the Fuel Cell manufacturing sector¹⁰⁰ by the capacity in fuel cells added to the stock of fuel cells in use in South Africa, which is determined by the energy systems part of the SATIMGE model. The former is straightforward in the case of the Local-H2 scenario in which all fuel cell capacity is destined for the domestic market, while for the H2-Export scenario the amount of Fuel Cells exported (as assumed, see section 0) have to be deducted first. Table B-3 summarizes, amongst other things, the Fuel Cell sector employment numbers, corrected by the employment estimated for exports, as well as domestic Fuel Cell capacity additions in a given projection year, and the resulting direct jobs per GW of fuel cell.

Table B-3 Direct and total TVET job creation associated with domestic use and production of H2FCs for HCVs class 6-9

Estimates by indicator \ Year	2035	2040	2045	2050	
Direct TVET jobs (in FC manufacturing)					
Low (Local-H2 vs NoH2)	32	580	934	830	
High (H2-Exports vs NoH2-Exports)	64	676	1 030	945	
Additional whole economy TVET jobs ('000s)					
Low (Local-H2 vs NoH2)	3,9	-10,6	-40,4	-11,3	
High (H2-Exports vs NoH2-Exports)	26,5	46,3	60,5	114,2	
Fuel Cell share in additional GHE GVA					
Low (Local-H2 vs NoH2)	100%	100%	100%	74%	
High (H2-Exports vs NoH2-Exports)	7%	34%	35%	25%	
Additional whole economy TVET jobs ('000s) allocated to FC production					
Low (Local-H2 vs NoH2)	3,9	-10,6	-40,4	-8,3	
High (H2-Exports vs NoH2-Exports)	1,9	16,0	21,1	29,0	
Fuel Cell production (GW), annual for SA market					
Local-H2 scenario	1,5	6,9	8,1	14,7	
H2-Export scenario	2,1	7,8	9,2	16,7	
Direct TVET Jobs / GW of FC produced for domestic use					<i>Weighted Avg (by GW)</i>
Low (Local-H2 vs NoH2)	21	84	115	57	76
High (H2-Exports vs NoH2-Exports)	31	86	112	57	76
<i>Average</i>	26	85	114	57	76
Indirect and induced TVET Jobs / GW of FC produced for domestic use					<i>Weighted Avg (by GW)</i>
Low (Local-H2 vs NoH2)	2 558	-1 549	-4 973	-566	-1 781
High (H2-Exports vs NoH2-Exports)	922	2 034	2 302	1 737	1 900
<i>Average</i>	1 740	243	-1 335	586	59

Source: Compiled by authors based on own calculations based on scenario results from SATIMGE model

¹⁰⁰ The number of TVET employees in a given projection year and scenario is a result of combining the historic share of TVET employees in a sector's or proxy sector's labour force and the number of employees as given by the CGE model (economic part of the SATIMGE model), which increases the size of the Fuel Cell manufacturing sector's capital stock and thus production capacity and labour requirements informed by the investment requirements coming from the energy systems part of the model.

