ENERGY SYSTEMS RESEARCH GROUP

WWF

Informing an Illustrative People's Energy Planning process

Final Report

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Energy Systems Research Group

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WWF

Executive Summary

This report presents the full modelling results for technical work undertaken by the Energy Systems Research Group (ESRG) to inform and support the ***Illustrative People's Energy Planning*** project (IPEP) led by World Wide Fund for Nature (WWF) South Africa. A separate paper on the policy implications and recommendations stemming from this work will accompany this report, and therefore policy issues are not dealt with in detail in this report except insofar as they informed modelling choices and results.

In this project, the scenario analysis has been divided into three 'sets', as outlined in Table 2. The set-up for each set of scenarios, as well as their results, are described in the subsequent sections for each set, namely section 3 (Set 1, Reference Cases), 4 (Set 2, Policy Scenarios) and 5 (Set 3, Ideal Energy Scenario and sensitivity analyses). Table 3 shows the full matrix for all scenarios and cases modelled and analysed in this work.

Table 1: Overview of Scenario Sets

Scenario Set	Name	Description
Set 1	**Reference Cases**	Allowing the model to build the energy sector based only on least-cost optimisation, firstly without emissions constraints and secondly with net zero carbon emissions in 2050 and cumulative emissions constraints.
Set 2	**Policy Scenarios**	Testing the impacts of current, proposed and potential policy cases on the energy system and related outcomes, to identify initial potential policy trade-offs. The choice of policy cases was led by WWF's stakeholder engagement process and project steering committee inputs.
Set 3	**Ideal Energy Scenario**	Modelling the energy system based on 'ideal' characteristics and outcomes expressed by participants at the Stakeholder Scenario Workshop, with sensitivity analysis for key uncertainties.

Analysis and results of Set 1 and Set 2 were provided in some detail in a previous report - ESRG's *Report on Reference Case and Policy Scenario modelling, and inputs for co-creation of an Ideal Energy Scenario* from February 2025. Updated Reference Case results are presented and discussed here, along with the addition of the Social Provisioning Policy Scenario. The report thereafter focuses on results from the scenario set 3 packages, i.e. the 'Ideal Energy Scenario' along with a series of sensitivity analyses.

It should be noted that the 'Ideal' Energy Scenario presented here is not intended as an "alternative IEP" and is by no means a comprehensive model representation of all key issues facing the current and future energy system; nor does it purport to represent a unanimous view among all stakeholders or the wider public of what would constitute an ideal energy system. The intention is rather to demonstrate what a future energy scenario could look like based on a series of goals, aspirations and priorities indicated by stakeholders, and then to show – using the least-cost SATIMGE optimisation model – different energy pathways to reach that future.

The Ideal Energy Scenario is characterised by an economy-wide net zero CO_2 emissions target to be reached by 2050, along with a cumulative GHG emissions limit of 8 Gt CO_2-eq between 2021 and 2050. The emissions budget is applied as a proxy for 'forcing decarbonisation', in the absence of which the model tends to delay decarbonisation action to reach net zero until the last five years and then faces extremely high and costly action those last five years to achieve the net zero target by 2050. While the modelling analysis does not include policy instruments such as a carbon tax ramp-up, this approach offers a proxy for such policy levers.

Social provisioning forms a central pillar of the Ideal Energy Scenario. Recognising that many low-income households remain reliant on coal and biomass for energy, the scenario introduces targeted interventions to expand clean, affordable energy access. These include a ramp-up in the free basic electricity (FBE) subsidy, deployment of 6.5 million solar water heaters (SWHs) for low-income households, and improvements in energy efficiency through enhanced building thermal performance and the adoption of efficient technologies such as LED lighting. The goal is to meet energy service needs while reducing energy poverty, indoor air pollution, and overall system demand. The approach taken for this is summarised below.

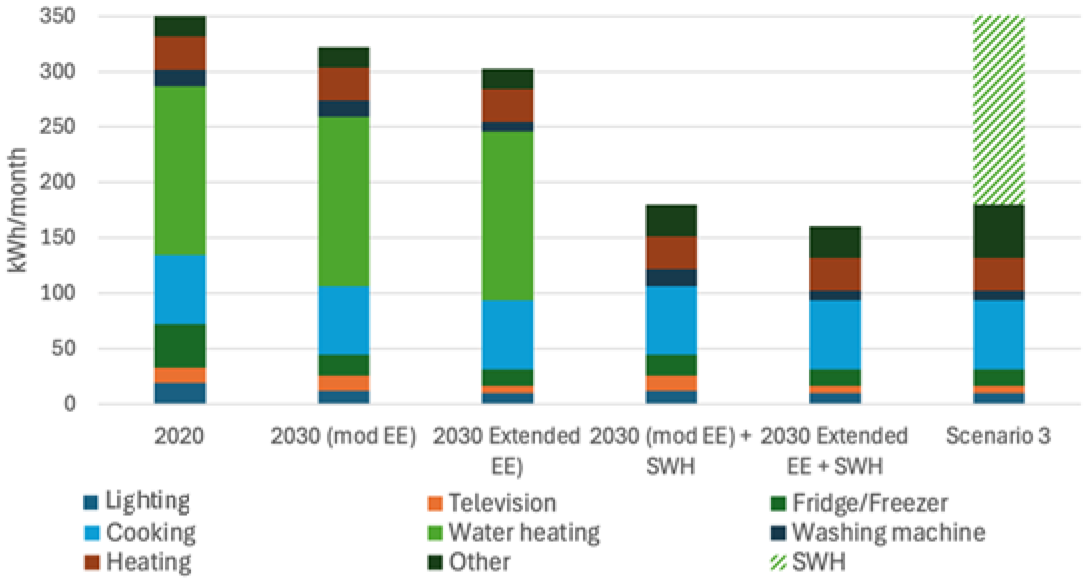

Figure 1: Effect of energy efficiency and SWH usage on household electricity usage

Transport reform is another key element of the Ideal Energy Scenario. A systemic shift is modelled from private to public transport modes, with the aim of reaching 80% public transport share by 2050. This is accompanied by significant electrification of both passenger and freight transport, excluding aviation. The scenario also envisages a transition in freight transport from road to rail, reducing fuel consumption and emissions. As a result, the total number of vehicles on the road in 2050 is lower than today, despite population and economic growth.

Industry and commercial sectors also undergo transformation. Through a combination of energy efficiency improvements and a shift from fossil fuels to electricity and green hydrogen, industrial energy intensity is reduced. Where feasible, industry switches from coal and diesel to electrified processes or low-carbon alternatives such as green hydrogen, particularly in hard-to-abate sectors.

To support economic development and resilience, the Ideal Energy Scenario incorporates a localisation component. A domestic clean energy manufacturing sector is established, with up to 85% local content in electricity technology supply chains such as solar PV and battery storage. This is intended to support job creation and enhance supply security, while reducing exposure to global supply chain volatility.

Figure 2: Transport mode shifting in the Ideal Energy Scenario compared to the Reference Case

On the supply side, the scenario restricts bioenergy to the use of alien invasive plant species only. This cap is designed to mitigate risks to biodiversity, land use and water systems that could arise from large-scale biomass cultivation. Hydrogen use (not necessarily 'green') is deployed for decarbonisation in hard-to-abate sectors, such as cement and iron and steel, but is not used for green exports, save for one sensitivity analysis where this is explored.

Key Modelling Results

The Ideal Energy Scenario shows a marked transformation in the energy system, with the following notable features:

- A rapid and sustained shift away from fossil fuels, with coal, oil and gas use declining significantly over time.
- Substantial energy efficiency improvements across all sectors, particularly households, commerce, and industry. These are modelled through a combination of structural change and adoption of efficient technologies, as well as widespread electrification. The results suggest existing energy efficiency policies and intentions could be significantly expanded to achieve greater sustainability (in terms of both emissions and cost savings).

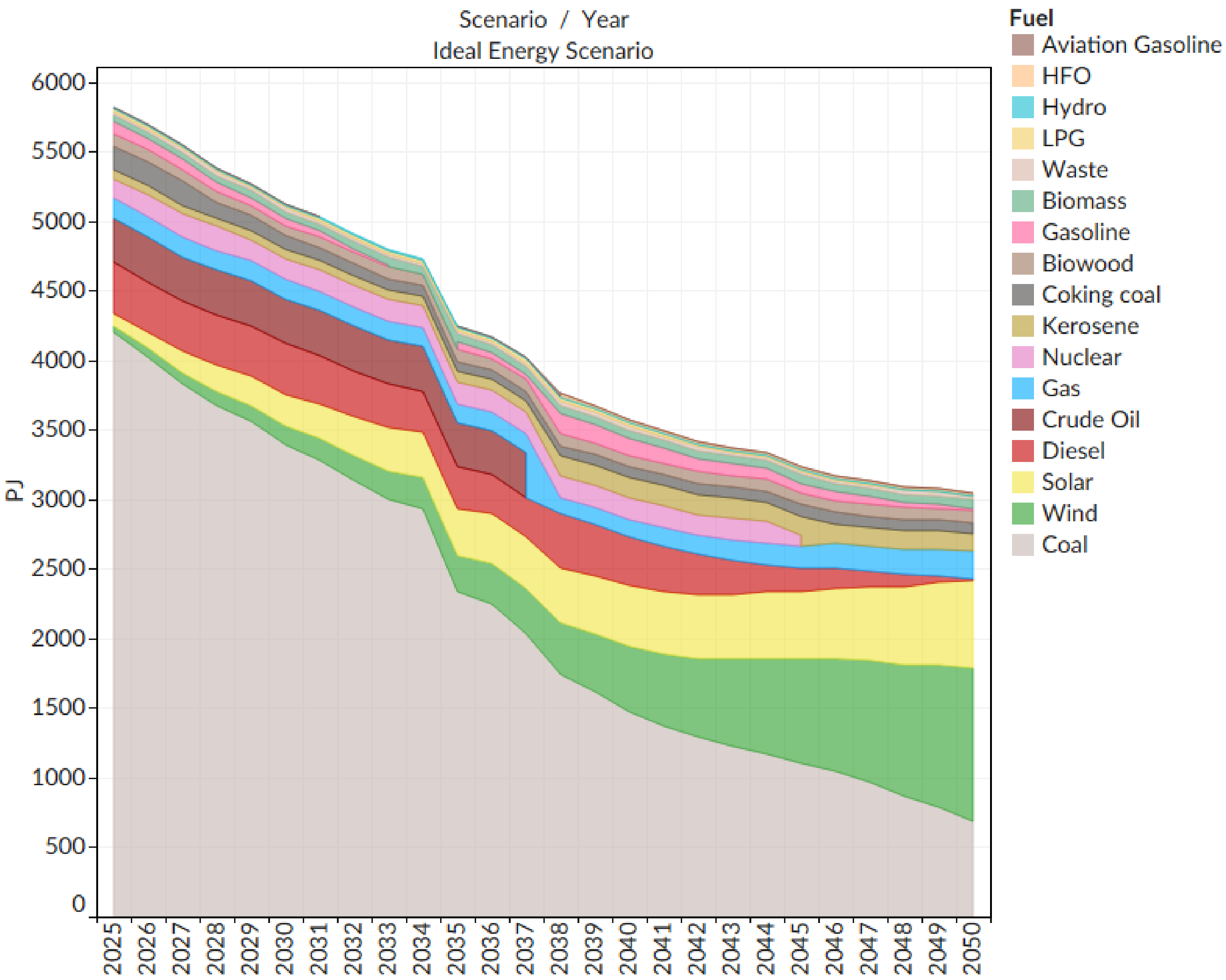

Figure 3: Primary energy supply for the Ideal Energy Scenario

- An electricity system dominated by renewable energy, primarily wind and solar PV. These are deployed in both centralised grid-scale form and distributed configurations such as rooftop PV. No new nuclear capacity is added, and gas plays a limited role as a backup and peaking resource. Sensitivity analysis shows that, where conditions might allow for a nuclear build programme, this would still have a negative effect on overall economic growth due to 'crowding out' of other economic investments by the high nuclear capital costs.

- While total energy system costs increase in absolute terms, these costs remain manageable, and don't differ significantly from the Reference Case. While greater investment is required in the power sector – the key driver of decarbonisation towards net zero – comparative savings can be realised through enhanced energy efficiency, particularly in industry and transport.

- Final energy demand is lower than in other pathways, despite improved access, due to structural efficiencies in transport and household sectors. Electrification of energy end-uses, particularly in industry and transport, provide significant gains in energy efficiency.

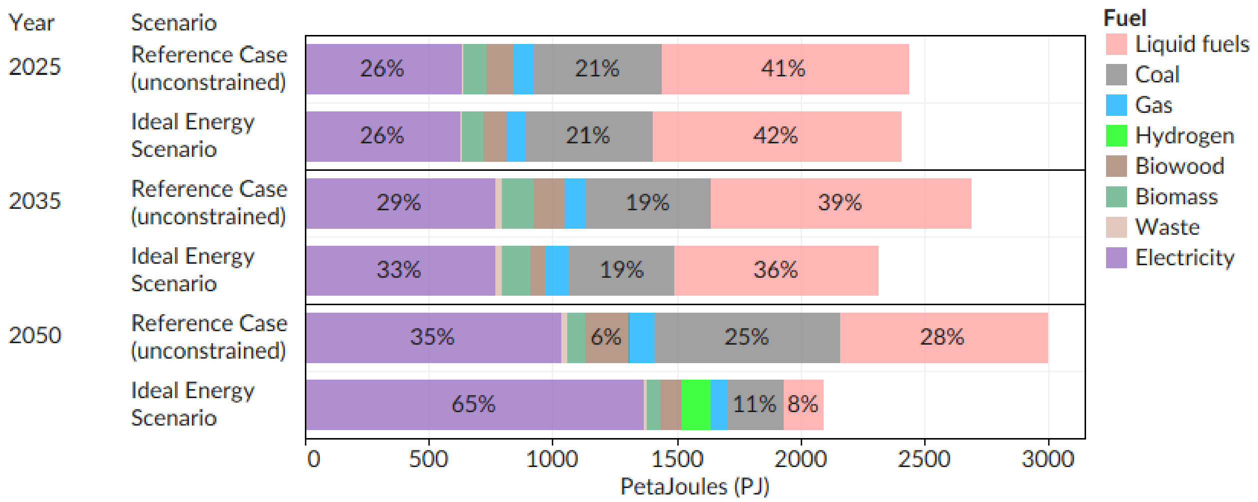

Figure 4: Final energy demand for the Reference Case and Ideal Energy Scenario

- Despite the imposition of the climate mitigation constraints, there is only a small drop in economic growth of the Ideal Energy Scenario relative to the Reference Case. Employment nearly doubles between 2025 and 2050 in the Ideal Energy Scenario and, although there is a small relative decline in economy-wide employment relative to the Reference Case, energy sector specific employment is increased, as a result of incorporating localisation measures into the clean electricity value chain.

Technology and Implementation Risks

Despite its benefits, the Ideal Energy Scenario introduces two key areas of technological uncertainty:

- The model relies on the deployment of carbon capture and storage (CCS) in key sectors to achieve net zero emissions. This introduces risks related to technology cost, performance, and availability at scale. In the absence of CCS, and a net zero target, results show that keeping within an emissions budget of 8 Gt CO_2-eq becomes more feasible from a cost perspective, but with some 80 Mt CO_2 emissions remaining in 2050.

- The analysis does not explicitly explore alternative configurations of coal-to-liquids (CTL) capacity or its retirement pathways, nor does it evaluate the extent to which the downstream chemicals industry would be affected by different CTL futures. The report does suggest that there is continued impetus for Sasol to consider expanding its low-carbon portfolio.

Limitations of the Modelling Framework

- The SATIMGE framework provides a robust platform for integrated energy-economy modelling, but it has limitations. These include:

- A lack of spatial resolution, meaning the model cannot assess regional land use, water impacts, or community-level effects of different technologies or infrastructure choices.

- No representation of the agriculture, forestry and land use (AFOLU) sector, nor of potential mitigation in livestock, food production, or diets.

- Transport infrastructure costs are included in aggregated form only; non-motorised transport options and detailed capital budgeting for rail and bus networks are not modelled.
- The model does not account for unmitigated climate change impacts or adaptation needs, which are critical to planning a resilient energy future.
- Pricing structures, tariff design and cost recovery mechanisms — including equity impacts of pricing reform — are outside the model's scope.

Areas for Further Research and Policy Development

Stakeholder engagement throughout the project highlighted a number of additional areas that merit deeper investigation:

- A comprehensive socio-economic analysis, including gendered impacts, youth employment, and rural equity, would be valuable to align energy planning with broader development goals.
- Just transition planning is essential to support workers and communities currently reliant on fossil fuel industries. The model assumes a smooth transition but does not simulate job creation or displacement at the sectoral level.
- There is a clear need for a Community Participation Framework to formalise how affected communities and citizens can shape energy policy and infrastructure development in practice.

Overall, the modelling confirms that an affordable, socially inclusive, and climate-aligned energy future for South Africa is possible. Achieving it will require decisive and early action, supported by deliberate public investment, institutional reform, and long-term vision. The Ideal Energy Scenario illustrates that it is not necessary to trade off decarbonisation against social development — with the right interventions, they can be achieved together. However, enabling this transformation will depend on the alignment of energy planning with broader questions of justice, inclusion, and participatory governance.

List of Acronyms

AFOLU	Agriculture, Forestry and Other Land Use
BESS	Battery energy storage system
(B)EV	(Battery) Electric Vehicle
BRT	Bus-rapid transit
CBAM	Carbon Border Adjustment Mechanism
CCGT	Combined-cycle Gas Turbine
CCS	Carbon Capture and Storage
CDR	Carbon Dioxide Removal
CGE	Computable General Equilibrium
CO	Carbon Monoxide
CO_2	Carbon di-oxide
CO_2-eq	Carbon dioxide equivalent
CH_4	Methane
CSIR	Council for Scientific and Industrial Research
CTL	Coal to Liquid
DFFE	Department of Forestry, Fisheries and the Environment
DMRE	Department of Mineral Resources and Energy (pre-June 2024)
DoEE	Department of Energy and Electricity (post-June 2024)
DST	Department of Science and Technology
EE	Energy Efficiency
EJ	Exajoule (1000 Petajoules)
EPRI	Electric Power Research Institute
eSAGE	energy South African General Equilibrium
ESM	Earth System Model-based framework
ESRG	Energy Systems Research Group
EVs	Electric Vehicles
FBE	Free Basic Electricity
GDP	Gross Domestic Product
Gt	Giga-tonne
GHG	Greenhouse gas
GJ	Gigajoule (1 billion Joules)
GMP	Gas Mater Plan
GUMP	Gas-Utilisation Master Plan
GVA	Gross Value Add
GW	Gigawatt
GWP	Global Warming Potential
HCV	Heavy commercial vehicle (HCV1 = class 1, HCV2 = class 2, etc. up to HCV9)
ICE	Internal combustion engine
IEA	International Energy Agency
IEP	Integrated Energy Plan
IPCC	Intergovernmental Panel on Climate Change
IPEP	Illustrative People's Energy Planning
IPPU	Industrial Process and Product Use
kW	Kilowatt (measure of power / electricity demand or supply)
kWh	Kilowatt-Hour
LCV	Light commercial vehicle
LNG	Liquified natural gas
LPG	liquified petroleum gas
MJ	Megajoule (1 million Joules)
MR	Million 2022 ZAR
Mt	Mega-tonnes
Mtpa	Mega-tonnes per annum
MW	Megawatt
NBI	National Business Initiative
N_2O	Nitrous oxide emissions
NEES	National Energy Efficiency Strategy

NREL	National Renewable Energy Laboratory
NOx	Nitrogen gases
p.a.	Per annum
PARI	Public Affairs Research Institute
PassPriv	Private passenger vehicle usage (see Transport figures)
PassPub	Public passenger transport demand (see Transport figures)
PJ	Petajoule (1000 Terajoules)
pkms	Passenger kilometres
PM10	Particulate Matter
PV	Photovoltaic
RE	Renewable Energy
REIPPPP	Renewable Energy Independent Power Producer Procurement Programme
SAFCEI	Southern African Faith Communities' Environment Institute
SANS	South African National Standard
SATIM	South African TIMES model
SATIMGE	South African TIMES model – computer Generated Equilibrium
SMR	Small modular reactor
SOx	Sulphur gasses
SUV	Sports utility vehicle
SWH	Solar Water Heater
TIPS	Trade & Industry Policy Strategies
TJ	Terajoule (1000 Gigajoules)
TWh	Terawatt-Hour (measure of electricity – 1 TWh = 3600 TJ)
UN	United Nations
WWF	World Wide Fund for Nature South Africa

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ENERGY SYSTEMS RESEARCH GROUP

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1. Introduction

This report serves as the final technical input provided by the Energy Systems Research Group (ESRG) to inform and support the ***Illustrative People's Energy Planning*** project (IPEP) led by World Wide Fund for Nature (WWF) South Africa. This technical report provides a comprehensive account of the scenario analysis and modelling work undertaken for this project, in order to inform the evidence base for the potential development of an ideal energy scenario as part of the IPEP project. The report represents the culmination of the ESEG's technical modelling analysis for the IPEP project and focuses on technical modelling results. An exploration of the policy implications and potential recommendations stemming from this work is documented in a separate policy paper, which complements this report.

1.1. Background

On 28 April 2023, following legal action by The Green Connection and the Southern African Faith Communities' Environment Institute (The Green Connection and SAFCEI, 2023), President Cyril Ramaphosa published a proclamation in the Government Gazette for the commencement of Section 6 of the National Energy Act of 2008 (Presidency, 2023; South Africa, 2008), which mandates the development and annual review and publication of the *Integrated Energy Plan* (IEP) for South Africa. The Act stipulates *inter alia* that the IEP "must have a planning horizon of no less than 20 years" and "must deal with issues relating to the supply, transformation, storage of and demand for energy in a way that accounts for

(a) security of supply.
(b) economically available energy resources.
(c) affordability.
(d) universal accessibility and free basic electricity.
(e) social equity.
(f) employment.
(g) the environment.
(h) international commitments.
(i) consumer protection; and
(j) contribution of energy supply to socio-economic development."

In response, WWF initiated **Illustrative People's Energy Planning** project (IPEP). The purposes of the IPEP are to provide an illustrative example of evidence-based, participatory and transparent energy planning, to engage with a broad and diverse set of stakeholders with interests in the process and outcomes of South African energy planning, and to enable stakeholders to engage meaningfully with the development and outcomes of the formal IEP process as it unfolds.

This includes equipping stakeholders in civil society and other advocacy and activism roles with information and understanding to interrogate and engage meaningfully with the formal IEP process, and to allow public participation that ensures the aspirations and priorities of all South Africans can be reflected in the energy planning process – i.e. that the IEP "leaves no one behind".

ESRG was appointed by WWF to provide technical analysis, in the form of long-term energy scenario modelling analysis, to equip stakeholders with an evidence base and analytical tools to support their engagement with the IEP and national energy dialogue more broadly.

ESRG is not developing either the "official IEP" or an "alternative IEP" through this work. The aim of the ESRG's work is to provide technical assistance, in the form of evidence-based energy systems modelling, to support and inform the IPEP project, and enable stakeholders to engage meaningfully with the official IEP process.

1.2. Scope and Limitations

This project is intended to provide an evidence base to inform the development of the official Integrated Energy Plan for South Africa, when its development commences, through the development of an evidence base that maps South Africa's trajectory to net zero CO_2 emissions among other key development and energy policy objectives and compares it to potential energy pathways based on current policy projections. As part of this process, the project team has aimed to illustrate how stakeholder engagement and participation can and should inform analysis and development of energy policy in order to enable energy planning to respond to the goals, objectives and aspirations of as wide a range of stakeholders as possible.

The complex interaction between energy and other sectors of society, especially in South Africa, make defining an 'ideal energy future' a non-trivial matter. It requires building an understanding and making decisions on trade-offs that may benefit some stakeholders at the cost of others or may require compromises in finding an optimal balance of outcomes that can achieve meaningful progress in energy access and development, while minimising costs as well as health and environmental impacts, and ensuring energy security.

This process is made more complicated at a time when energy systems world-wide, and particularly in South Africa, are already undergoing fundamental transitions away from historic 'central-planning-and-distribution' systems to more disaggregate and decentralised systems. The rapid advancement and cost reduction of technologies, such as electric vehicles (EVs) and solar PV-battery systems, provide greater opportunities for clean energy development and decentralised systems, that allow for community-level ownership and engagement that may not have been possible previously – for example, community-owned mini-grids powered by solar PV. However, this also poses new questions and challenges for energy models, which have to adapt continuously in order to reflect and keep up with the new realities developing on the ground.

The SATIMGE model, applied in this work, has been developed over the better part of two decades, using the IEA-ETSAP TIMES modelling infrastructure at its core for performing least-cost optimisation analysis of future energy pathways in South Africa. Over time, and with the additional linkage of the Treasury-developed South African General Equilibrium (SAGE) economy model, SATIMGE has been able to analyse the links between energy sector developments and (largely macro-economic and high-level) economic impacts, a capability which is continually improving with continued model development and the availability of new and better data.

However, the South African TIMES model (SATIM) is still largely rooted in the 'conventional' central planning approach to energy modelling, and the sophistication of the link to the CGE model remains fairly limited at lower levels of disaggregation. As the energy sector evolves, so SATIMGE will need to adapt and evolve to accommodate and analyse these new energy paradigms, and this is a process that will continue over time.

For the purposes of this project and providing some insight into the opportunities and challenges for integrated energy planning in the short and particularly long-term in South Africa, the SATIMGE model has been used to illustrate potential energy pathways, at a high and more granular sectoral level. This has been done in two phases:

- Firstly, an assessment of the *status quo* of South Africa's energy system and the current prevailing and potential policies and measures that are being considered in contemporary policy discourse, and

- Secondly, on defining an 'ideal' future energy scenario in terms of meaningful energy, development, climate and socio-economic indicators that would reflect a good, or at least better by today's standards, life for all.

The latter, ideal energy scenario, is further unpacked through a series of sensitivity analyses to explore specific uncertainties – known and unknown unknowns – that may impact on the long-term outcomes of such an energy pathway.

Defining an 'ideal energy scenario' is an inherently challenging and contestable task. The term itself – "ideal" – is highly subjective and cannot be strictly or universally defined in an energy (or, indeed, many other) context(s). After all, what is 'ideal' to person A may not be ideal to person B. In the South African energy context, there are numerous trade-offs that have to be taken into account when conceptualising an 'ideal' energy system – e.g. minimising energy costs and emissions whilst maximising employment; choosing whether to support local EV manufacturing, or a local transition to green hydrogen, or both – and then deciding what other sectors may thus have to receive less support under the confines of a constrained and ever more challenging fiscal environment.

The approach taken in this work has been to attempt to define a set of parameters that would constitute an 'ideal' energy future for South Africa, based on a collection of inputs provided by project stakeholders and partners at various stages (most notably, the Stakeholder Workshop held in January 2025) that have been 'converted' into quantifiable indicators that can be modelled and assessed in the SATIMGE modelling framework. It should be noted that not all inputs and factors can be readily quantified in modelling, and in particular some aspects cannot be analysed in the SATIMGE modelling framework – for example, detailed social justice factors (e.g. on gender or youth impacts), extensive externality impacts or community-level planning.

For example, a "wholesale shift to public transport" has been modelled as reaching a state in 2050 where 80% of land passenger transport, as measured by the 'passenger-kilometre' (pkm) metric, is provided by public transport options, including rail, buses, bus-rapid-transit and (less so than today) minibus taxis (the role of which remains contentious). Doubtless, this will not go far enough for some stakeholders, who might want to see 90% or even 100% public transport by 2050; whilst others may wish to see a greater long-term future for continued private transport and rather prefer a scenario that shows 100% of the population owning an EV by 2050. Such a decision is highly important and influential for policy-making, as it would inform whether, for example, South Africa provides large sums of financial support to local OEMs to develop domestic EV manufacturing capacity, or whether it instead uses those resources to build large sections of new rail and bus infrastructure (the latter then being fulfilled by a continuation of imported buses, with the corresponding reduction in private domestic market potentially leading to OEM plant relocations, and ensuing job and revenue losses).

The SATIMGE model cannot fully analyse or comprehend all of these and other interrelated trade-offs for long-term energy policy, and indeed no single energy model can do this completely and effectively. Within the confines of the existing model capability, what this project *has* done is characterised a set of parameters for a version of an 'ideal energy scenario', that broadly but not universally aggregates the many inputs, suggestions and aspirations of stakeholders, and then modelled a set of energy pathways to reach that future. The modelling, using the SATIMGE framework, has been based on the principles of least-cost optimisation, and rests on a wealth of data and assumptions about current and future energy technology stocks, performance, efficiencies and costs, fuel costs, energy access, needs and uses, and corresponding potential impacts on emissions (greenhouse gas and air pollutant), energy prices and investment needs, and socio-economic impacts (employment, inequality and GDP), among others.

Analysis of the results of modelling all of the above factors is provided in this report. Additional analysis on policy implications and recommendations derived from this work is provided in a separate but complementary policy paper. Additionally, a summary of results of the scenario modelling are provided in a supplementary Results Framework, whilst more detailed result data can be viewed in a supplementary online dashboard.

At this juncture the technical work of the modelling team for the wider Illustrative People's Energy Planning project reaches its conclusion. Subsequent interpretation of the results and evidence generated in this work, and their use in advocacy or further engagement with energy planning and policymaking, including the official IEP, is left to WWF and other project partners and stakeholders. This includes aspects of participatory energy planning, such as just transition planning and implementation, and community-centred planning, for example through the development and implementation of a Community Participation Framework. These elements are undoubtedly critical for ensuring fully participatory and inclusive energy planning and giving meaning and direction to the concept of "leaving no one behind" but fall beyond the scope of the technical work of this project.

The material generated in this project is intended to provide stakeholders with an understanding of current and future dynamics and indicators in the South African energy system, and to illustrate some of the factors and issues that should be considered in national energy planning and modelling, while the process of developing and modelling the ideal energy scenario aimed at demonstrating how such energy modelling can be conducted in an inclusive and participatory manner. However, it must be fully recognised that the model work presented here can and should not by any mean be considered an exhaustive analysis of the South African energy landscape or future, and further that the stakeholder engagement conducted in this work reflects a small microcosm of the wider public engagement that is required for such a process to be considered truly inclusive and participatory.

1.3. Objectives of this report

The objectives of this report are as follows:

- To provide a full overview of the scenario approach applied in this project, and to describe in brief the modelling methodology as well as key parameters and assumptions applied to the various scenarios (including articulating the boundaries for the scope and limitations of the modelling analysis in this work)
- To provide a recap (updated from previous reports) of the Set 1 (Reference Cases) modelling results, as well as reference to the Set 2 (Policy Scenario) modelling reported previously
- To present the analysis and results of the additional Policy Scenario, namely the Social Provisioning scenario, which directly informs the electricity access and social provisioning component of the Ideal Energy Scenario
- Present the full description, analysis and modelling results of the Set 3 scenario package, namely the Ideal Energy Scenario as well as the various accompanying sensitivity analyses
- Provide a comprehensive set of key data and assumptions that informed the scenario modelling process
- Provide discussion and qualitative analysis on stakeholder-led energy planning and risk analysis, particularly for matters of energy planning that go beyond quantifiable modelling

This report should be read in conjunction with and in the context of the project Methodology Report, the report on Set 1 (Reference Case) and Set 2 (Policy Scenario) modelling and results, and all other project publications to date.

2. Methodology

A Methodology Report for this project was issued in June 2024 (ESRG, 2024), which describes the details of the SATIMGE modelling framework and methodology, as well as key data and assumptions. The intention here is not to repeat what is already covered in that document, but to highlight where the methodology has evolved based on stakeholder needs and preferences since the first iteration of the report, specifically focusing on:

- Scenario development
- Modelling methodology and assumptions
- The Results Framework

2.1. Scenario development

Long-term scenario analysis forms the basis of integrated energy planning (Akom et al., 2021; Eberhard, 2017). Scenarios can be defined to illustrate potential futures of the energy system, encompassing demand and supply, in terms of a range of characteristics or outcomes over the duration of the modelling horizon.

Scenarios can be set up to identify and analyse the impact of potential policy measures, development pathways, aspirations and/or other key uncertainties, to support in building an understanding of how potential futures may play out. It should also be noted that the main use of the scenario analysis process in integrated energy planning is not in interpreting the results in a predictive sense, but rather in unpacking the trade-offs and synergies and identifying risks and mitigation strategies to inform planning decisions.

In this project, the scenario analysis has been divided into three 'sets', as outlined in Table 2. The set-up for each set of scenarios, as well as their results, are described in the subsequent sections for each set, namely section 3 (Set 1, Reference Cases), 4 (Set 2, Policy Scenarios) and 5 (Set 3, Ideal Energy Scenario and sensitivity analyses). Table 3 shows the full matrix for all scenarios and cases modelled and analysed in this work.

Table 2: Overview of Scenario Sets

Scenario Set	Name	Description
Set 1	**Reference Cases**	Allowing the model to build the energy sector based only on least-cost optimisation, firstly without emissions constraints and secondly with net zero carbon emissions in 2050 and cumulative emissions constraints.
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Set 3	**Ideal Energy Scenario**	Modelling the energy system based on 'ideal' characteristics and outcomes expressed by participants at the Stakeholder Scenario Workshop, with sensitivity analysis for key uncertainties.

The scenarios and runs are described in more detail in each of the subsequent results sections – Section 3 (Reference Cases), Section 4 (Policy Scenarios) and Section 5 (Ideal Energy Scenario).

2.1.1. Is Full scenario matrix

Table 3 below shows a matrix of all the scenarios explored and modelled in this project, with key modelling parameters that are adjusted for each scenario. The left-hand column shows the specific scenario parameter, and each subsequent column shows how that parameter is handled for each scenario. The code row refers to the labelling for each of the scenarios in the subsequent analysis figures in this report.

Table 3: Full scenario matrix

Element	Set 1: Reference Cases		Set 2: Policy Scenarios				
	Reference - Unconstrained	Reference - Net Zero 08 Gt	Policy - Big Gas	Policy - Green Hydrogen	Policy - Green Transport	Policy - Efficiency	Policy - Social Provisioning
CODE	IEP-1a-REF-UNCONS	IEP-1b-REF-NZ08GT	IEP-2a-POL-BIG-GAS	IEP-2b-POL-GRN-HYD	IEP-2c-POL-GRN-TRA	IEP-2d-POL-EFFNCY	IEP-2e-POL-SOCIAL
Discount Rate	8.2%	8.2%	8.2%	8.2%	8.2%	8.2%	8.2%
Net Zero CO2 by 2050	N/A	Yes	N/A	N/A	N/A	N/A	N/A
Cumulative GHG budget (2021-2050)	N/A	8	N/A	N/A	N/A	N/A	N/A
Indigenous Gas Supply	Ibhubesi available only from 2037 (Brulpadda and other domestic offshore gas options excluded)	Ibhubesi available only from 2037	Ibhubesi available early (2027)	Ibhubesi available only from 2037	Ibhubesi available only from 2037	Ibhubesi available only from 2037	Ibhubesi available only from 2037
Green Transport options	No policy	No policy	No policy	No policy	Moderate shift (policy scenario)	No policy	No policy
Energy Efficiency	No policy	No policy	No policy	No policy	No policy	Moderate shift (policy scenario)	No policy
Green hydrogen exports	Not included	Not included	Not included	Included	Not included	Not included	Not included
Social provisioning (increased FBE and SWH for low-income households)	Not included	Not included	Not included	Not included	Not included	Not included	Included
Biomass supply	Unconstrained	Unconstrained	Unconstrained	Unconstrained	Unconstrained	Unconstrained	Unconstrained
Oil and Gas Prices	Constant	Constant	Constant	Constant	Constant	Constant	Constant
CTL endogenous retirement allowed from	2034	2034	2034	2034	2034	2034	2034
Localisation	Low	Low	Low	Low	Low	Low	Low
Battery cost learning	Conservative	Conservative	Conservative	Conservative	Conservative	Conservative	Conservative

Table 3: Full scenario matrix (cont'd)

Element	Set 3: Ideal People's Energy Scenario + Sensitivities										
	Ideal Scenario	**Ideal Sensitivity - 9Gt**	**Ideal Sensitivity - 7Gt**	**Ideal Sensitivity - No CCS**	**Ideal Sensitivity - Low Localisation**	**Ideal Sensitivity - Early CTL Phase out**	**Ideal Sensitivity - Late CTL Phase out**	**Ideal Sensitivity - Low Fossil Fuel prices**	**Ideal Sensitivity - Low Disc Rate**	**Ideal Sensitivity - High Disc Rate**	**Ideal Sensitivity - Green Exports**	**Ideal Sensitivity -Opt. Battery learning**
CODE	**IEP-3a-SCN-IDEALS**	**IEP-3b-SEN-GHG9GT**	**IEP-3c-SEN-GHG7GT**	**IEP-3d-SEN-NOCCST**	**IEP-3e-SEN-LOLOCL**	**IEP-3f-SEN-ECTL29**	**IEP-3g-SEN-ECTL45**	**IEP-3h-SEN-LOWFFP**	**IEP-3k-SEN-LOWDRT**	**IEP-3m-SEN-HIGDRT**	**IEP-3n-SEN-HIGGXT**	**IEP-3p-SEN-LOBATC**
Discount Rate	8.2%	8.2%	8.2%	8.2%	8.2%	8.2%	8.2%	8.2%	3.0%	12.0%	8.2%	8.2%
Net Zero CO2 by 2050	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Cumulative GHG budget (2021-2050)	8	9	7	8	8	8	8	8	8	8	8	8
Indigenous Gas Supply	(De-fault) Ibhubesi available only from 2037	Ibhubesi available only from 2037	Ibhubesi available only from 2037	Ibhubesi available only from 2037	Ibhubesi available only from 2037	Ibhubesi available only from 2037	Ibhubesi available only from 2037	Ibhubesi available only from 2037	Ibhubesi available only from 2037	Ibhubesi available only from 2037	Ibhubesi available only from 2037	Ibhubesi available only from 2037
Green Transport	High (Ideal scenario shift)	High (Ideal scenario shift)	High (Ideal scenario shift)	High (Ideal scenario shift)	High (Ideal scenario shift)	High (Ideal scenario shift)	High (Ideal scenario shift)	High (Ideal scenario shift)	High (Ideal scenario shift)	High (Ideal scenario shift)	High (Ideal scenario shift)	High (Ideal scenario shift)
Energy Efficiency	High (Ideal scenario shift)	High (Ideal scenario shift)	High (Ideal scenario shift)	High (Ideal scenario shift)	High (Ideal scenario shift)	High (Ideal scenario shift)	High (Ideal scenario shift)	High (Ideal scenario shift)	High (Ideal scenario shift)	High (Ideal scenario shift)	High (Ideal scenario shift)	High (Ideal scenario shift)
Green hydrogen exports	Not included	Not included	Not included	Not included	Not included	Not included	Not included	Not included	Not included	Not included	Included	Not included
Social provisioning (FBE)	Included	Included	Included	Included	Included	Included	Included	Included	Included	Included	Included	Included
Biomass supply	Limited	Limited	Limited	Limited	Limited	Limited	Limited	Limited	Limited	Limited	Limited	Limited
Oil and Gas Prices	Constant	Constant	Constant	Constant	Constant	Constant	Constant	Low	Constant	Constant	Constant	Constant
CTL endogenous	2034	2034	2034	2034	2034	2029	2045	2034	2034	2034	2034	2034

retirement allowed from												
Localisation	High	High	High	High	Low	High	High	High	High	High	High	High
Battery cost learning	Conservative	Conserva-tive	Conserva-tive	Conserva-tive	Conserva-tive	Conserva-tive	Conserva-tive	Conserva-tive	Conserva-tive	Conserva-tive	Conserva-tive	Optimistic

2.2. Least-Cost Energy Modelling

This sub-section provides a brief description of the SATIMGE modelling framework and its limitations. For a full description of the model methodology, see the Project Methodology Report. Key assumptions are provided here, with a more comprehensive set of data and assumptions provided in **Appendix A**.

2.2.1. SATIMGE

The modelling framework used for the technical analysis in this project is the ESRG's SATIMGE model framework. The model is described in full detail in the Methodology Report, as well as a recently published journal paper (Hughes et al., 2024). A brief recap is provided below.

The SATIMGE framework consists of the following components:

1. **The South African TIMES model ('SATIM')**: a bottom-up least-cost energy systems optimisation model for the South African energy system that comprises multiple energy demand (agriculture, commerce, industry, residential and transport) and supply (electricity, liquid fuels refining and primary energy extraction) sectors.

   SATIM is single-region – i.e. it does not include a spatial component – but defines each sector bottom-up from demand and supply technologies. The model base year is calibrated to the 2017 energy balance (the last year before Covid and sustained load shedding) and solves least-cost energy pathways for the modelling horizon using linear programming algorithms.

2. **The energy South African General Equilibrium ('eSAGE') model**: a dynamic, recursive, country-level CGE model that simulates the South African economy. eSAGE is calibrated to the South African's Treasury's Social Accounting Matrix (SAM) and includes 104 sectors and commodities and 5 factors of production (capital and labour divided into 4 groups based on skills level).

3. **Simulation models for greenhouse gas emissions from the waste and AFOLU sectors** (energy and IPPU emissions are included in SATIM).

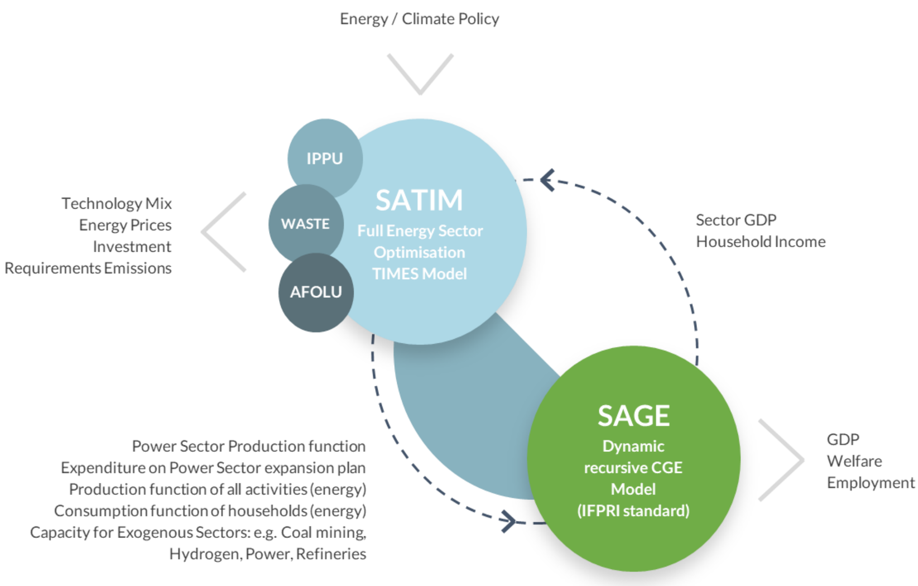


Figure 5: SATIMGE modelling framework

These models (1 and 2 above) are linked together and solved iteratively, so that shifts in energy pathways from least-cost optimisation in SATIM lead to updated economic drivers (GDP and fuel costs), which in turn lead SATIM to rebalance around a new optimal least-cost point. This unique model configuration mimics and captures how the economy and economic agents (consumers, producers, etc.) would respond to changes in energy prices and in-turn provides a more responsive view of the energy pathway in the longer term.

2.2.2. Key assumptions

Table 4 shows key assumptions applied in the modelling analysis for all scenarios shown in Table 3, unless where specifically stated otherwise. Table 29 shows the emissions factors applied for all combustion and process emission processes. Figure 7 shows the domestic carbon tax applied for all scenarios. Detailed assumptions for the electricity and other sectors are provided in Appendix A.