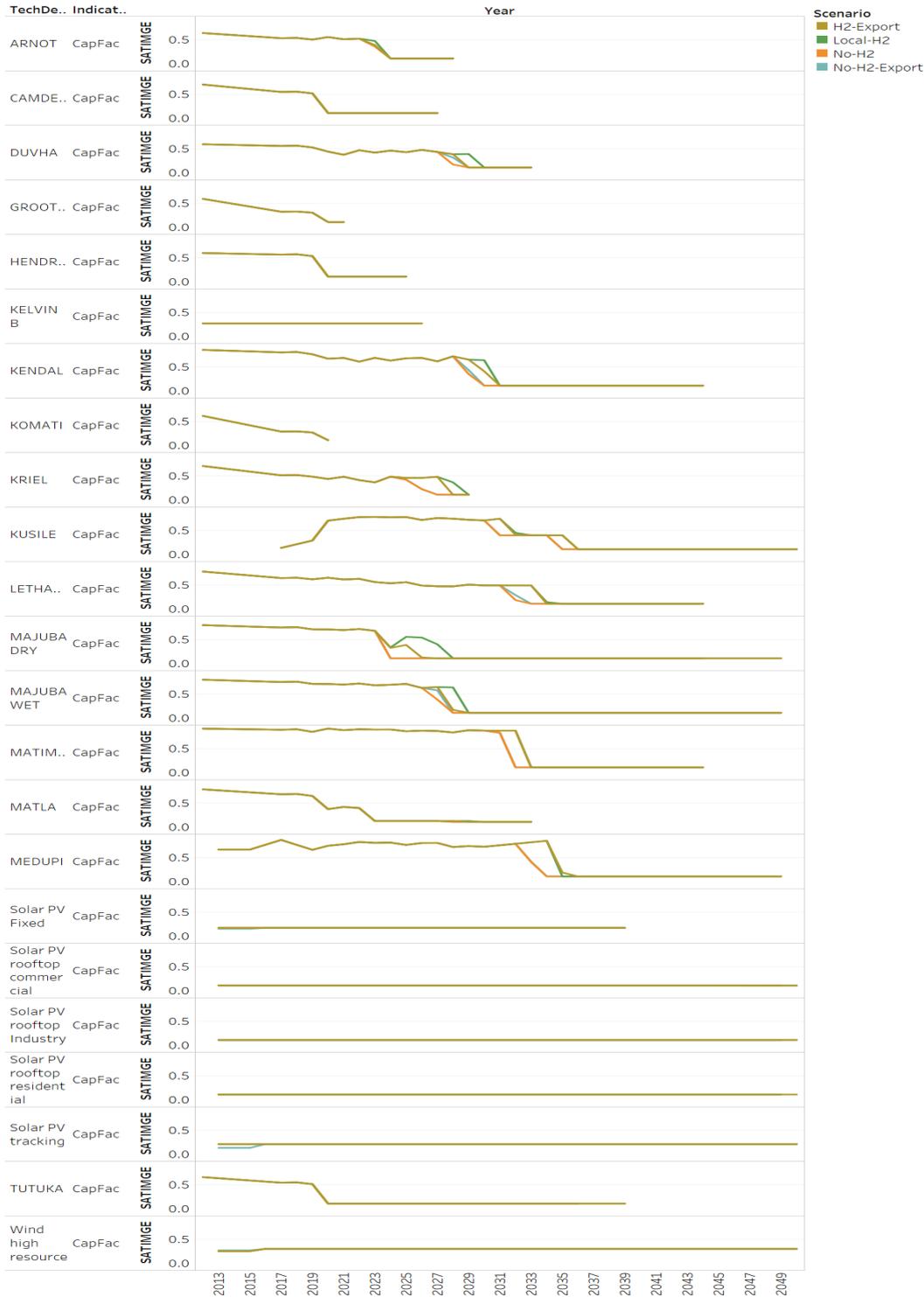
For the calculation of induced TVET employment, first the difference in employees of scenarios with and without domestic fuel cell use related to the use of green hydrogen was calculated, notably comparing the Local-H2 scenario with the NoH2 scenario, and the H2-Export scenario with the NoH2-Export scenario. In both cases, it is not only the domestic use of fuel cells which is the only difference (or “shock”) between the two scenarios. In the case of the Local-H2 vs NoH2 the employment impact of local use and production of fuel cells had to be distinguished from the parallelly appearing local manufacturing and use of PEM electrolyzers. In the case of the H2-Export vs NoH2-Export scenario the same parallel domestic fuel cell & electrolyser-use shock is a main difference between the two scenarios, but not only, as also the introduction of Green Ammonia and Green Iron& Steel exports plays a role. To allocate total employment impacts to Fuel Cell manufacturing and use shares in additional GVA in these scenarios were used (as reported in Table B-3). Due to higher economic growth the amount of domestic fuel cell use is higher in the H2-Export scenarios than in the Local-H2 scenario.¹⁰¹ For most years the Local-H2 to NoH2 comparison leads to a low or most negative estimate of employment impacts while the Export scenario comparison produces a high or most positive induced employment impact, the reasons for which have been previously discussed in the present report. The weighted average is an approximation and (for reason of simplification) weighs the employment impacts for the in Table B-3 presented projection years by the amount of GW of fuel cells produced for domestic use in those years.

¹⁰¹ Recall that only the use of fuel cells in HCV trucks appears as an industrial-scale application of H2FCs in our model, and that niche applications of stationary use in remote or emergency locations was not considered, while H2FCs did not prove an economic option for long duration electricity storage for the main grid in the technology trade-offs modelled in SATIMGE, and use in other transport means, notably in shipping was considered out of scope for the present study (see sections 2.1 and 2.2)

B.4 Capacity at which power plants are run by plant or technology

The figure below presents the capacity (share) at which power plants are run for a least-cost energy system given all other constraints (emissions and availability of GHE and exports) in NZ scenarios.

Figure B-3: Capacity factors for different power plant types and power technologies for Net Zero scenarios



Source: Compiled by authors based on own scenario results from SATIMGE model

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