Table 4: Overview of key assumptions

Assumption/Indicator	Description
Base GDP growth	Calibrated to 2024 Budget forecasts (National Treasury, 2024a)) up to 2028, rising to 3.5% y/y by 2035, and constant thereafter (see detailed description in Appendix A)
Base year	2017
Carbon, Capture and Storage (CCS)	CCS is available with 90% 'efficiency' (i.e. captures 90% of CO_2 emissions), available from 2035, for CCGT power tech as well as Iron and Steel, Cement and Ferroalloy industry sectors Assumed carbon would be stored in the Durban basin Costed are estimated based on EPRI (EPRI, 2017) and World Bank studies (Beck et al., 2017). Electricity intensity, heat requirements, and capture efficiency data sourced from EPRI for the 2019 IRP (EPRI, 2017) and Danish Energy Agency: Carbon Capture and Storage report (The Danish Energy Agency, 2024) Total costs for capture, transport and storage are assumed constant, as follows: - Power sector: 674 ZAR/tCO2 - Iron and steel: 587 ZAR/tCO2 - Ferrochrome: 587 ZAR/tCO2 - Cement: 670 ZAR/tCO2 The risks associated with CCS as a potential, and at this stage non-commercial technology, are discussed in the results for the Ideal Energy Scenario in Section 5.
Coal prices	Modelled at individual mine level based on mine contract data, not for disclosure
Coal-to-liquids refineries	Allowed to retire endogenously from 2034
Crude Refineries	Atlantis and Natref operate until 2036; other closed refineries remain closed; no new crude refining capacity
Discount Rate	8.2% (two sensitivities in Set 3 explore a high – 12% - and low – 3% - discount rate; the latter should not be confused with a 'social' discount rate, which is not examined in this work.
Domestic Gas Options	Ibhubesi (29 PJ/a) comes online from 2037 (delayed by 10 years relative to the draft GUMP (DMRE, 2024a)), fully available by 2040

Assumption/Indicator	Description
	This assumption is made on the basis of consultation with industry experts who anticipate a ten-year window for Ibhubesi operations to fully come online.
Fuel import prices	International crude oil price constant at $75 per barrel (higher than IEA projections across all their scenarios (IEA, 2024a)) Local and regional LNG prices set at 121 R/GJ (2022 ZAR) excl. pipeline costs (further costed at 94 million 2022-rands [MR]/PJ-a). Note the Petajoule-annum is a unit used in TIMES modelling to indicate capacity of infrastructure – i.e. LNG pipeline costing is dependent in SATIM on the cumulative volume of gas flow through the pipeline. LNG import costs set to constant 160 R/GJ These costs are combined in SATIMGE, depending on gas usage, to estimate overall gas costs.
GHG emissions	SATIMGE optimises GHG emissions for energy and IPPU, in terms of GWP-100 CO_2eq (IPCC, 2022a); it does not optimise CH_4 and N_2O emissions from Waste and AFOLU, but assumes these scale with demand (which is assumed directly proportional to economic growth). See emission factors for GHGs and air pollutants inTable 29 in Appendix A.
Net land sink	Assumed constant -10 Mt CO_2, a conservative estimate derived from the baseline work of Stevens et al. (2016). Note that the true size and potential of the land sink is highly uncertain and a key source of variability for net zero planning (Crisp et al., 2022; Dooley and Kartha, 2018). Revisions of the land sink are ongoing as part of continuing work on South Africa's climate change strategies and analyses (see e.g. DFFE, 2024).
Population Growth	UN 2022 World Population Prospects (grows to 58 million 2019 to 73.5 million by 2050) (UN, 2022)

It should be noted in Table 4 that import fuel prices are set at constant levels. Whilst this does not reflect reality – global oil and gas prices fluctuate constantly and are particularly volatile to international market dynamics and geopolitical events – it is difficult to replicate the 'randomness' of this behaviour in the existing SATIMGE set-up. Therefore, for sake of simplicity, prices here are assumed to be constant and, in the case of oil, conservatively assumed at a higher level than the future average projections provided by the IEA.

All scenarios (Reference, Policy Scenarios and Ideal Energy Scenario and sensitivities) assume a fixed annual new build of rooftop PV over the modelling horizon, ramping up from 500 MW per annum in 2026 to 900 MW by 2030, and then plateauing (Figure 6). Rooftop PV build is fixed in SATIM as the model cannot otherwise optimally select its use, relative to utility-scale PV. The level of 900 MW per annum reflects recent discussions surrounding the ongoing development of the Integrated Resource Plan for electricity (IRP), as well as short and long-term estimates of South African rooftop PV potential – see, for example, Senatla et al. (2020).

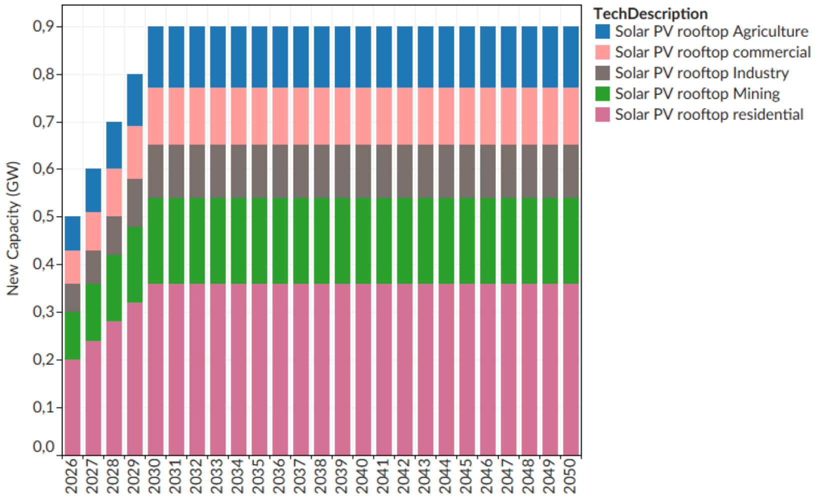


Figure 6: Rooftop PV new build (annual additional, not total/cumulative) capacity assumed for all scenarios

A base carbon tax is assumed for all scenarios, based on the current (low) effective rate after factoring in existing allowances. The rate, shown in Figure 7, is applied consistently to all CO_2 emissions for all scenarios. This analysis did not examine the effects of ramping up the carbon tax for emissions-constrained scenarios – rather, for emissions-constrained scenarios, a cumulative greenhouse gas limit is applied over the duration of the modelling horizon, which has a similar effect to a high carbon tax of forcing decarbonisation in the South African energy system. It should be noted that detailed analysis of the carbon tax, whilst beyond the scope of this work, would require analysis of how carbon tax revenue can be recycled to support complementary policy measures, and could, for instance, support the social provisioning measures analysed in this work.

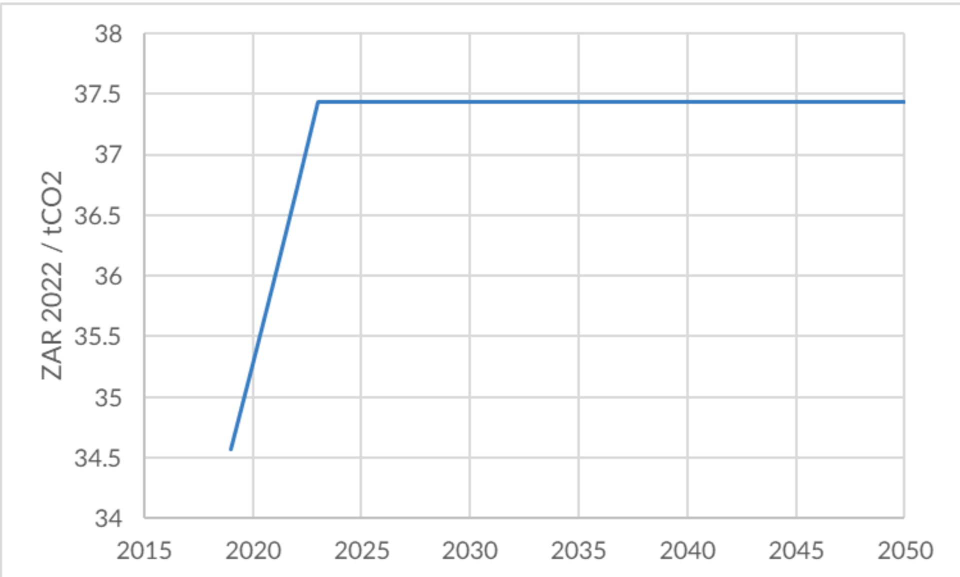


Figure 7: Assumed constant carbon tax, applied to all CO_2 emissions

For most scenarios, battery storage CAPEX prices are assumed to follow a conservative learning trajectory based on IRENA analysis. The set 3 scenario analysis includes one sensitivity run with a more optimistic learning trajectory.

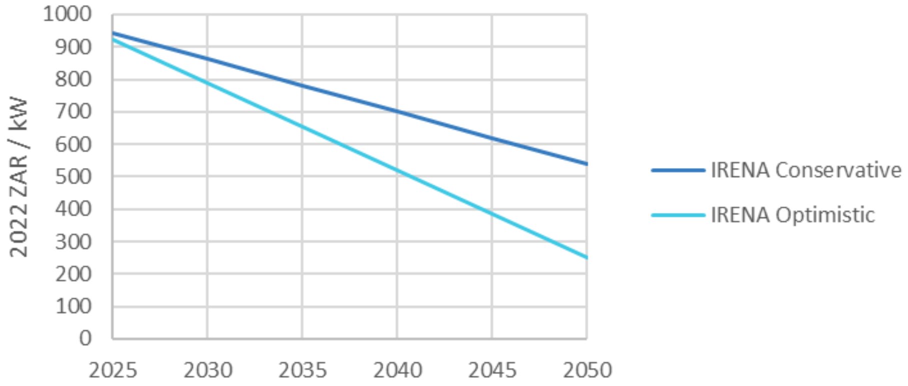


Figure 8: Battery learning costs

2.2.3. Limitations

Energy models, such as the SATIMGE developed and applied in this work, provide meaningful analysis of the potential development and continued evolution of global and national energy systems. The strength of SATIMGE, and similar full sector models, lies in the ability to compare indicators across a range of areas – energy, as well as emissions, development, employment and economy – between different scenarios and based on different input data and assumptions. However, no single computational model can comprehensively assess *all* the myriad factors and elements that need to be taken into account for developing a comprehensive understanding of the energy system and its interconnections with other aspects of society.

Some energy models are better equipped at handling relatively smaller components within a wider energy system – for example, PLEXOS electricity dispatch modelling used by the developers of the Integrated Resource Plan (IRP) to develop and analyse future electricity build paths.

The South African TIMES model does not have the granular (hourly) resolution of a PLEXOS dispatch model but does provide a bottom-up representation of South Africa's entire energy sector – encompassing all energy carriers, end-users and supply options, at up to stock- and technology-level disaggregation where possible. The model is therefore able to compute least-cost pathways from a range of different supply options to meet present and future demand needs.

There are a number of key areas that the SATIMGE modelling framework cannot analyse quantitatively, that are still important for consideration in energy planning and in the development of an integrated energy plan. Some of these issues were specifically highlighted by stakeholders, whilst others reflect common limitations in full sector single-node energy modelling. These are as follows:

Spatial planning

SATIM is currently modelled as a single region, without a detailed spatial representation of the locations of energy users or energy supply technologies. Such a representation is particularly useful for modelling the large-scale deployment of renewable energy systems, as climate and weather patterns vary considerably by geography, such that, for example, a PV system in the Northern Cape will likely operate at a higher capacity factor than an equivalent system in Kwa-Zulu Natal. This is also relevant in short-term electricity modelling, given the existing prevailing grid constraints in some parts of the country – like the Northern Cape – where renewable resources are most abundant.

In an effort to provide some spatialisation analysis of renewable energy, SATIM has introduced different renewable resource profiles and availability assumptions for different provinces. Additional constraints have been placed on the deployment of capacity in the short-term in areas where the grid is currently constrained – i.e. the Northern, Western and Eastern Cape grid areas – which forces the model to focus its build of renewable energy in more 'expensive' areas, such as Limpopo and Kwa-Zulu Natal. These constraints are implemented according to data provided in the Eskom Transmission Development Plan 2025 – 2034 (Eskom, 2024a) and the Eskom Generation Connection Capacity Assessment (GCCA) 2025 (Eskom, 2023).

Tax effects

The model excludes the imposition of taxes such as VAT, fuel levies, import duties and other taxes, with the single exception of the domestic carbon tax. The exclusion of taxes is applied in order to allow the model to determine and compare least-cost pathways on the basis of technologies and base costs, so that the model can optimise for the lowest overall cost without the impact of taxes and other policy measures and layers. The carbon tax included in this study is modelled at the existing constant, low rate as currently applied (with allowances) by National Treasury (see Figure 7). Recent proposals, such as the National Treasury phase 2 discussion document (National Treasury, 2024b), were not included in this analysis. International taxes, such as the European Union's Carbon Border Adjustment Mechanism (CBAM) or the recent tariff announcements by the United States, are also excluded from detailed analysis in this study.

Household and consumer energy pricing

Similar to the tax limitations above, the model analyses the base cost for supplying fuels (based on technology and import costs) for consumption by end-users, whether in industry, residential, commercial or transport sectors, but does not consider the additional layers that affect the prices consumers actually pay for fuels, such as electricity tariff structures, gasoline price regulations or the impact of retail and distribution factors on costs of other fuels.

Land and Community Ownership

The SATIM model acts as a 'central planner' and deploys technology based on least-cost optimisation in conjunction with various constraints and other scenario parameters. It does not however indicate whether the technology deployed is owned by a public or private entity, or by communities in a social ownership framework. This is the case for both utility-scale and embedded generation (rooftop PV), as well as for other energy infrastructure.

Detailed environmental impact analysis

SATIM is not capable of performing detailed environmental impact analysis for various energy technologies that it models. The model can provide an estimate of air pollution emissions from fossil fuel combustion, in thermal power plants as well as gasoline- or diesel-powered vehicles, based on emissions factors, but it does not go further to model the effects of these emissions on ambient air quality, or the consequent effects on health at aggregate or localised levels. There are other models that are capable of performing this analysis, most relevantly at the Council for Scientific and Industrial Research (CSIR) where the Climate and Air Quality Modelling Group use a state-of-the-art Earth System Model-based (ESM) framework to model air pollution dispersion around the Highveld and other areas of South Africa, and the consequent impacts on air quality and health (CSIR, 2025).

Modelling of other environmental impacts is limited to estimates of water consumption for large thermal power stations (coal and gas) and coal mining and estimates of the land area footprint for utility-scale renewable energy systems. Other impacts and externalities, such as ecological footprint or biodiversity, are important for consideration, but are beyond the scope of SATIMGE.

Social protection

Social protection is vital for the energy transition, and a key component of ensuring an effective just transition. For example, retraining programs and employment policies are needed to help workers—especially women—access new opportunities in the changing energy landscape. This includes making sure women are not excluded from roles in the reform of electricity distribution systems, and that they are actively included in the Independent Power Producer (IPP) process for generating renewable energy. These kinds of interventions help to ensure that the benefits of the transition are more fairly shared. However, this detailed level of social and workforce planning goes beyond what the SATIMGE modelling framework is designed to capture, as it focuses primarily on technical and economic energy system dynamics rather than labour or equity-specific policy design.

Climate change resilience and adaptation

This work did not include analysis of the potential impacts of future temperature rises caused by unmitigated climate change on energy systems (for example potential increased domestic and commercial cooling loads), nor does it examine adaptation measures that could be considered to enhance climate resilience. Such planning is increasingly important given the current rate at which temperatures are rising, and the rapidly closing window for global mitigation efforts to avoid global warming overshoot above 1.5°C (IPCC, 2022b) – which, research shows, will disproportionately affect developing countries in the Global South (Civil Society Equity Review, 2024).

Agriculture, forestry, land-use and waste modelling

While the SATIMGE model framework provides optimisation analysis for GHG combustion and process emissions from the Energy and Industrial Processes and Product Use (IPPU) sectors (including from, for example, diesel use in agriculture), it relies on simulation models to measure the emissions and sinks of CO_2 and other emission species, such as methane (CH_4) and nitrous oxide (N_2O), from the Agricultural, Forestry and Land Use (AFOLU) and Waste sectors. This includes, for example, emissions from livestock farming as well as land sinks for CO_2. The average land sink is conservatively estimated at -10 $MtCO_2$ per annum – see Table 4 – which is more conservative than the DFFE's recent estimate of -20 $MtCO_2$ (DFFE, 2024). This is an important consideration, as overestimation of the land sink could lead to underestimating the level of effort required to decarbonise to meet net zero objectives but is not explored in depth in this work. Therefore, the modelling framework has not analysed, for example, the potential for emissions mitigation through shifts in agricultural practices or household diets. For some initial analysis on this area, see, for example, work performed by the National Business Initiative (NBI, 2021).

Transport infrastructure costs and non-motorised options

SATIM uses a stock model to estimate and model the South African current and future road vehicle parc, but does not have the equivalent capability for modelling rail transport or non-motorised transport options such as walking and cycling. Furthermore, the model does not have transport infrastructure costs built into it, and therefore cannot estimate the infrastructure costs that would be associated with either the rollout of a large-scale public transport system or increasing road capacity and maintenance to accommodate greater private vehicle volumes in the absence of increased public transport (including increased EV charging stations). For the sake of this work, it is assumed that these costs would offset each other, but further work would be required for a detailed analysis and estimate of these costs.

Data availability

A key challenge underpinning energy modelling work in this context is the lack of availability of quality data for the South African energy system, particularly at low-level disaggregate energy use such as in rural communities. This is coupled with uncertainty on key variables such as future technology costs and economic growth (which is, along with population, a key driver of future energy demand). Several approaches have been used in the development and maintenance of SATIM to overcome these challenges. Where official data is incomplete or inconsistent, SATIM integrates and reconciles data from multiple sources, including industry reports and grey literature. For areas with limited data, such as informal industries or rural energy use, SATIM employs proxy indicators and scaling factors based on better-documented sectors or data from comparable countries (Hughes et al., 2024).

In many instances however, as shown above and throughout the results, modellers have had to make estimated assumptions based on inference from the limited data that is available. This risk is partly addressed by the use of sensitivity analyses to unpack the effects of different assumptions for key variables, as is discussed in the results for the Ideal Energy Scenario in Section 5.

2.3. Results Framework

A key component of this project exercises is the collaborative approach to developing scenarios with non-modellers. This exercise and the resulting insights and energy pathways are incredibly useful and is an essential component of inclusive planning and decision-making. As a tool to support in facilitating this collaborative approach, a Results Framework was developed and tested at the stakeholder workshop.

The aim of the Results Framework is to provide a simple tool for stakeholders to interpret and understand model results based on indicators that are relevant to energy policymaking. The current version is set up to align broadly with the high-level objectives of integrated energy planning as described in the National Energy Act Section 6 on the IEP.

These high-level objectives, such as 'security of supply' and 'universal access', are then broken down into 'elements' that contribute to these objectives (and can be traced quantitatively in the SATIMGE model). For example, 'security of supply' is broken down into 'reliance on imports', 'electricity capacity' and 'diversification of supply'.

Elements are then further broken down into specific results indicators that can be characterised and quantified by the model. Results are then presented for a base year, in this case 2021, and for two future years, in this case 2035 (not shown in the figure above) and 2050. The choice of two years allows the results to be shown both for the long-term horizon, for which IEP modelling is ultimately purposed, as well as for a shorter-term point, so that the 'direction of travel' of indicators can also be determined.

Green-to-amber shading is added to the results to allow quick visual comparisons between scenarios for specific indicators. The shading is intended to provide a simple visual indication of where trade-offs may lie between scenarios for different indicators, and therefore different objectives of an energy plan – however it is not intended as a definitive indication of which scenarios perform 'best' or 'worst'.

It should be noted that the Results Framework is *not* intended or designed as a multi-criteria decision analysis (MCDA) tool and deliberately does not assign any weightings or indices to indicators. It could however be used to inform such a process in a subsequent step of analysis – but this has not been the purpose of the project work to date. The intention is simply to present and communicate modelling results in as close to an 'indicator-neutral' manner as possible, with a focus on building an understanding of potential trade-offs and priorities, without reducing the analysis to a final 'score'/number.

Figure 9 provides a sample screenshot of the final version of the Results Framework.

Elements of themes	Indicators	Units of measure	2035											
			Set 3											
			Ideal Scenario	Ideal Sensitivity - 9Gt	Ideal Sensitivity - 7Gt	Ideal Sensitivity - No CCS	Ideal Sensitivity - Low Localisation	Ideal Sensitivity - Early CTL Phase out	Ideal Sensitivity - Late CTL Phase out	Ideal Sensitivity - Low Fossil Fuel prices	Ideal Sensitivity - Low Disc Rate	Ideal Sensitivity - High Disc Rate	Ideal Sensitivity - Green Exports	Ideal Sensitivity - Opt. Battery learning
Reliance on imports	Percentage of primary energy supply from imports	%	27.1%	22.9%	33.2%	33.0%	27.1%	26.8%	23.3%	34.8%	26.7%	28.3%	30.1%	27.0%
	Natural gas imports	PJ	152	161	191	159	152	139	172	134	143	144	203	147
	Crude oil imports	PJ	319	319	319	319	319	319	319	319	319	319	319	319
	Refined liquid fuel imports	PJ	458	388	415	580	457	466	313	745	265	527	546	458
	Electricity imports as % of consumption	%	3.7%	3.7%	3.5%	3.7%	3.7%	3.7%	3.5%	3.8%	3.5%	3.8%	2.9%	3.7%
Diversity of elec supply	Electricity generation - Coal	TWh	66	84	18	45	65	69	51	53	52	63	68	65
	Electricity generation - Wind	TWh	72	65	87	72	72	72	79	72	72	72	89	72
	Electricity generation - Solar PV	TWh	91	83	125	108	91	88	108	97	96	87	130	93
	Electricity generation - Nuclear	TWh	14	14	19	14	14	14	14	14	37	14	14	14
	Electricity generation - Gas	TWh	2	2	8	5	2	1	5	2	2	2	11	2
	Elec generation - Gas + CCS	TWh												
Provincial Grid RE Capacity	Solar PV - Free State	GW	2.1	2.1	4.7	3.7	2.1	2.1	2.7	2.1	2.1	2.1	7.0	2.1
	Solar PV - Gauteng	GW	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
	Solar PV - Hydra (Central)	GW	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
	Solar PV - Limpopo	GW	3.4	0.1	3.4	3.4	3.4	3.4	3.4	3.4	3.4	1.4	3.4	3.4
	Solar PV - Northern Cape	GW	9.8	9.5	13.4	12.8	9.6	8.6	12.6	10.2	9.3	10.0	15.4	10.3
	Solar PV - North West	GW	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
	Solar PV - Western Cape	GW	0.5	0.5	1.9	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
	Solar PV - Mpumalanga	GW	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2
	Solar PV - KZN	GW	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5

Figure 9: Sample of the Results Framework

3. Reference Case

This section provides the results of the Reference Cases that were modelled for this work. The reference cases were reported in full in a previous report for this project – see ESRG's *Report on Reference Case and Policy Scenario modelling, and inputs for co-creation of an Ideal Energy Scenario* from February 2025 – but subsequent modelling adjustments have meant some of the results have changed since that report was issued.

3.1. Overview

Two reference cases – one 'pure' least-cost, and one with an additional net zero CO_2 target and cumulative GHG limit of 8 Gt CO_2-eq for the period (2021 – 2050). The limit of 8 Gt CO_2-eq was chosen on the basis of previous work on the feasibility and ambition of potential emissions budgets leading to net zero (Marquard et al., 2024, 2022; World Bank Group, 2022).

The previous report (mentioned above) showed an additional case – the Reference Case with a net zero target but without the emissions limit. That case showed that, in the absence of an emissions limit, the model delays decarbonisation action to reach net zero until the last five years and then faces extremely high and costly action those last five years to achieve the net zero target. This was considered entirely infeasible and unpractical. The 8 Gt GHG limit is thus included here as a proxy for 'forcing' decarbonisation action. A similar effect could be achieved by ramping up the carbon tax – and in practice, this is a policy option for driving increased decarbonisation – but this was not explored in detail in this work.

Results for the Reference Cases are unpacked in subsequent sections. Unless specifically stated otherwise, all assumptions shown in Table 4 above are applicable to the Reference Cases. Note the coding shown for each of the Reference Cases shown in Table 5 (and in the full scenario matrix in section 2.1.1) which is used to indicate the scenarios in all figures throughout this report.

Table 5: Overview of updated Set 1 Reference Cases

Scenario	Reference Case without emissions constraints	Reference Case with emissions constraints
Code (shown in figure legends)	IEP-1a-REF-UNCONS	IEP-1b-REF-NZ08GT
Description	Pre-Covid (2017) energy balance, policies and measures, and social accounting matrix	Reference case, with net zero CO_2 from 2050 and an 8 Gt GHG cumulative cap (2021 – 2050)
Net Zero CO2	N/A	From 2050
Emissions limit	N/A	8 $GtCO_2$-eq (CO_2 and non-CO_2) over 2021-50, incl. AFOLU, Energy, IPPU and Waste

3.2. Energy demand

Figure 10 shows final energy demand projections for the Reference Cases – i.e. quantities of energy carriers consumed in aggregate by demand sectors (agriculture, commerce, industry, residential and transport). The figure does not show upstream energy generation and conversion (e.g. coal into electricity). Table 6 shows differences in energy carrier use in 2050 b etween the two Reference Cases.

Note that, for all figures in this section unless stated otherwise, the Reference Case without emissions constraints appears on the left-hand side of the figure, and with emissions constraints on the right-hand side.

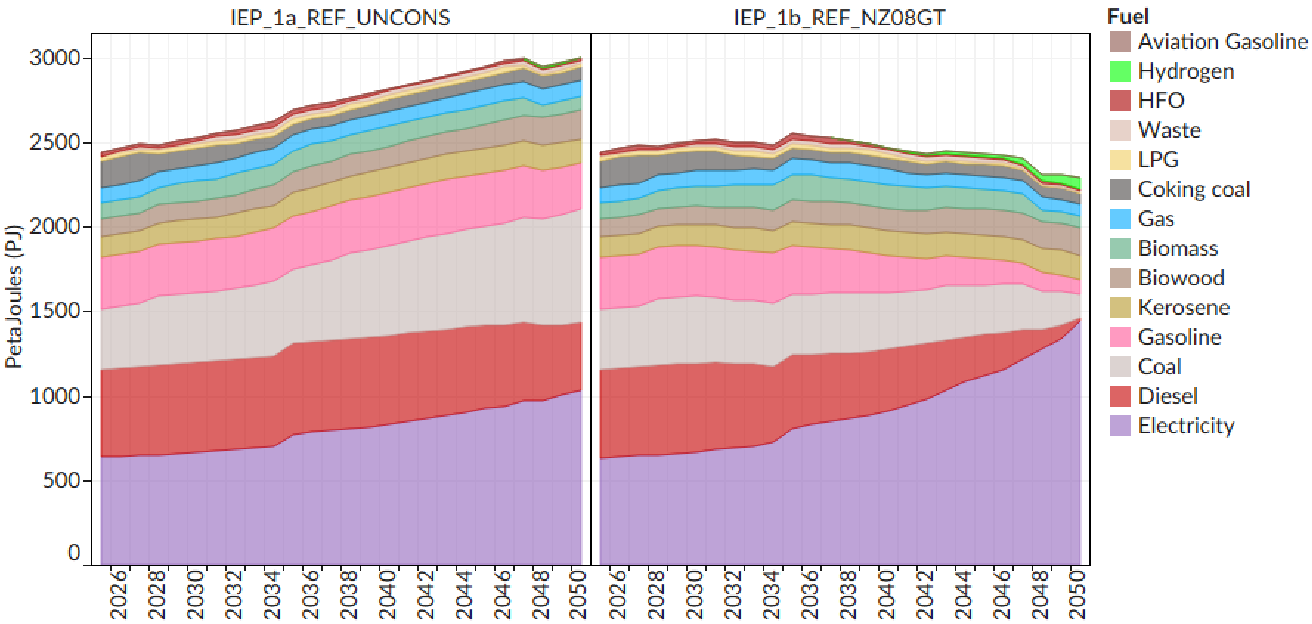


Figure 10: Economy-wide final energy demand for the Reference Cases

Table 6: Energy use by carrier in 2050 and difference between Reference Cases

Scenario	Elec-tricity	Diesel	Gaso-line	Wood	Kero-sene	Gas	Bio-mass	Cok-ing coal	Waste	LPG	HFO	Hydro-gen
Reference (PJ)	1 034	398	264	172	146	104	76	75	25	14	10	2
Reference (8GT Con-straint) (PJ)	1 438	25	85	164	141	67	73	66	14	3	6	71
Percent dif-ference	39%	-94%	-68%	-5%	-3%	-35%	-3%	-12%	-45%	-76%	-38%	3971%

The figure shows that, in the absence of an emissions constraint, coal use continues to grow to a 22% share of final energy consumption by 2050, with only moderate growth in electricity use and moderate decline in gasoline and diesel use economy wide. By contrast, the emissions constraint causes coal use to decline to 6% of final energy consumption, with only small remaining shares of gasoline and diesel. The emissions constrained reference case shows significant growth in electrification across all sectors, with electricity accounting for 63% of final energy consumption by 2050. Quantities and shares of natural gas, LPG and kerosene remain constant across both cases, while a relatively small amount of green hydrogen is used in the emissions-constrained case in hard-to-abate industrial sectors.

Reference Case energy consumption is unpacked further for residential (households), transport and industry sectors in the subsequent sections. It should be noted that reduced energy demand does not necessarily result in reduced economic growth. Figure 11 shows that, although the GDP per capita grows to a slightly lower level in the emissions constrained Reference Case compared to the unconstrained case, the corresponding difference in energy use between the two scenarios is considerably larger. With the addition of further measures such as enhanced energy efficiency, the economic gap can be reduced further (as discussed further later in this work).

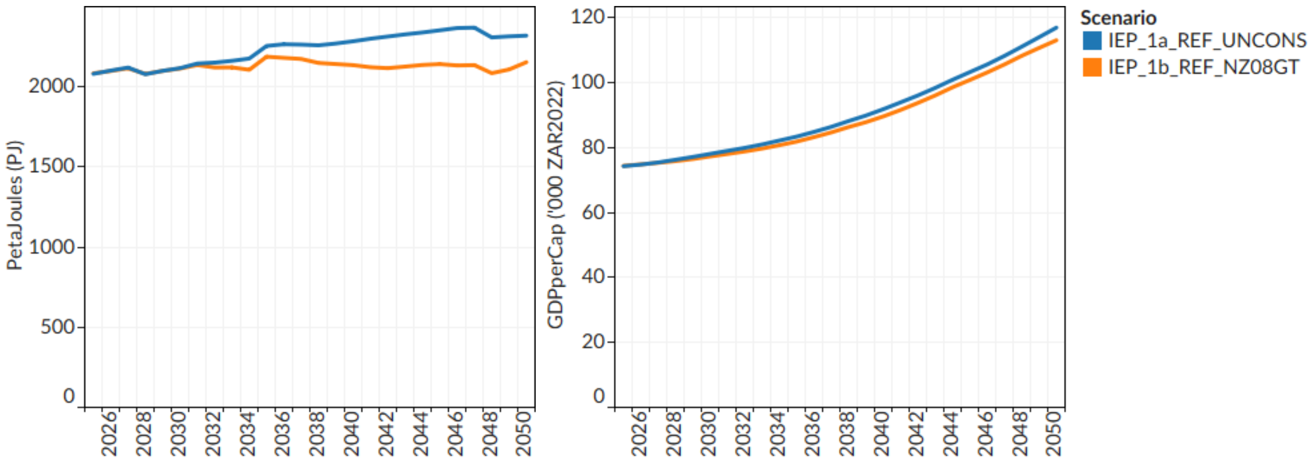


Figure 11: Comparing aggregate final energy demand (LHS) and per-capita GDP growth (RHS) for the Reference Case scenarios '

A note on the different classifications of energy

Energy modelling aims to represent the flows of energy from raw energy sources – such as coal, or sunlight, or wind flow – through conversions into energy carriers such as electricity or petrol – and their transmission/transportation and distribution to the point of the user – e.g. plug socket in a house – to becoming something useful – e.g. light. Recalling that energy cannot be created or destroyed, only transformed from one form to another, energy modelling aims to capture the full energy transformation path from 'raw energy' to useful energy, whilst accounting for energy losses along the way.

This is done by classifying energy into different forms:

- Primary – e.g. the raw coal or solar power that is extracted from mining or the sun
- Secondary – the energy that emerges from, e.g., a power station in the form of electricity
- Final – the energy, e.g. in the form of electricity, that arrives at a plug point having been delivered from the power station through a series of power lines (transmission and distribution)
- Useful – the energy in its useful, usable form – e.g. the light (lumens) that emerge from a lightbulb that is powered by electricity.

Figure 12 provides a useful illustration of this framework, as developed by Hannah Ritchie for *Our World In Data*.

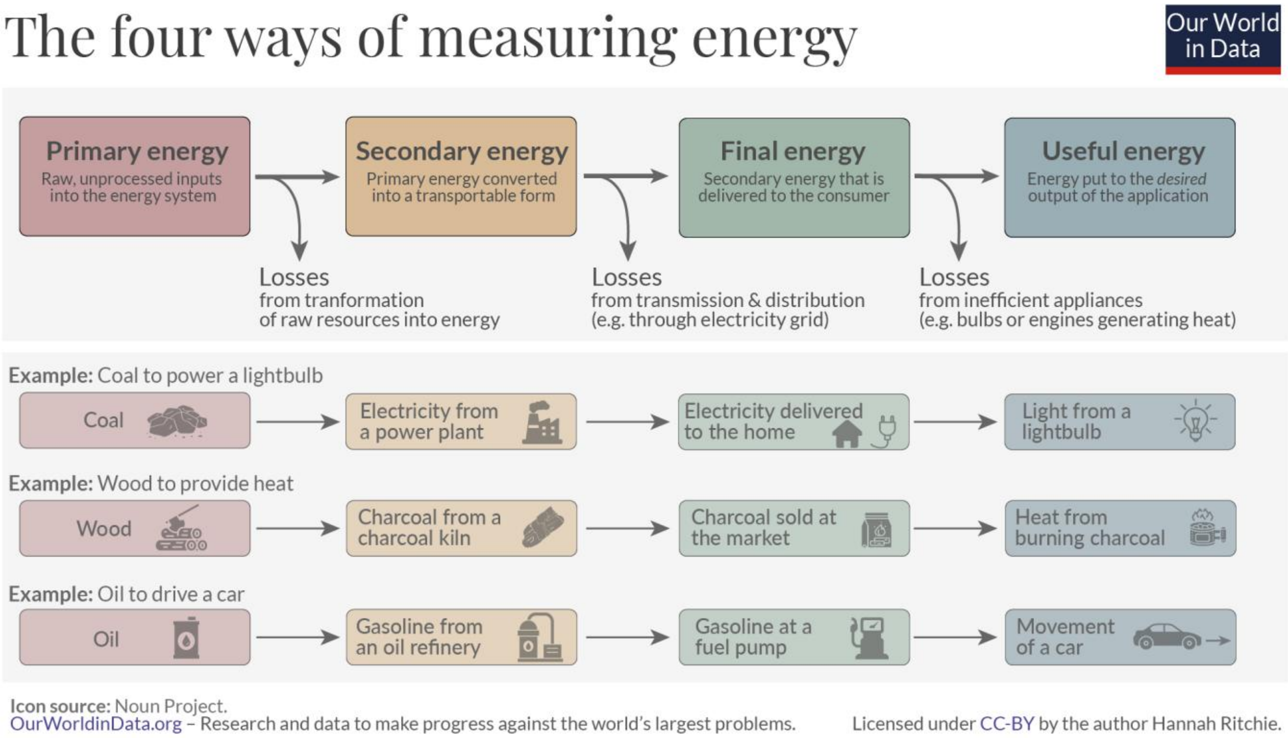


Figure 12: Primary, secondary, final and useful energy, a framework for modelling energy flows in a system (Ritchie, 2022)

3.2.1. Households

Household energy use is modelled by dividing households into three income groups, based on monthly income thresholds as shown in Table 7 (in 2022 ZAR). Each income group is further disaggregated into a demand for energy services capturing energy consumption for lighting, cooking, space heating, refrigeration and a combination of other (mostly electrical) appliances, as shown in Table 8 (which also shows the drivers of household growth, energy service demands, fuel use and appliance ownership captured in the model). Each service demand is also characterized by a particular seasonal/diurnal profile.

Table 7: Monthly income thresholds for household groups

Group	Income cutoff (2022 ZAR) p.m.	Base year population share (2017)
Low-income	<R5 584	45%
Middle-income	R5 584 - R22 336	31%
High income	>R22 336	24%

Table 8: Modelling structure and disaggregation for the residential sector in SATIM

Disaggregation level	Drivers
Households: Low-, Middle- and High-income **groups**	Population, household size, GDP
Energy Service Demands: Lighting, cooking, water heating, space heating and cooling, Refrigeration, Other	Household income, electrification, Policies and regulations such as building standards Behaviour change
Fuels: Wood, coal, paraffin, gas, electricity **Appliances: (televisions, washing machines, dish washers, etc). The energy intensity and efficiency of a core group of appliances is captured individually and represented as an "average" in the model under "other".**	Household income, electrification, Policies and regulations such as fuel subsidies, appliance standards

Base year electrification rates, as well as base assumptions about future electrification, are shown in Table 9.

Table 9: Default electrification rate assumptions

Electrification Rates		2017	2020	2030	2040	2050
Low Income	%	71%	80%	85%	90%	95%
Middle Income	%	83%	90%	95%	95%	100%
Overall Electrification	%	82%	87%	92%	95%	99%

In SATIM, the income thresholds shown in Table 7 remain static, and all economic modelling is done in constant real terms (i.e. excluding inflation). Therefore, as households become wealthier (which is assumed to correlate with overall economic growth, in line with the base assumptions for GDP growth as shown in section 2.2.2 and Appendix A)), they shift from the low to the middle income group, and from the middle to the high income group. This happens at different rates, depending on how the modelling parameters impact on macroeconomic performance – as shown by the slight differences between the two Reference Cases in Figure 13.

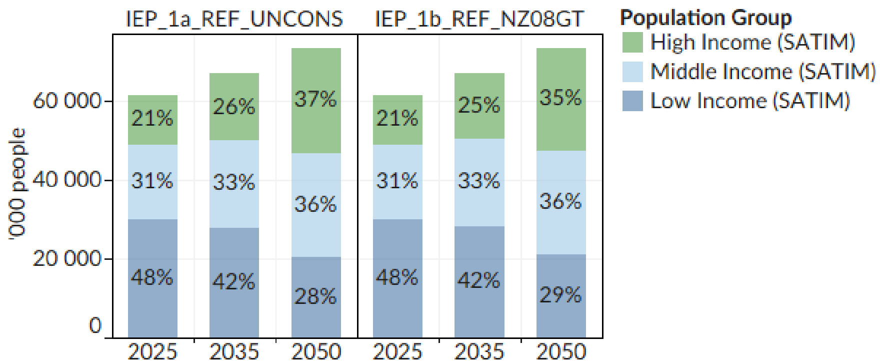


Figure 13: Population shifts for the Reference Cases

Figure 14 shows aggregate household energy use for the three income groups over time, for the Reference Case. The growth in aggregate energy use in the middle- and high-income household groups, and corresponding reduction in aggregate energy use for the low-income households is driven by the population shifts as shown in Figure 13 (i.e. more people move from the 'low-income' to the 'middle-income' bracket, and therefore aggregate energy use per bracket shifts accordingly). Note however that the composition of energy carriers used by each household, under the Reference Case, does not change significantly: high-incomes households rely primarily on electricity, and a decreasing amount of LPG, while low-income households continue to rely on wood and some coal (note that the terms 'wood' and 'biowood' are used interchangeably in this report). The imposition of the emissions constraint does not alter this situation (Figure 15) which shows that, in the absence of any social provisioning measures, existing inequities in energy access would continue to persist into future decades.

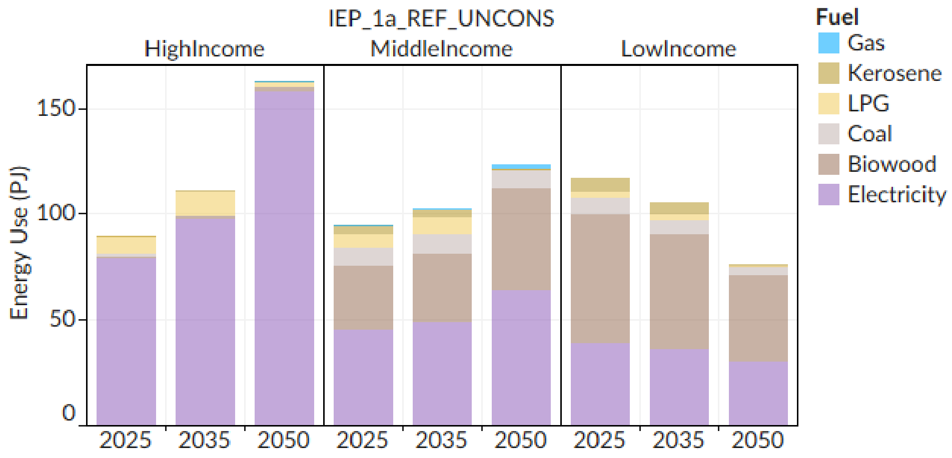


Figure 14: Reference case (without emissions constraints) aggregate household energy use. Note that reduction in total low-income energy use is primarily because of social mobility, with households entering the middle-income group, leaving less people in the low-income category.

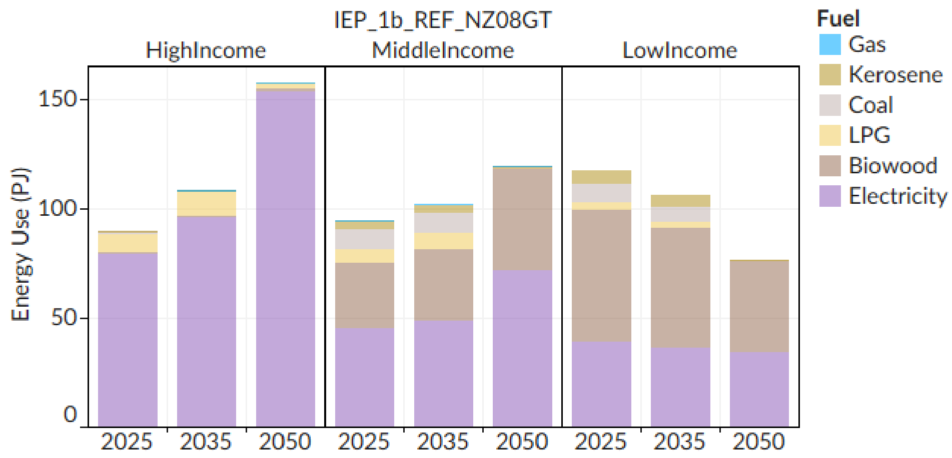


Figure 15: Reference case (with emissions constraints) aggregate household energy use

3.2.2. Transport

Base assumptions for the transport model are provided in Appendix A. Figure 16 shows the overall energy consumption and shares of energy carriers for the transport sector, with and without an emissions constraint. In the absence of an emissions constraint, the sector transitions slowly to electricity and there is still a majority share of liquid fuels. By contrast, the emissions constraint causes greater electrification of the transport sector, and comparative decline in gasoline and diesel usage. Note that kerosene, mainly used in aviation consumption, as well as aviation gasoline do not decline, as the model currently does not have alternatives for clean aviation fuel. Storage of aviation and other fuels is not analysed in the model, so results show only fuel *use*, not total imports or storage.

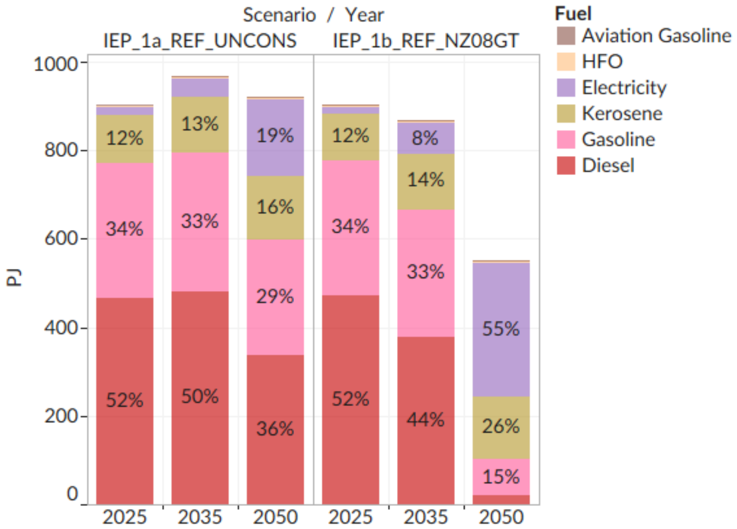


Figure 16: Comparison of Transport Fuel for the Reference Cases

Figure 17 shows the Reference Case evolution of passenger transport demand, measured in passenger-kilometres (where 1pkm = 1 passenger travelling 1 km). The Reference Cases do not include any effort towards mode shifting, and therefore private passenger vehicle usage grows significantly whilst public transport remains increasingly underutilised. The main difference between the two Cases is the extent and pace at which electric vehicles (EVs) are deployed in order to allow the sector to decarbonise. This is similarly the case for Reference Case freight transport (Figure 18), which shows only a modest increase in rail use (but not in the overall share of rail).

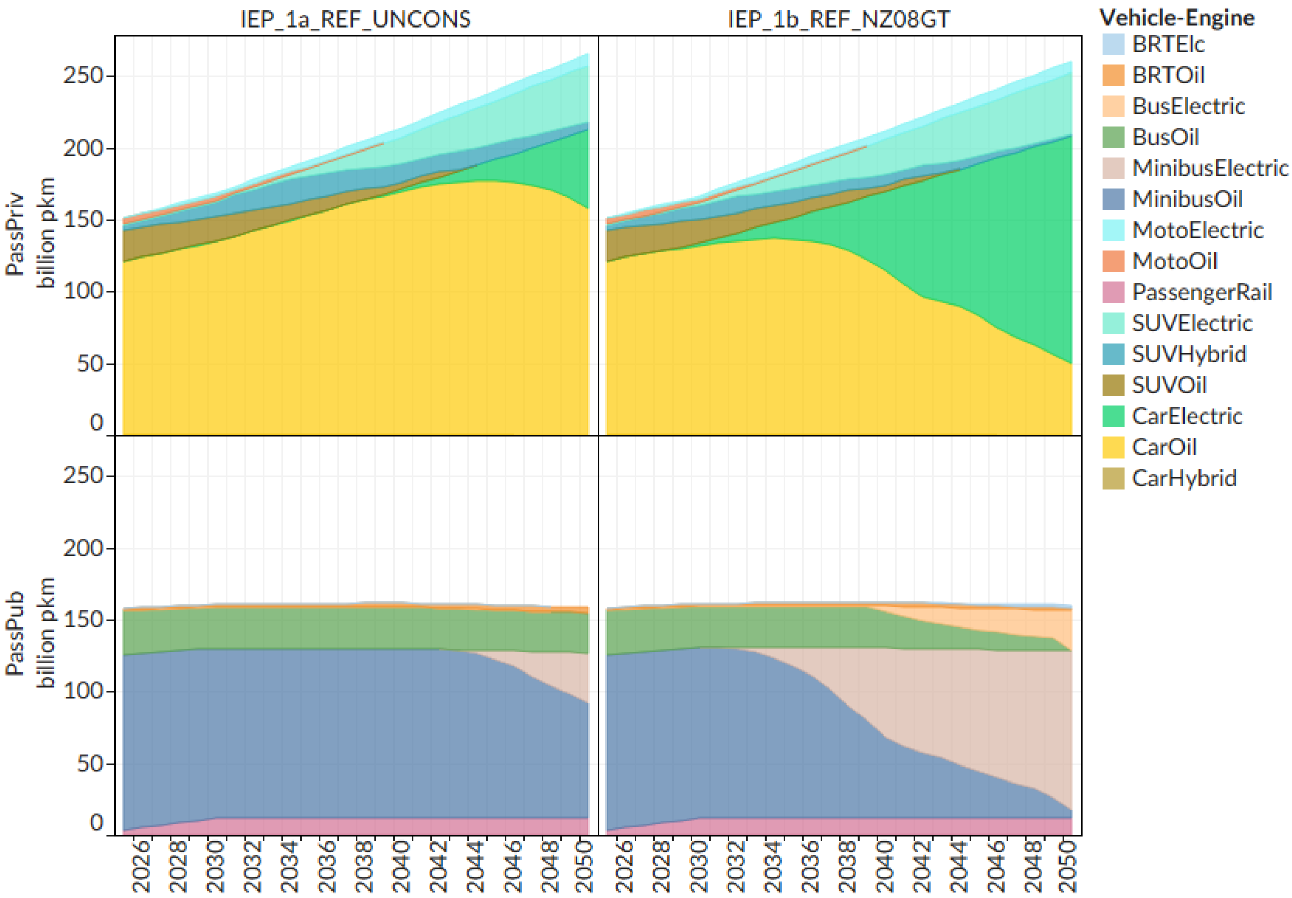


Figure 17: Reference case passenger demand by vehicle and fuel type

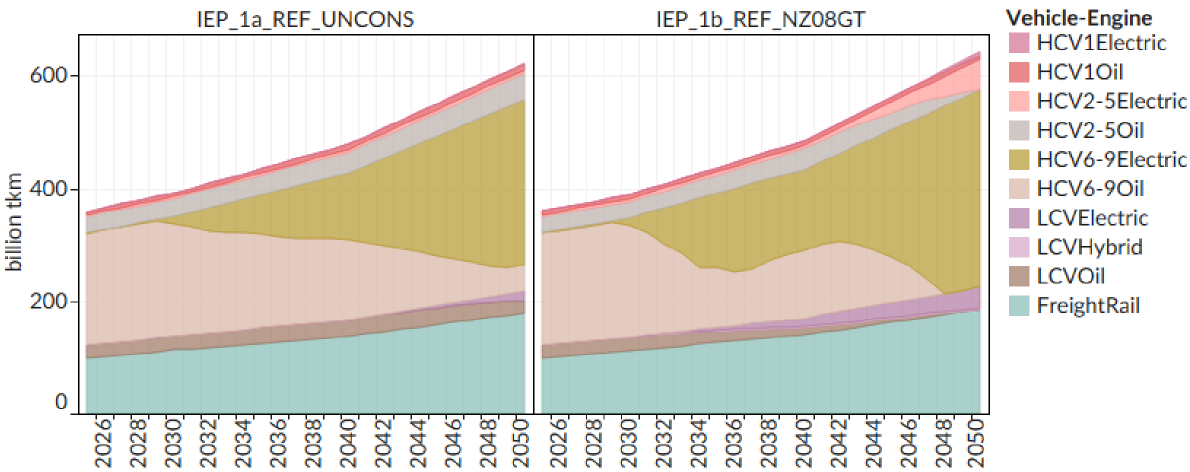


Figure 18: Reference Case freight transport (tonne-kilometres) by vehicle and fuel type

Glossary for transport figures

Note throughout this report figures for transport results are distinguished by private passenger transport ('PassPriv'), public passenger transport ('PassPub') and commercial transport. For commercial vehicle transport, vehicles are classified by their weight class as light commercial vehicles (LCVs) or heavy commercial vehicles (HCVs), distinguished by weight class from HCV1 (small 2-axle trucks) up HCV9 (large articulated trucks for abnormal loads). For all vehicle classes, results show the vehicle type and fuel type, e.g. 'SUVOil' refers to SUVs fuelled (only) by either gasoline or diesel; MotoElectric refers to electric motorbikes, etc. BRT refers to bus-rapid transit systems.

3.2.3. Industry

Consistent with the economy-wide picture in Figure 10, the main difference between industry energy use in the Reference Cases without and with an emissions constraint, respectively, is the use of coal and electricity (Figure 19). By 2050, aggregate energy use for the constrained case amounts to 1 175 PJ, some 300 PJ below the unconstrained case. In the unconstrained case, coal use continues to grow unabated, with comparatively moderate growth in electricity. Meanwhile, coal use is reduced in the emissions-constrained case, and electricity grows to share of 56% of industry energy by 2050. Hydrogen also features in the emissions-constrained case, with use in the iron and steel, bricks and ceramics, mining and chemical processes sectors (accounting for around 6% of overall final energy use). Coal use does however remain, predominantly in the cement industry as well for other process heat applications in hard-to-abate sectors.

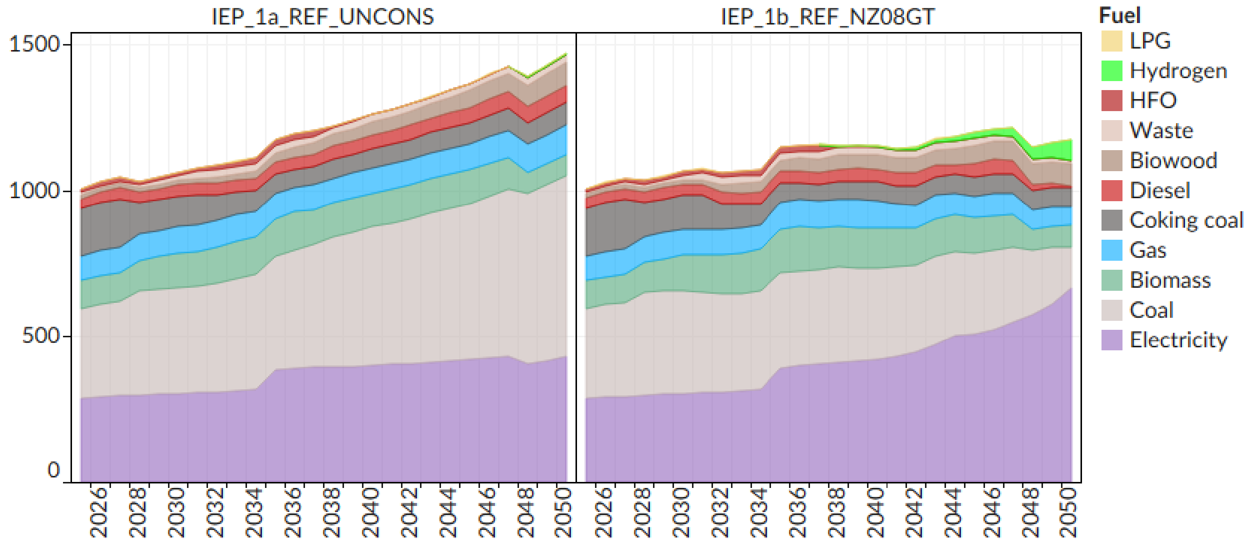


Figure 19: Reference Case final energy demand for Industry (aggregate)

It should be noted that, although overall energy use is reduced in the emissions-constrained case relative to the unconstrained case, this does not reflect reduced industry output so much as it does the improved energy efficiency that occurs with increased electrification (since, for example, electric motors are more energy efficient than thermal engines). Energy intensity of industry overall (measured as industry output, in terms of gross value add, relative to energy input) actually decreases for the emissions-constrained case relative to the unconstrained case, as shown in Figure 20. By 2050, total energy use in industry is 20% lower in the constrained reference case than the unconstrained reference case, whilst corresponding GVA difference is under 10% (Figure 21).

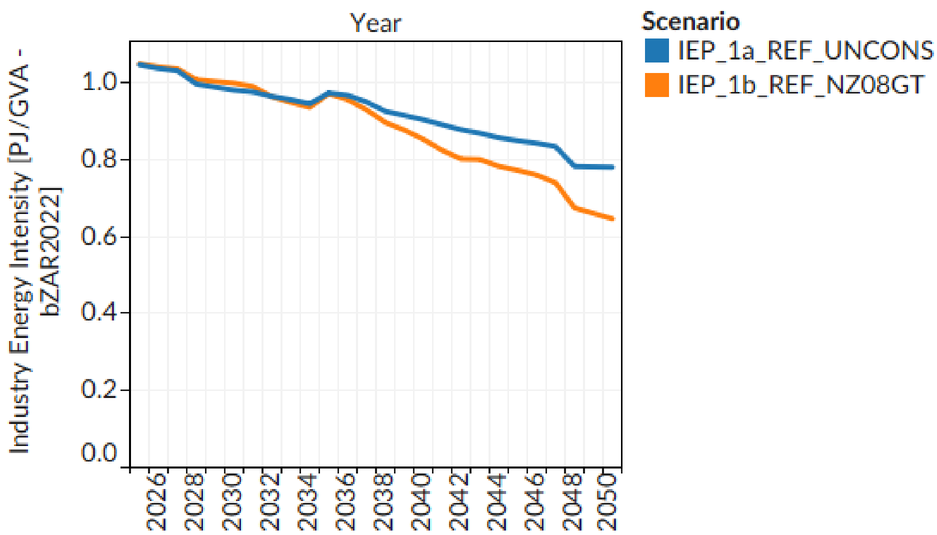


Figure 20: Energy intensity of industry relative to Gross Value Add by Reference Case scenario

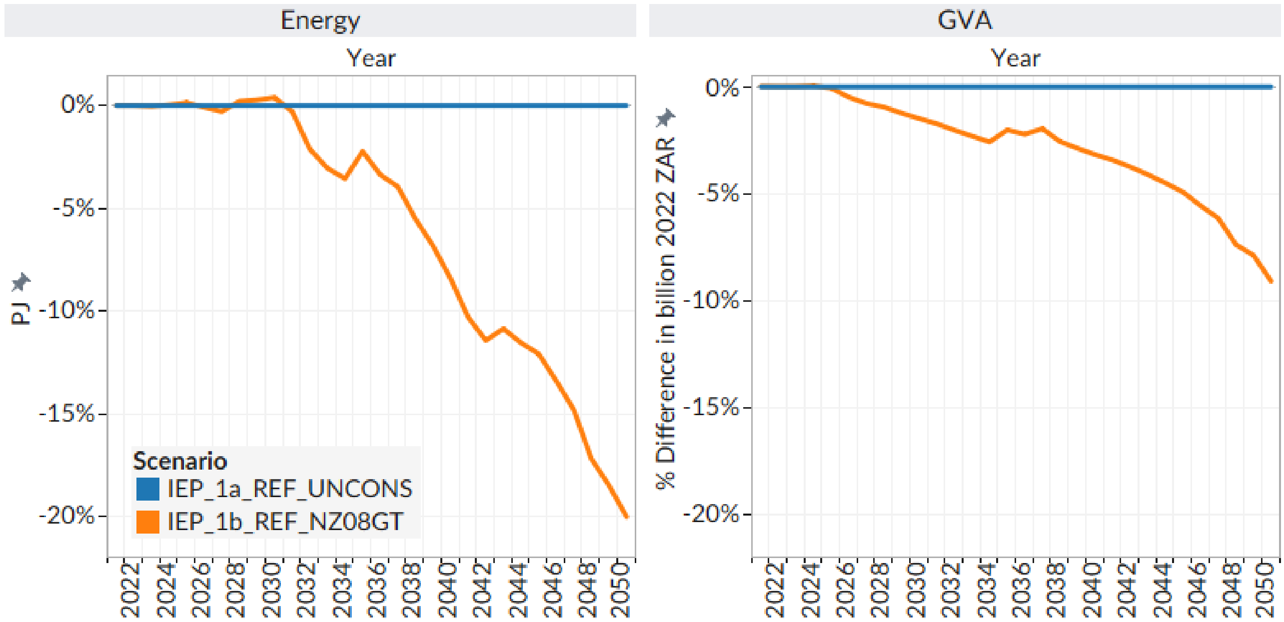


Figure 21: Aggregate energy consumption and GVA for industry in the Reference Cases

The next section provides high-level results from the Reference Cases for energy supply – particularly electricity, as well as coal-to-liquids.

3.3. Energy supply

Figure 22 shows economy-wide primary energy supply for South Africa under the Reference Cases without and with an emissions constraint.

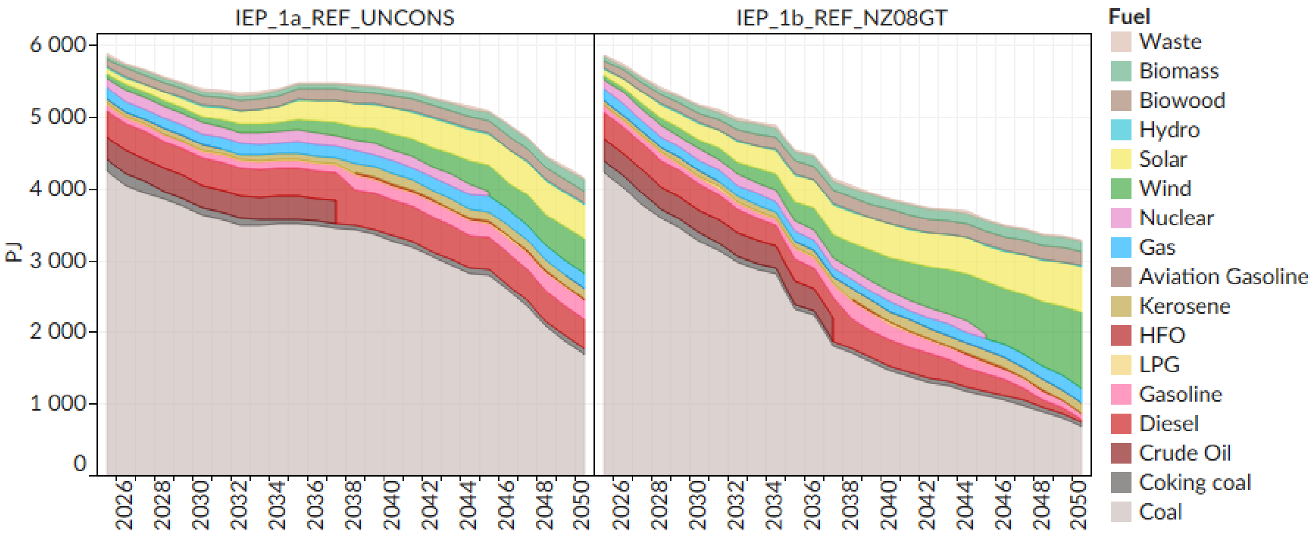


Figure 22: Reference Case primary energy supply by fuel type

Both cases show a decline in the dominance of coal from today's levels – where it accounts for an estimated three-quarters of South African energy supply – to lower levels by 2050, without being completely phased out in either case (see proportions in Figure 23). In the unconstrained Reference Case, coal still accounts for 42% of primary energy, while imported refined liquid fuels (mainly diesel) maintain a 21% share. Overall reduction in primary energy is partly due to fewer losses from fossil fuel conversion (e.g. coal power stations), and the system becoming more efficient with greater electrification.

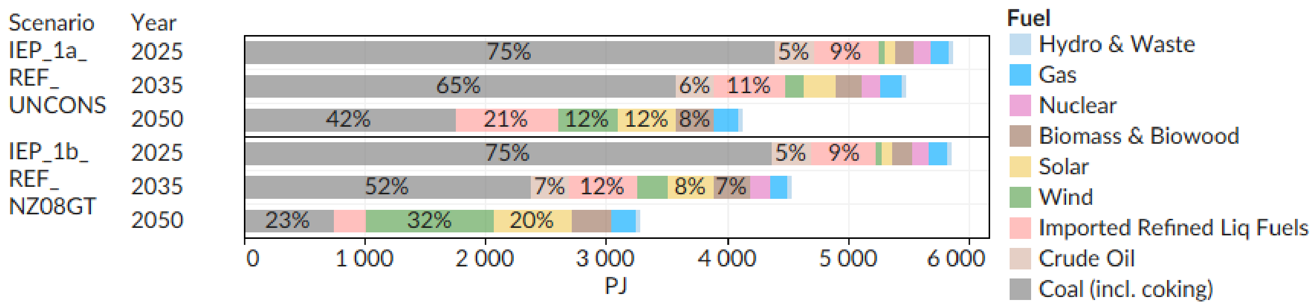


Figure 23: Primary energy shares in selected years for the Reference Cases

In the constrained Reference Case, greater levels of wind and solar renewable energy penetrate the system, partially offsetting coal and liquid fuel use. The lower aggregate primary energy levels also reflect greater electrification, and therefore a more efficient energy system (as was shown above in the industry sector). In both cases, natural gas (mainly from imported LNG, with a small contribution from Ibhubesi by 2050) contributes roughly 200 PJ per annum – a relatively small (but not insignificant) share compared to other energy carriers.

3.3.1. Electricity

Turning to the electricity sector, Figure 24 shows generation capacity by technology for the Reference Cases. Figure 25 shows electricity generation (generation for pumped storage and batteries not shown, as these technologies are net-consumers of electricity – they are charged (or pumped) up during low electricity demand and then used to provide additional during times of high demand). Both cases show a significant growth in electricity capacity relative to current levels, coupled with a phase down of existing coal capacity (see assumptions about Eskom's coal plant closure schedule in Figure 99 in Appendix A). However, electricity capacity growth is considerably higher (more than 250 GW total by 2050) in the carbon-constrained Reference Case, with most of that capacity supplied by wind, PV (grid and rooftop – see assumption in Figure 6 above) and battery storage.

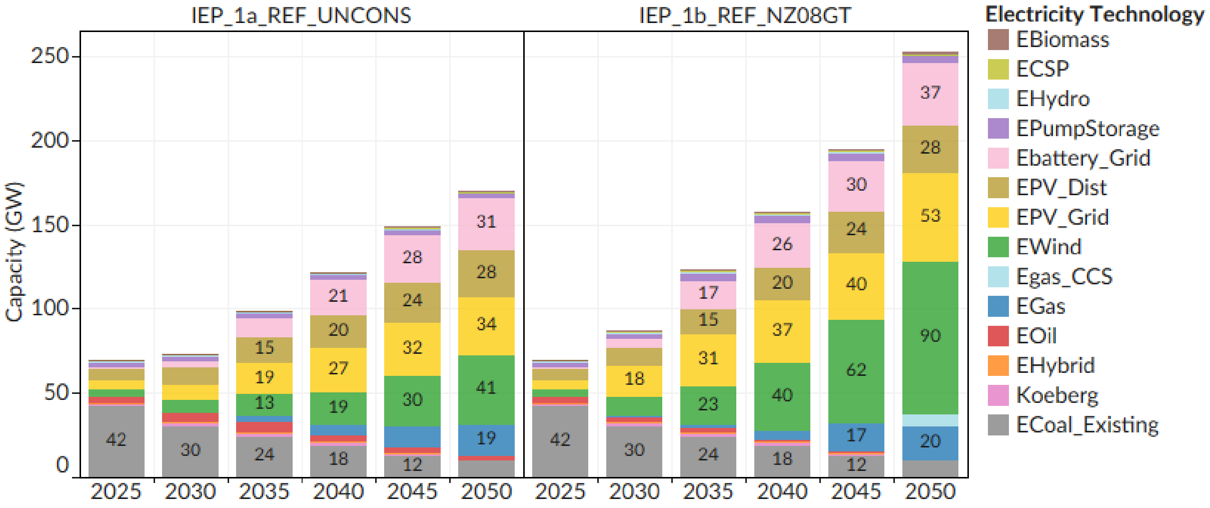


Figure 24: Reference Case electricity capacity by technology

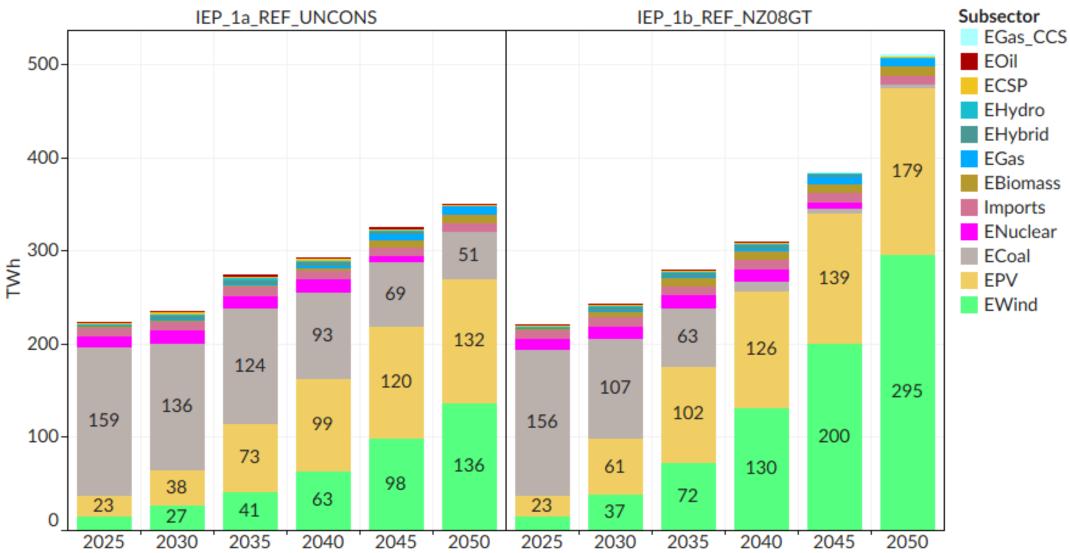


Figure 25: Reference Case generation by technology

The constrained Reference Case still has some coal capacity remaining in 2050 – Medupi and Kusile – as well as gas with and without carbon capture and storage. Utilisation of these technologies is however minimal.

The coal and gas without CCS are used as a 'backup' to the system for periods when insufficient renewable resources may be available to provide sufficient renewable generation (and/or to charge battery storage). The gas with CCS is used to augment power supply during peaking periods when solar PV generation is not directly available.

From a net zero perspective, emissions from the unabated coal and gas would have to be offset by the land sink, as well as potentially other carbon dioxide removal (CDR) methods not explored here (which, aside from biological sequestration, are at similar levels of technological infancy and uncertainty). Use of CCS in scenarios presents significant risks (discussed further in the ideal energy scenario), due to the lack of progress and uncertainty in developing this into a commercially viable technology option, particularly for the power sector.

3.3.2. Liquid fuels

In all modelled scenarios (with the exception of two sensitivity analyses discussed in Section 5.3.3), the model can choose to retire South Africa's existing coal-to-liquids (CTL) energy production capacity on a least-cost basis, in stages or in full, from the year 2035. Figure 26 shows how this can materialise in scenarios with and without an emissions constraint. In the unconstrained Reference Case (blue line), CTL production continues at full capacity until 2045, where it ramps down linearly to retirement in 2050 (in line with Sasol's projections for the useful life of the refinery). By contrast, the emissions constraint causes CTL capacity to be endogenously retired in stages – partially in 2035 and fully by 2037.

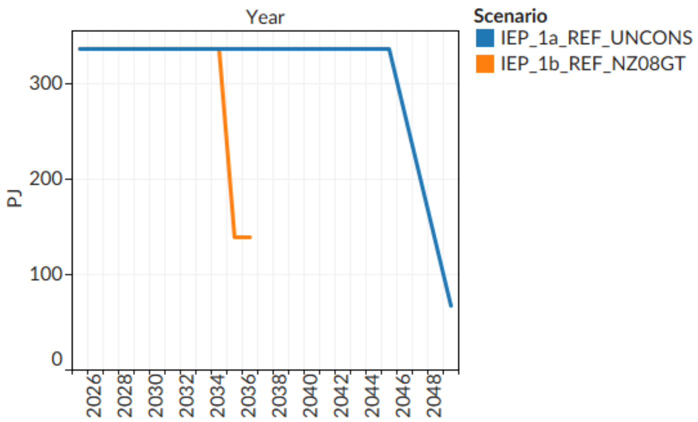


Figure 26: Comparison of coal-to-liquids activity and production between the Reference Cases without and with an emissions constraint

It should be noted here that the analysis in this work does not look in detail at the full possibilities and implications for different future scenarios of Sasol's coal-to-liquid fuels facilities. For example, the report does not look in depth at different production options that are under consideration, nor does it factor the role Sasol plays in supplying the downstream chemicals industry with petrochemical feedstocks, or for that matter potential short and long-term constraints that may arise in coal use and gas supply. The model assumes that any downstream chemical feedstock requirements not met by Sasol are replaced by imports but does not quantify this in detail. Detailed analysis of these and other questions surrounding Sasol's role in the energy transition is provided in a TIPS (Trade & Industrial Policy Strategies) report published in 2024 (Crompton et al., 2024).

In the context of this work, the analysis can only say that, given its prominence in the energy sector and wider economy, but also its significant contribution to GHG and other emissions, effective planning for the future of Sasol is a very important component of integrated energy planning.

3.4. Greenhouse gas emissions

Figure 27 shows sectoral greenhouse gas emissions profiles for the Reference Cases without and with an emissions constraint. The constrained case shows that by 2050 the majority of remaining GHG emissions are from the AFOLU and Waste sectors, as a result of the modelling limitation expressed for these sectors in section 2.2.3. Although there is potential for reduction in emission in these sectors, for AFOLU the overall sink is unlikely to exceed sectoral emissions and therefore will not be able to provide a long-term compensatory sink for other sectors. Figure 28 shows cumulative GHG emissions over the period 2021 – 2050.

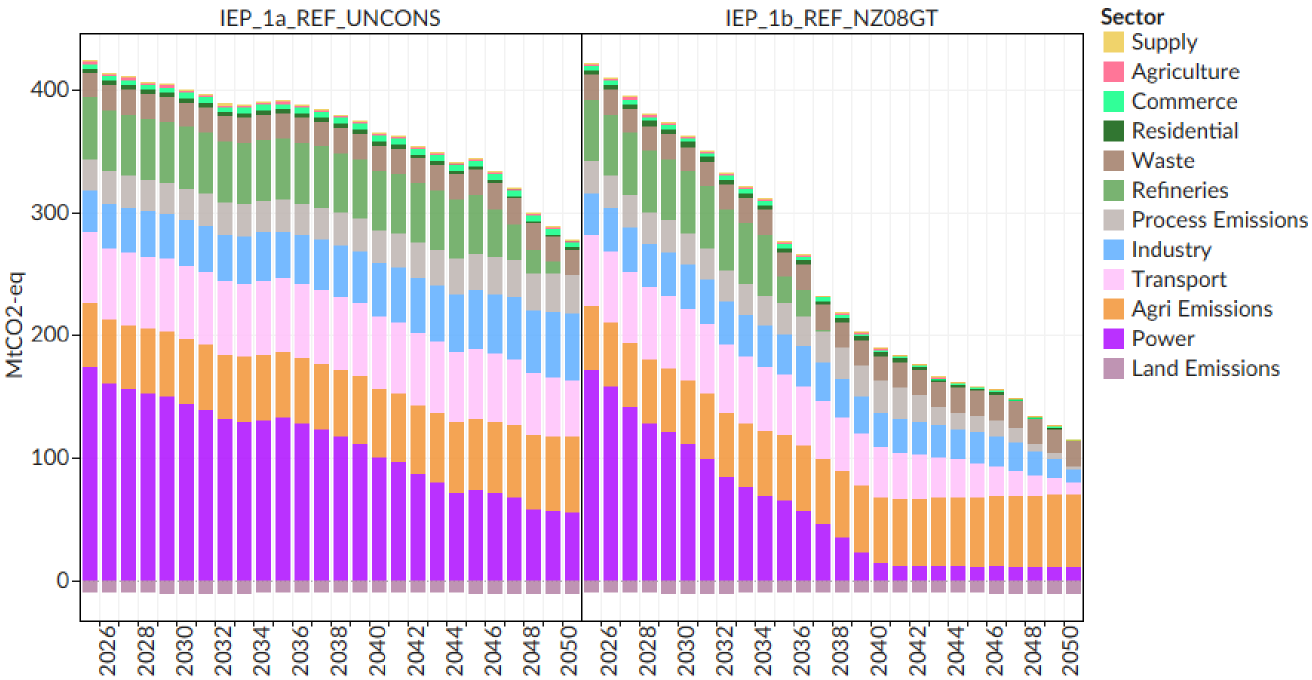


Figure 27: Reference Case GHG emissions trajectories without and with an emissions constraint

As Figure 28 shows, the greatest reduction in emissions lie in the power, transport and refineries (coal-to-liquids) sectors, with smaller reductions in industry combustion and process emissions. This reflects a common finding in global mitigation studies that the power sector is the 'easiest' (in relative terms) to decarbonise, due to the maturity and global growth in low-carbon technologies such as wind and PV (Davis et al., 2018; DeAngelo et al., 2021). Decarbonised electrification therefore remains the primary strategy available for achieving net zero CO_2 ambitions worldwide (IEA, 2021a).

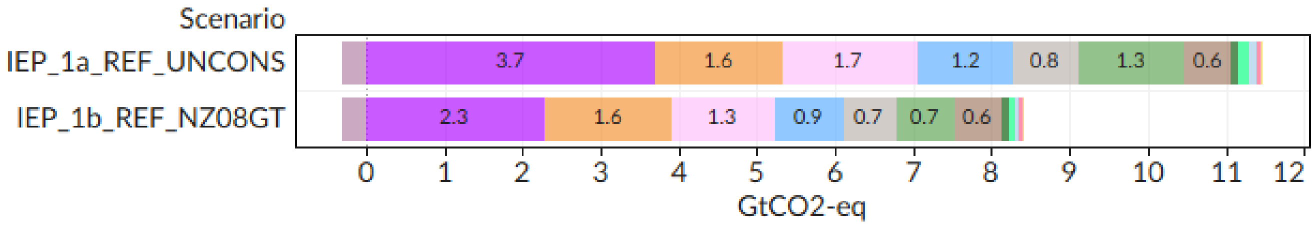


Figure 28: Cumulative emissions (2021-2050) for Reference Case without and with emissions constraints

Figure 29 shows annual methane (CH_4) emissions for the Reference Cases, in terms of 100-year Global Warming Potential common emissions metrics (CO_2-eq). Given the greater global warming effect of methane, over a very short half-life (~10 years, as opposed to ~1000 years for CO_2), some stakeholders have argued that the GWP_{20} metric should be used, as well as or instead of the GWP_{100} metric. However, it should be noted that the IPCC pathways that align with different warming factors use the GWP_{100}, so use of these factors, net zero CO_2 by 2050 and net zero GHG by 2070 are consistent with IPCC model budgets. Therefore, this report focuses only on GWP_{100} metrics going forward.

However, climate scientists have established a significant potential role for methane reductions in terms of overall efforts to limit and prevent global cooling – with some suggestions that a significant reduction could, in fact, provide a temporary 'global cooling' effect (Hanaoka and Masui, 2018; Ocko et al., 2021). This is particularly important with respect to near-term climate tipping points, with the IPCC highlighting that the likelihood of triggering tipping points increases significantly with incremental warming.

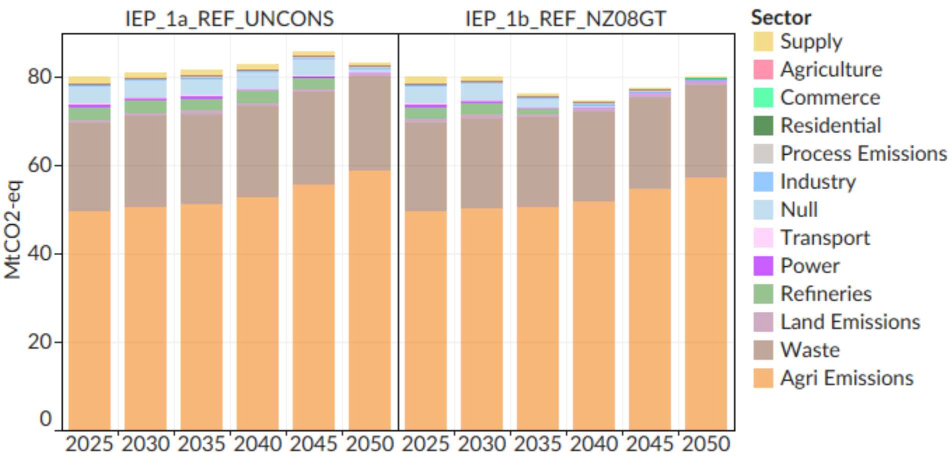


Figure 29: Methane emissions (in GWP_{100} CO_2 equivalent units) for the Reference Cases

3.5. Environmental externalities

3.5.1. Air pollution

Figure 30 below shows aggregate emissions of different air pollutants – sulphur oxides (SOx), nitrogen oxides (NOx), particulate matter (PM10) and carbon monoxide (CO) – from different sectors and sources in the unconstrained Reference Case. As the figure shows, the leading sources of SOx, NOx and PM10 are Eskom's coal power stations as well as the coal-to-liquids and crude refineries. The leading sources of carbon monoxide, by contrast, are the internal combustion engine (ICE) vehicles on the roads.

As SATIM is currently a single-node model, it cannot determine the cumulative effects of air pollutants on ambient air quality. However, the model does allocate emissions by technology type and, in the case of existing liquid fuels and electricity supply infrastructure, by the physical plant contributing the emissions. It is therefore possible for other dispersion models to be developed and informed by the data provided by SATIM, to model and estimate the long-term effects of these air pollution results on ambient air quality, and consequent health impacts and expenditure, at local resolutions. Such work has been performed previously by the Climate and Air Quality Modelling Group at the CSIR. Tracking of total annual emissions by the SATIM model provides indicative guidance on the overall quantities of such pollutants, which can be used as a proxy for pollution and human health impacts. Further work on quantifying health impacts from such data can be found for example in the Gray report commissioned by the Centre for Environmental Rights (Gray, 2019).

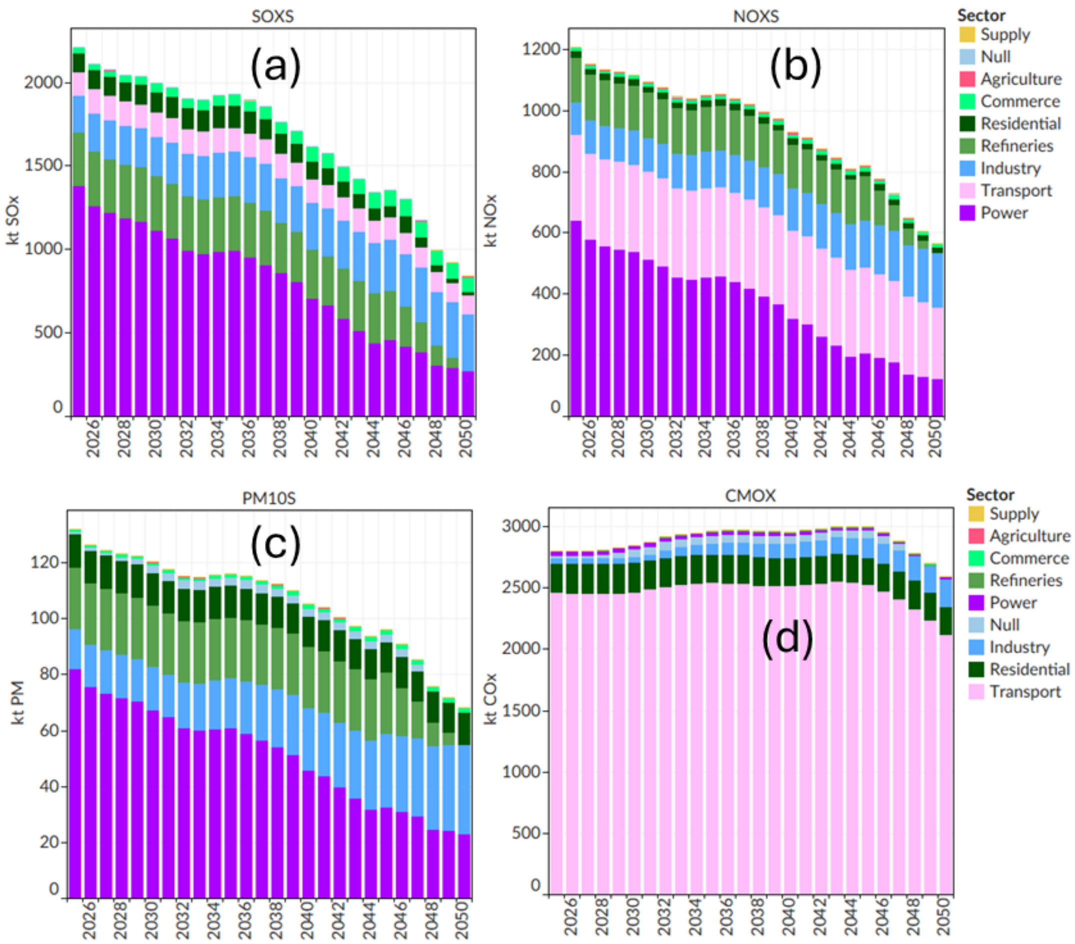


Figure 30: Emissions of (a) sulphur oxides (SOx), (b) nitrogen oxides (NOx), (c) particulate matter (PM10) and (d) carbon monoxide, by sector for the Reference Case (no emissions constraints) – note the different scales for each emission species

3.5.2. Water consumption

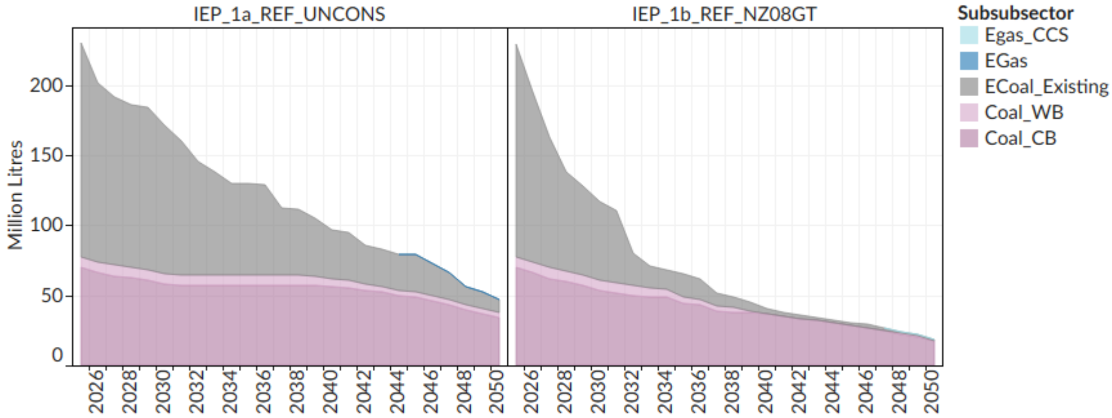


Figure 31: Water consumption for coal mining and coal and gas power for the Reference Cases without and with an emissions constraint

Figure 31 above shows water consumption for fossil fuel extraction and conversion infrastructure, namely coal mining and coal power stations, as well as (barely visible in blue on the graph) gas power stations. As would be expected, declining coal use leads to declining water consumption. Currently not included in the model is the water footprint of other technologies, such as solar PV (for cleaning), as well as water pollution and quality impacts from acid mine drainage and other effects of coal mining. Such externalities are important for consideration in energy planning but are dependent on spatial factors and hard to cost, and consequently difficult to accurately estimate and include in modelling analysis. Again, as a first pass proxy, the absolute quantities of consumption, combined with the total amount of water-impacting technologies gives a sense of the relative footprint of different energy mixes.

3.6. Socio-economic indicators

This section provides a summary of high-level socio-economic indicators that are produced by the SATIMGE model, specifically from the eSAGE linked model. The results provide an indication of employment, GDP effects and shifts in income distribution.

3.6.1. Employment

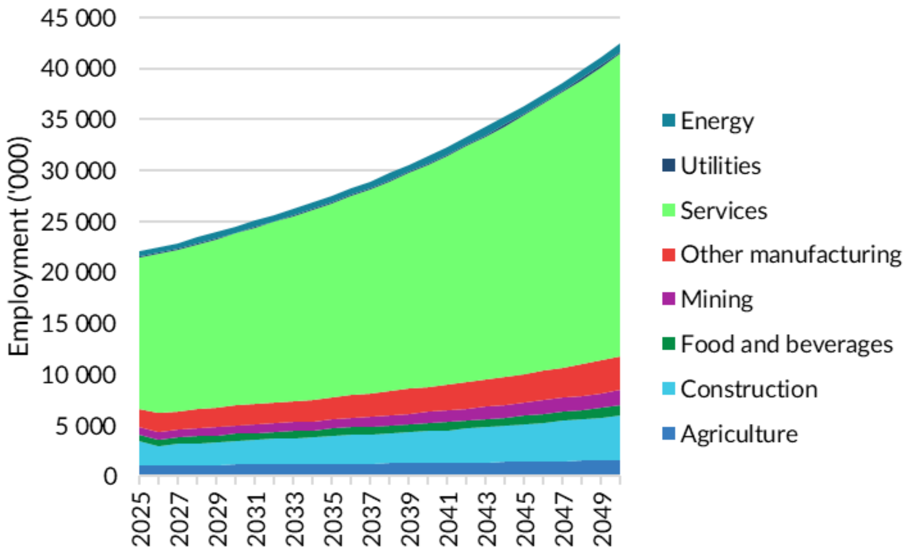


Figure 32: Economy-wide employment for the Reference Case (without constraints)

Figure 32 above shows total economy-wide employment projections for the Reference Case (without constraints). Base year employment data in the SATIMGE model are calculated from the StatsSA Labour Force Surveys, with projections for different sectors and subsectors linked to assumptions about sectoral employment intensity coupled with economic activity growth. This representation is fairly limited and quite crude at aggregate level but nevertheless provides some high-level indication of employment trends. This can be seen in **Error! Reference source not found.**, which compares employment projections for total employment b etween the two Reference Cases.

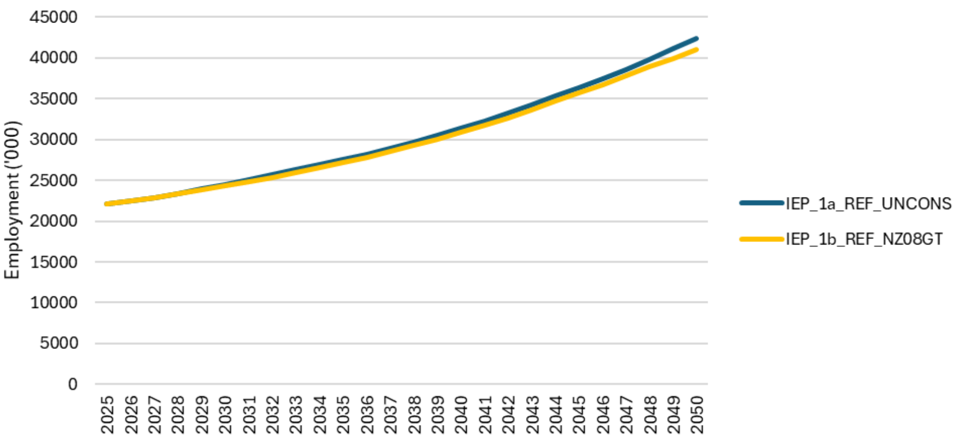


Figure 33: Comparing total employment for the Reference Cases without and with emissions constraints

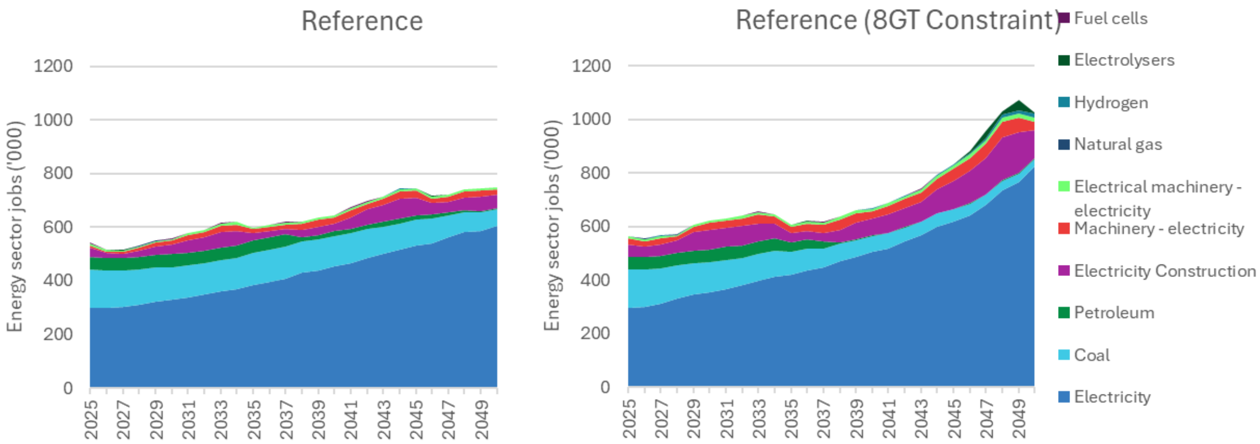


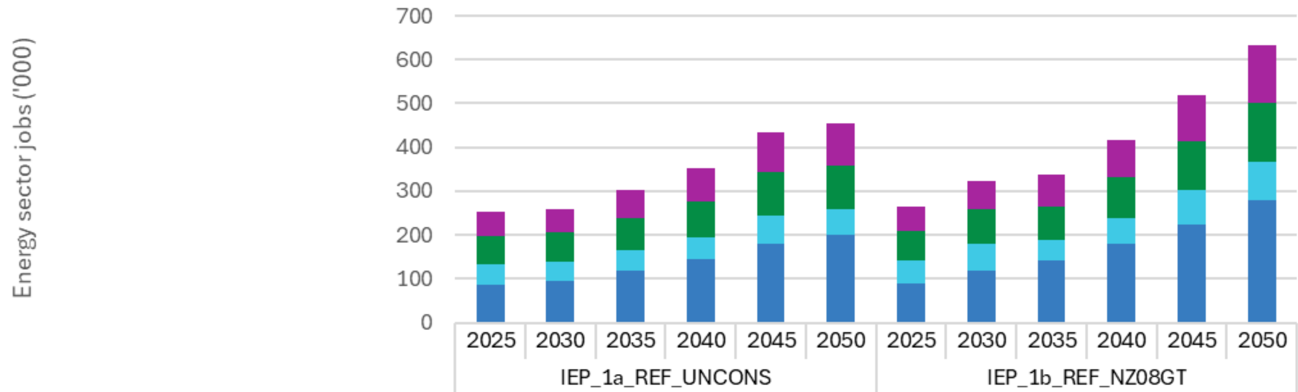
Figure 34: Energy sector jobs for the Reference Cases

Figure 34 compares energy sector specific employment between the two Reference Case scenarios. The eSAGE model reports on a set of aggregate sub-sectors of employment, of which the following relate directly to the energy sector:

- Electricity (operation and maintenance of power plant separate from construction)
- Coal (coal mining)
- Petroleum (incl. upstream extraction, excl. downstream forecourt distribution)
- Machinery (incl. electrical machinery separately) manufacturing for electricity construction
- Natural gas extraction and distribution
- Hydrogen (incl. electrolysers, and fuel cells, separately)

The constrained case shows a significant increase in electricity jobs, with a corresponding decline in coal mining jobs, relative to the unconstrained case (Figure 34).

Employment data is also broken down in the eSAGE model by skill level, as shown in Figure 35. As shown above, the constrained case shows higher total employment than the unconstrained case for the energy sector, with growth primarily in secondary skills (50% greater in 2050) and primary skills (39% increase).



	IEP_1a_REF_UNCONS						IEP_1b_REF_NZ08GT					
	2025	2030	2035	2040	2045	2050	2025	2030	2035	2040	2045	2050
4 Tertiary-educated labor	53	54	64	75	90	95	55	65	71	86	105	131
3 Secondary-educated labor (grade 11-12)	66	65	73	83	99	99	69	78	77	92	112	133
2 Middle-educated labor (grade 8-10)	47	46	46	49	65	59	52	62	48	60	79	89
1 Primary-educated labor (grade 1-7)	86	94	118	144	180	200	89	118	140	179	222	279

Figure 35: Breakdown of energy sector jobs by skill level – Reference Cases

3.6.2. Income inequality

The economic impact of the emissions constraint – shown in the different GDP trajectories in Figure 36 - results in a slight reduction in total employment, relative to the unconstrained case, by 2050.

Figure 37 shows long-term shifts in inequality for the Reference Cases, visualised by the Palma ratio (a ratio of the income of the top 10% of earners relative to the bottom 40%). South Africa has one of the world's highest levels of inequality, and this is reflected in the current Palma ratio above 6.6 (implying that the average income of the top 10% is 6.6 times higher than the bottom 40%). The results of the CGE model show, over time, that income distribution improves slightly not significantly, with a relatively small difference between the two Reference Cases. Again, the representation of inequality, and the ability to determine and track shifts meaningfully, is fairly limited in the eSAGE model, and further work would be needed to unpack this in greater detail.

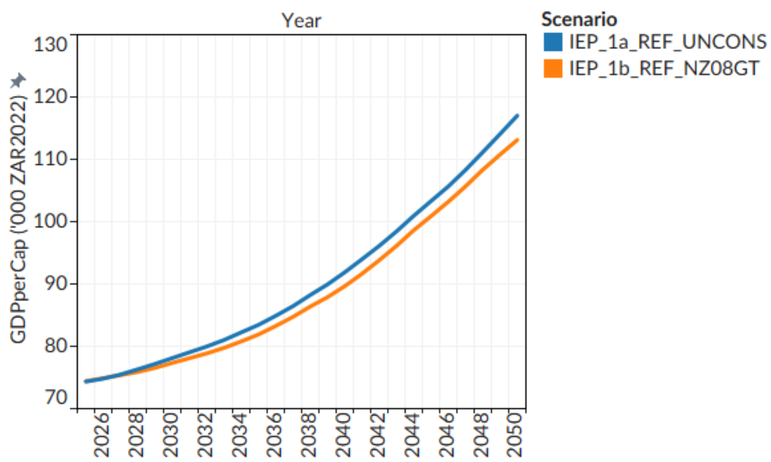


Figure 36: Comparing GDP per capita projections for the Reference Cases without and with an emissions constraint

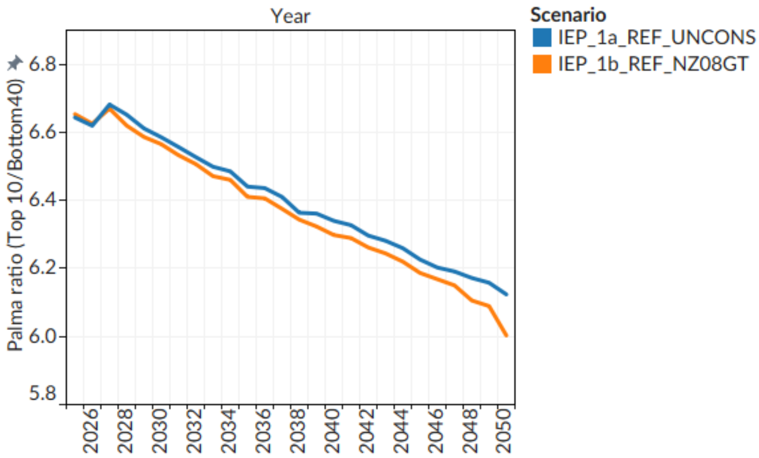


Figure 37: Palma ratio for the Reference Cases without and with emissions constraints

Figure 38 shows the overall income distribution by decile for the two Reference Cases in 2050. The figure shows that income is slightly lower for the constrained case than the unconstrained case in the higher deciles, however there is very little difference among the lower deciles. This indicates a very marginal overall effect on inequality between the two cases, and shows that, without further intervention (not just in the energy sector), South African society will remain largely unequal into the future.

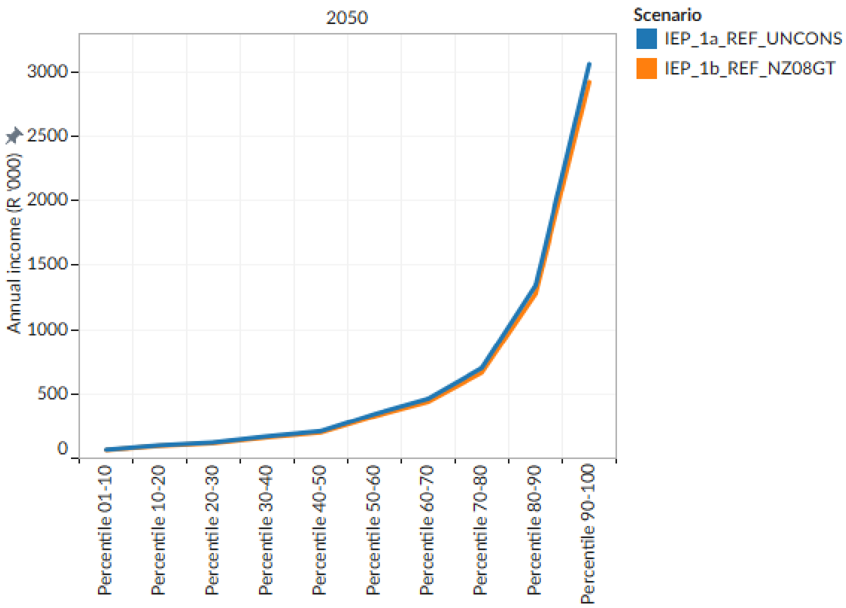


Figure 38: Income distribution by decile for the Reference Cases in 2050

4. Policy Scenarios

The following sub-sections provide a brief overview of the set-up and key results of each of the Policy Scenarios described in Table 10 above. Results for the policy scenarios – with the exception of the Social Provisioning scenario - were reported in the previous report (published February 2025), but subsequent modelling adjustments have meant some of the results have changed since that report was issued.. The main focus of this section will however be the social provisioning policy scenario that was added subsequent to the previous report.

4.1. Overview

The policy scenarios considered for this analysis are described in Table 10. These scenarios were chosen as part of the WWF stakeholder engagement process to reflect contemporary energy policy in South Africa. They are based either on policies that already exist in official or at least draft form, such as the draft Gas Masterplan (DMRE, 2024a), or are derived from existing policies that are currently being updated, e.g. the Green Transport Strategy (DoT, 2018), or have otherwise received considerable policy attention, e.g. from the Just Energy Transition – Investment Plan (Presidency, 2022) process (as is the case of green hydrogen), or the previous National Energy Efficiency Strategy (DoE, 2016).

The additional social provisioning scenario aims to examine a method for representing increased access to affordable electricity access to low-income households, with subsidies also serving to reduce energy poverty (recalling that an IEP by itself cannot solve broader poverty and inequality challenges in South Africa). This is modelled as a ramp-up of free-basic electricity (FBE) provision and utilisation, as well as rollout of solar water heaters (SWHs) and more efficient appliances (such as better fridges). The characteristics and modelling of this scenario were largely informed by the work of the Public Affairs Research Institute (PARI) into continuing challenges with electricity access – and meeting SDG 7 by 2030 – in South Africa (Ledger and Rampedi, 2022).

Table 10: Overview of updated Set 2 Policy Scenarios

Name	Description
Big Gas	Ibhubezi supply option introduced early (from 2027 as opposed to 2037); 6 GW gas CCGT 'forced' before 2030 as per draft IRP 2024 (DMRE, 2024b). Previous versions of this scenario also included the Brulpadda (Block 11B/12B) supply option, however this has been excluded from the final version due to the current uncertainties on the future of this project. No speculative inclusion of other offshore resources is included, so the majority of gas in this scenario is provided by imported LNG.
Hydrogen	Production and export capacity of commodities fuelled by hydrogen: ammonia, iron and synthetic aviation fuel – export demand for these ramps up drastically
Green Transport	Subsidised costs applied to EVs over 2030 - 2040 as well as moderate (5% p.a.) shift of passenger transport from road to buses/BRTs and rail, broadly in line with the Department of Transport's Green Transport Strategy.
Energy Efficiency	Modest energy efficiency gains in industry, due to efficient motors and lighting, with improved EE due to building compliance and tech shifts in the residential and commercial sectors
Social provisioning	Ramping up electricity usage in low-income households through increased deployment of free basic electricity (up to 350 kWh a month) and solar water heaters which offset some of the 350 kWh

4.2. Big Gas

The purpose the Big Gas policy scenario is to test the impacts of some of the proposals and assumptions for the development of an indigenous natural gas supply industry, as stated in the DMRE's draft Gas Masterplan (GMP) of 2024 (DMRE, 2024a). In particular, the scenario examines the potential effects of the Block 2A (Ibhubesi) coastal gas resource reaching production levels envisaged in the Base Case of the draft GMP, in terms of offsetting LNG import demand as well as increasing the potential role of gas in the South African energy system. Previous versions of this policy scenario also considered the Brulpadda blocks (11B/12B), but these were omitted from the final versions of this analysis as the mounting challenges for this resource – in terms of physical location, high capital costs, and market uncertainty – have made it increasingly unviable at this point in time.

Whereas the Reference Case assumes that the Ibhubesi resource, off South Africa's west coast, only becomes available from 2037, the Big Gas scenario accelerates this timeline to 2027, in accordance with the draft GMP Base Case timeline. The scenario also assumes that Ibhubesi is able to supply gas at the 'Mid Indigenous Production cost' level, expressed in Table 6 of the draft GMP, of USD 6 per GJ (equivalent to ZAR 98 in 2022 ZAR), as opposed to the higher base cost assumption for gas supply shown in Table 4.

Table 11: Indigenous gas supply assumptions for the Big Gas scenario

Parameter	Block 2A Reference Case	Block 2A Big Gas Policy Scenario
First year	2037	2027
Peak production [PJ/a]	29.2	29.2
Peak production reached in	2041	2030
Supply cost [R/PJ]	121	98

Finally, the scenario also assumes that a fixed 6 GW of gas CCGT capacity are built by 2030 (3 GW each in 2029 and 2030), in line with the draft GMP and draft IRP 2024 (DMRE, 2024b). Whilst the building of the capacity is fixed in the model, the model determines the extent to which this capacity gets utilised endogenously.

Figure 39 shows the earlier availability of Ibhubesi and increased gas demand before 2030 in the sector increases overall gas consumption in the short term (up to 180 PJ in 2030 in the policy scenario, compared to 140 PJ in the Reference Case), but results in only a marginal increase in the longer term (223 PJ compared to 203 PJ by 2050). There is no additional use of gas in other sectors, such as refineries or industry.

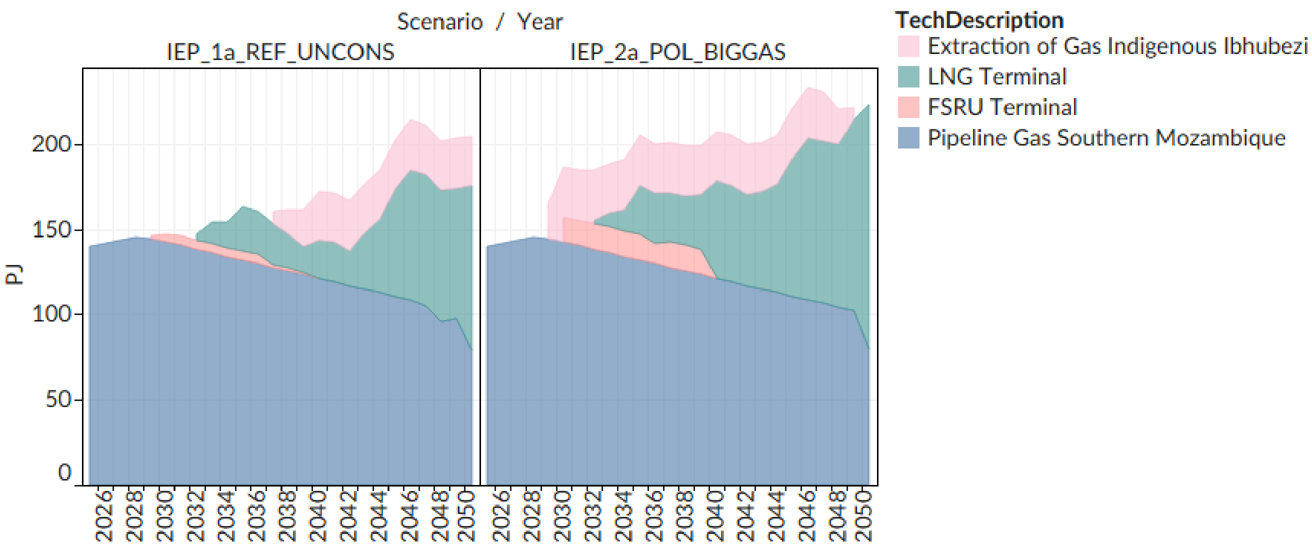


Figure 39: Comparison of gas supply options between the Reference Case (unconstrained) and Big Gas policy scenario

In discussions at the Stakeholder Scenario Workshop, participants expressed doubts and concerns about the Big Gas scenario. While additional indigenous production would potentially offset risk from exposure to volatile international markets, the extent to which this could happen would depend on the ownership and operational characteristics of the gas fields, and how they would determine their prices (i.e. the extent to which international benchmarks would still determine local supply prices). Participants expressed views that the production costs provided in the draft GMP are likely too optimistic. Furthermore, if South Africa does embark on a transition to net zero CO_2 emissions, gas can only play a significant long-term role in the power sector, and only if it is coupled with CCS technology.

4.3. Energy Efficiency

The Energy Efficiency Policy Scenario examines the effects of specific measures to improve energy efficiency in the commerce, residential and industry sectors of the SATIM model. Transport efficiency measures are considered separately in the 'Green Transport' Policy Scenario (see below).

Both the residential and commercial sector improve their energy efficiency in two ways. The first is a lowering of useful energy demand, for example the SANS 10400 standards require better thermal performance in buildings, and this is assumed to decrease the demand for heating and cooling in both new residential and commercial buildings. The second is at the technology level, and here it is possible to both increase the share of efficient technologies supplying an energy service, as well the efficiency of a technology, for example the penetration of LED's to supply lighting is increased to mimic a faster adoption rate and there is also an increasing in the lumens/Watt of LED's over time, that together contribute to a higher efficiency in supplying lighting whilst the useful energy demand for lighting remains the same.

Useful energy demand adjustments

- In Residential this affects space heating and cooling demand
- In Commerce this affects space heating, space cooling and lighting
- These adjustments are only applied to new commercial and residential buildings.

Technology efficiency adjustments

- In Residential this affects electrical efficiency primarily and is applied differently in different household income groups (but is the same in new and existing buildings) –
    - In low-income households the efficiency of cooking, refrigeration, space heating and televisions and other small appliances improves
    - In middle income households the efficiency of cooking, refrigeration, space heating and televisions and other small appliances and water heating improves
    - In high income households the efficiency of cooking, refrigeration, space heating and televisions and other small appliances and water heating improves
- In Commerce these changes are applied differently in new and existing buildings- new buildings are assumed to have a higher aggregate efficiency of supplying energy services in the base year compared to existing buildings as well as more flexibility to adopt newer and more efficient technologies as they become available.
- However the basket of technologies that see an improvement in new and existing buildings is largely the same, the difference lies primarily in the share of technologies that supply the energy services in each year.

Energy services that see an improvement in technology efficiency in commerce are cooling, heating, lighting and refrigeration.

Fairly minor efficiency improvements are considered for industry – specifically a switch to more efficient motors, and installation of more efficient lighting. Whilst such measures provide some energy savings, they are relatively small compared to the potential for savings from improved efficiency of process heating, for example, in heavy industries such as iron and steel. However, the status of the level of efficiency and application of energy efficiency measures in such large energy-users is currently highly uncertain. Given the concerns expressed repeatedly by industry about the effects of rising energy prices, it could be reasonably assumed that much of the 'low-hanging fruit' for efficiency gains has already been attained.

Previous work by ESRG has used the targets set in the draft post-2015 National Energy Efficiency Strategy as a benchmark for estimating and modelling potential efficiency gains in industry. However, this draft report is now considered largely out-of-date, and it is not clear to what extent industry has made progress on reaching these targets (or whether they were attainable in the first place).

In light of this, ESRG is currently undertaking work under a different project to update its industry data – however this process is still ongoing, and thus in the interim the Energy Efficiency Policy Scenario here shows only the improvements outlined above. shows aggregate savings of around 4% for commercial energy use and 10% for residential energy use for the energy efficiency policy scenario, relative to the Reference Case in 2050. There is very little difference in industrial energy intensity between the two model runs.

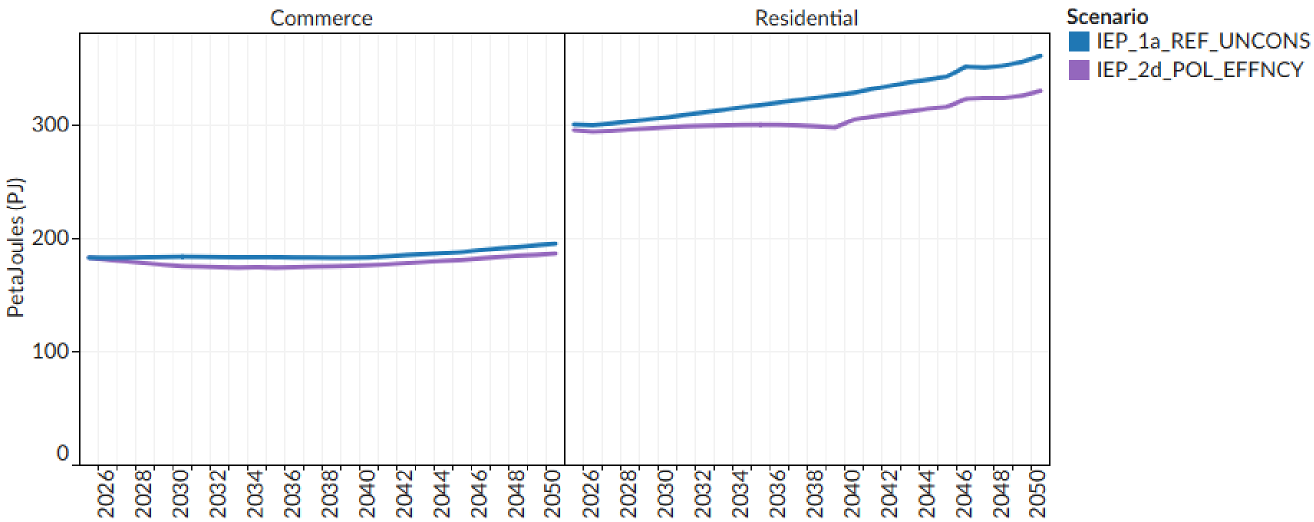


Figure 40: Aggregate energy for Commerce and Residential Sectors, Reference Case and EE

4.4. Green Transport

The Green Transport Policy Scenario examines the impacts of a potential subsidy on electric vehicle purchase prices and a small mode shift from private to public transport for passengers. Subsidies on EVs are modelled as a reduction in capital cost of the vehicles below Reference Case baseline assumptions, with the 'discount' value adjusted with time as shown in Table 12 (baseline vehicle cost projections are shown in Appendix A).

Table 12: Electric vehicle capital cost reductions below baseline assumed for the Green Transport scenario

Vehicle type	Engine	2030	2035	2040	2045	2050
Passenger Priv	BEV	10%	5.0%	0.0%	0%	0%
Passenger Pub	BEV	15%	10%	5%	0%	0%
Freight Road	BEV	15%	10%	5%	0%	0%

Passenger demand shifts from private to public transport means are modelled with the following assumptions:

- Annual mileage of private vehicles reduces 0.5% p.a. for middle- and high- income households
- Integration of public transports (improved urban planning) reduces walking and waiting time 1% p.a.
- Increase of public transport (BRT) utilisation of 5% p.a. across income groups
- Reduction in SUV usage of 0.5% p.a. and increase in motorcycles of 2% p.a.

The results, reflected in passenger-kilometre shifts in Figure 41, showed a considerable increase in uptake of electric vehicles in the policy scenario, relative to the Reference Case. However, the scenario showed only a very moderate shift in transport demand from private to public modes.

Reflecting on these results, participants at the Stakeholder Scenario Workshop felt that the Green Transport Scenario Policy was not ambitious enough, and that a truly 'green' transport strategy would envision a much greater shift to public transport, as well as a greater role for non-motorised transport. Other considerations raised at the workshop for transport modelling included assessing whether infrastructure costs can be incorporated into the model, as well as the costs of traffic congestion that would be incurred with significant increases in private road vehicles, and a greater emphasis on integrated public transport modalities, for example by reducing walking distances to and from, and waiting times at, bus and metro rail stations. The extent to which these elements can be factored into the modelling will be explored in detail in the scenario set 3.

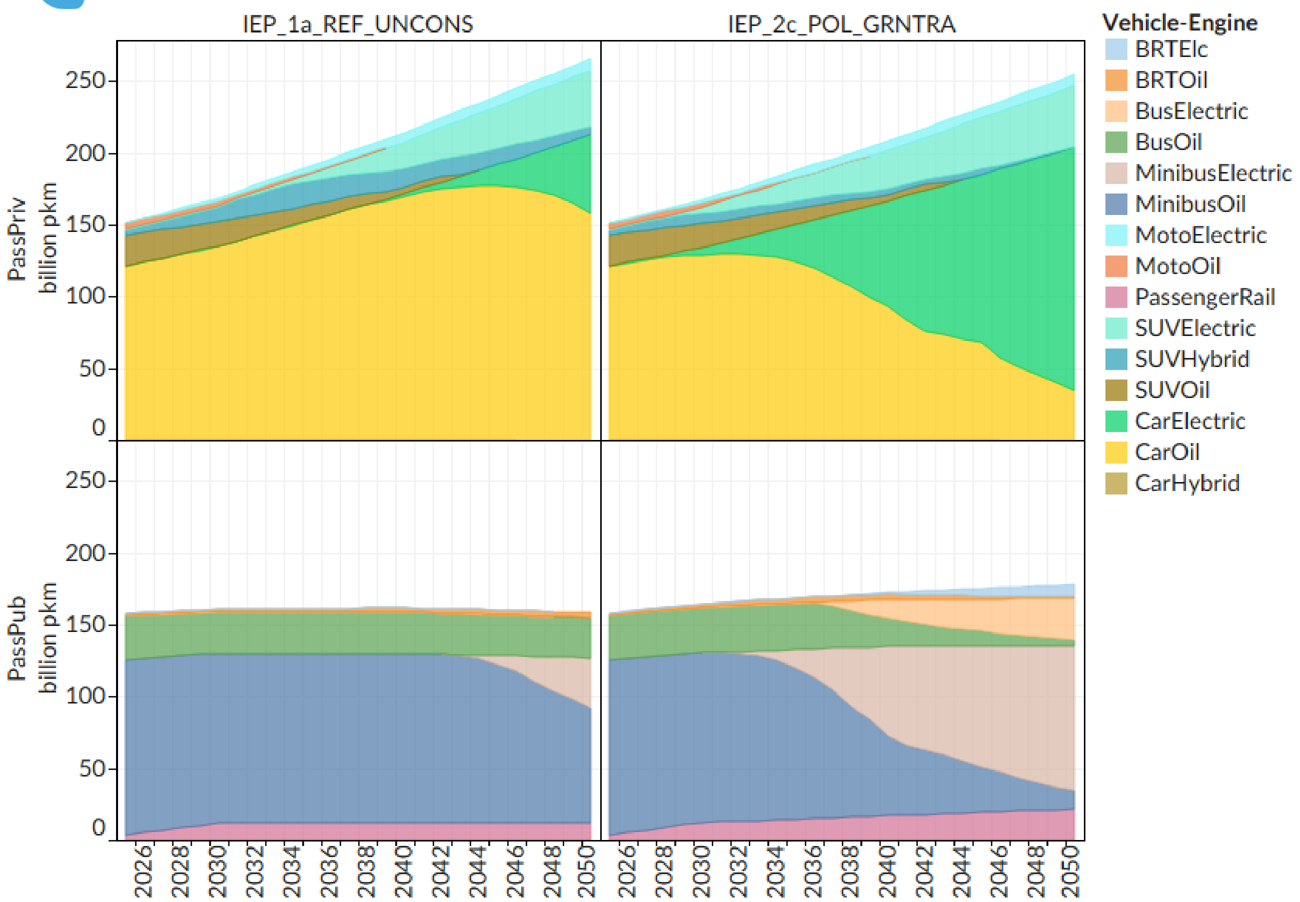


Figure 41: Passenger transport by vehicle and fuel comparing the unconstrained Reference Case and Green Transport Policy scenario

4.5. Hydrogen

The Hydrogen scenario assumes a significant ramp-up in the production of export commodities using green hydrogen in the process: namely direct reduced iron, ammonia, synthetic aviation fuel, and hydrogen itself.

Green ammonia has previously been identified as a key potential market for South Africa (DST, 2022), it's uses extend from energy storage (fuel) for power, and shipping fuel, to fertilizer. Extensive research has also identified renewable rich countries with iron ore deposits as potential global players in decarbonised global steel industries – South Africa is well positioned to export to regions like the EU market (Trollip et al., 2022).

The hydrogen technology characterised in SATIM is the alkaline electrolyser, which uses electricity to convert water into hydrogen and oxygen. 'Green' hydrogen is created when the electricity driving the electrolysis process is derived from low or zero-carbon power generation (as opposed to 'grey' hydrogen, such as what is produced from coal in Sasol's Fischer-Tropsch process, or 'blue' hydrogen, produced from natural gas). However, the way hydrogen is implemented in SATIM – essentially by drawing power from the electricity grid to power electrolysis – means it cannot technically be 'pure green', since South Africa's electricity mix still includes some 'non-green' technologies, even under the emissions constrained Reference Case variants.

Table 13: Parameters for hydrogen technology in SATIM

Hydrogen electrolyser assumptions				
Technology:	Alkaline electrolysers (use electricity to convert H_2O to hydrogen and oxygen)			
Measure	**Unit**	**2020**	**2030**	**2050**
Capital costs	(2022 ZAR / kW-electrolyser rating)	16 848	11 084	7 980
FOM costs		842	554	399
Life	(years)	8	10	14
Efficiency	(Hydrogen output / electric input)	0.67	0.68	0.75
Source:	IEA (2021b)			

The table below summarises the hydrogen-based products in this scenario. Iron production based on the work by Trollip et al. (Trollip et al., 2022). For ammonia, and synthetic aviation fuel, and hydrogen gas, these numbers were based on the ambitious ENERTRAG's Green Hydrogen export opportunity for South Africa, the Green Hydrogen Commercialisation Strategy (DTIC, 2023), and Ricardo and Environmental Defense (Ricardo and Environmental Defense Fund, 2021).

Table 14: Export of hydrogen and hydrogen-based commodities in the Hydrogen scenario

Commodity	**Unit**	**2030**	**2050**
Green iron (DRI)	Mt pa	0.5	7
Green ammonia	PJ	5.5	49.7
Green H2	PJ	8.3	193.1
Jet fuel	PJ	3.15	94.60

In general, the Hydrogen scenario did not gain much support from participants at the Stakeholder Scenario Workshop. Concerns were raised about the potential toxicity of ammonia production and storage in tanks at harbours close to fisheries, whilst indicators shown in the Results Framework suggest that upscaled hydrogen production places a lot of extra risk for security of supply, with comparatively little benefit in terms of social development or equity. This despite the potential international demand for exports of hydrogen and hydrogen products, for which there is still considerable uncertainty at this stage.

4.6. Social provisioning

One of the foremost challenges that integrated energy planning should address is the high and persistent levels of energy poverty experienced by millions of households in South Africa. Using an expenditure-based benchmark where households spending more than 10% of their income on energy are considered “energy poor”, it is estimated that nearly half of all South African households are energy poor, with some households in the lowest quintile spending more than 25% of their income on energy (SEA, 2017). Additionally, distribution networks within local municipalities are inefficient and fragmented. Thus, community members within informal communities and some within the recognized urban centres do not have access to electrical supply within the grid.

It is also the case that, while more than 80% of households officially have electricity access – in the sense that they have a mains electricity connection to their household (see Figure 42 below) – in many cases the cost of electricity is too prohibitively high for households to *use* electricity; these households therefore still rely on fuel stacking, including ‘dirty’ and harmful fuels like coal and wood (Phogole et al., 2022; Wernecke et al., 2024). Even with the availability of 50 kWh in the form of free basic electricity (FBE), estimates indicate that fewer than 25% of funded and eligible households actually receive FBE, implying that there are more than 8 million households who are funded for GBE but not receiving it (Ledger, 2021). Furthermore, 50 kWh is insufficient for basic energy needs, with the costs thereafter still prohibitive for further use (Ledger, 2021). In addition, because of shared connections in backyards shacks and families sharing low-income accommodation, many households that should qualify for FBE exceed a consumption threshold that consequently excludes them from receiving this allocation.

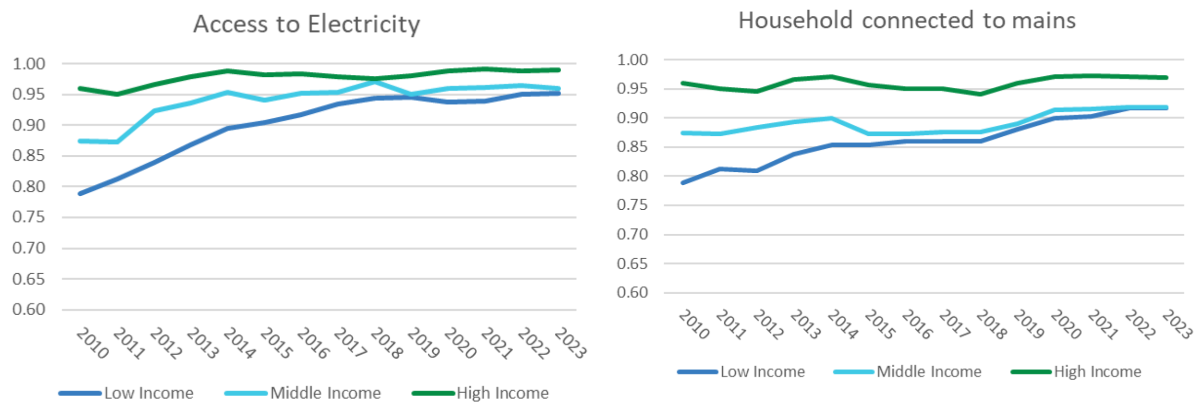


Figure 42: Historic trends in household electricity access (authors’ calcs from StatsSA surveys and other data collection); access is higher than mains connections due to a combination of off-grid access as well as shared connections

In this work, energy poverty in low-income households is tackled through modelling two primary measures: increasing the FBE allocation and rolling out solar water heaters (SWHs) to provide hot water (and offset additional electricity load for geysers). It is not suggested that these measures would solve (energy) poverty in their entirety but would provide significant improvement relative to the *status quo* for low-income households. The model assumes that these measures would be fully subsidised, and therefore not result in additional financial burden for low-income households. Full modelling of the effects of such measures on, for example, the country’s fiscus or revenue streams could not be fully incorporated into the eSAGE model and will require substantial further work – but will be necessary to ensure such measures are accurately and fully costed. For this reason, the model results do not reflect improvements in overall inequality or poverty (for example, reduced Palma ratio) that may result from these measures.

The social provisioning measures modelled here are also only applied to low-income households, with effects on middle and high-income households not considered (thus, for example, some biomass use may still occur in middle income households, whilst being largely phased out of low-income households).

For the 'Social Provisioning' scenario here, it is assumed that the rate and pace of electrification and enhanced energy access for low-income households, through a combination of increased FBE allocations and rollout of solar water heaters (SWHs) to all 'eligible' low-income households, with full implementation of these measures achieved by 2030. Households must have mains water access (see historic trends in Figure 43) to be eligible for SWHs; it is assumed that this rate rises to 70% by 2035 and 100% by 2050.

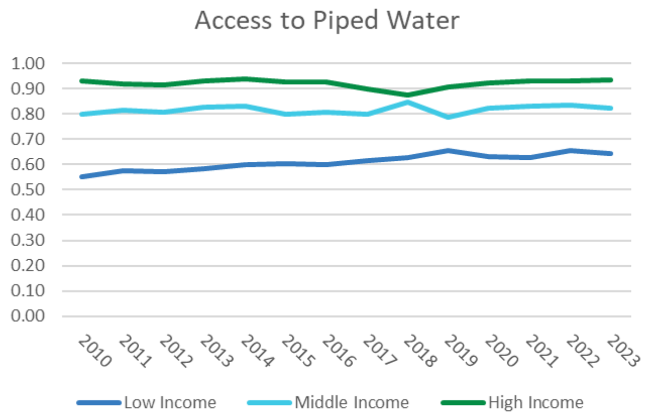


Figure 43: Historic water access (authors' calcs from StatsSA surveys and other data collection)

Using the PARI 2022 report as a benchmark, it is assumed that each household needs 350 kWh per month to replace use of coal, paraffin and most wood. A small amount of wood use is assumed to remain, for some heating and cooking, reflecting some socio-economic factors that go beyond pure cost and access means – such as cultural beliefs and taste preferences (Masekela and Semenya, 2021). It is further assumed all households are able to access efficient appliances, such as refrigerators, that meet minimum efficiency standards, under an expansion of the current MEPS programme. With these measures, it is assumed that households' electricity needs for all end-uses, *other than water heating*, amount to 180 kWh per month.

The water heating requirements are assumed to be fulfilled entirely by low-pressure solar water heaters that get rolled out to low-income households, which account for the remaining estimate 170 kWh of energy requirements for monthly household water heating. This is shown in Figure 44 below. Based on the aforementioned eligibility criteria, it is thus determined that, under this scenario some 6 493 thousand SWHs would be rolled out to low-income households by 2035 (covering most households in this income bracket), rising to 6 774 thousand by 2050.

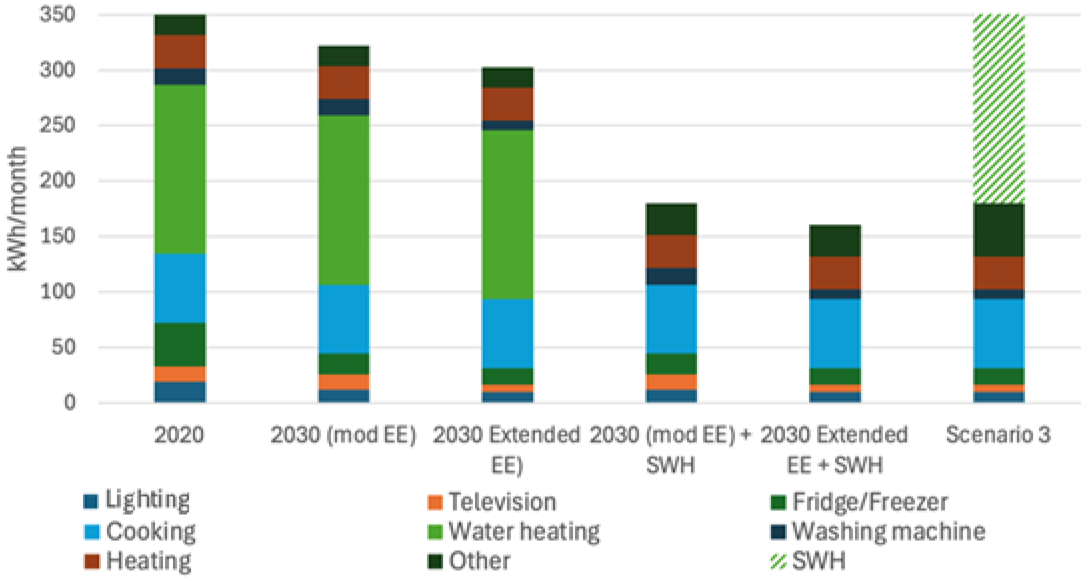


Figure 44: Effect of energy efficiency and SWH usage on household electricity usage

The effects of these measures are shown in Figure 45 below (comparing the Social Provisioning scenario in maroon to the Reference Case in blue), where average electricity consumption per person increases 85 – 100% above the Reference level, while solid fuel use drops by more than 70%.

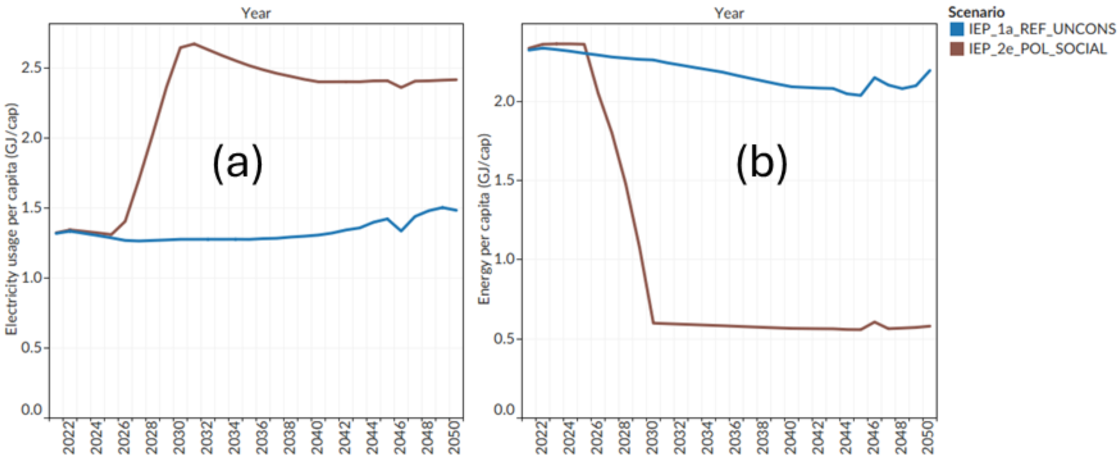


Figure 45: Low-income household energy uses per capita, showing (a) electricity and (b) solid fuels (coal and wood)

5. Ideal Energy Scenario

This section describes the set-up and results of the set 3 scenario analysis – the 'Ideal Energy Scenario' with a series of sensitivity analyses for key areas of interest and uncertainty. As stated above, the 'Ideal Energy Scenario' is not intended as a comprehensive 'alternative' integrated energy plan, nor does it purport to represent a unanimous view among stakeholders on what would constitute an "ideal" energy system. It rather represents a set of model results based on a series of inputs gathered from stakeholders that broadly describe elements of an ideal energy future for South Africa, in terms of aspirations for improved energy access and efficiency, as well as reduced greenhouse gas and air pollution emissions, without greatly impacting on long-term socio-economic growth and development.

Furthermore, the model results themselves only provide one half of a full narrative towards the realisation of an ideal energy future for South Africans – the other half, which goes beyond the model, concerns the policy, societal institutional measures that would be necessary to ensure a holistic and participatory transition, founded on the principles of a just transition and ensuring that no one is left behind. Some of these elements are addressed in the policy paper that accompanies this report. For the rest of this section, the report will address the parameters used to characterise and model the Ideal Energy Scenario in SATIMGE, and the results in terms of key indicators that emerge from this analysis.

5.1. Overview

The key input parameters for the Ideal Energy Scenario were determined based on stakeholder inputs and comments, and in particular on feedback to the Reference Case and Policy Scenarios discussed previously. The following characteristics form the basis of the Ideal Energy Scenario (given the modelling code IEP_3a_SCN_IDEALS), with additional variations for sensitivity analyses (and their modelling codes) provided where relevant (where not stated, all other model and scenario assumptions are the same as was the case for the unconstrained Reference Case above):

- As with the Reference Case with constraints, net zero CO_2 to be reached economy-wide by 2050 with cumulative net GHG emissions over the period 2021 – 2050 limited to 8 Gt CO_2-eq
    - Sensitivity analyses: cumulative limits over the 2021 – 2050 of 9 Gt CO_2-eq (IEP_3b_SEN_GHG9GT) and 7 Gt CO_2-eq (IEP_3c_SEN_GHG7GT) respectively
    - Sensitivity analysis: removing the option of CCS and the net-zero CO_2 by 2050 target (but keeping the 8 Gt GHG limit) to ascertain residual CO_2 emissions in the absence of CCS or other last-mile/CDR technology options (IEP_3d_SEN_NOCCST)
- Public transport to account for 80% of total passenger-kilometers by 2050, of which
    - Bus-rapid transit accounts for more than 20%
    - Electric rail accounts for more than 25%
    - Minibus taxis account for less than 50%
    - Average walking and waiting time for public transport reduced from 55% to 30% of trip durations (see detailed Transport base assumptions in Appendix A)
- Social provisioning: FBE increase to an *equivalent* 350 kWh per month for low-income households (including SWH rollout – actual electricity use amounts to between 160 – 180 kWh, depending on

EE measures) and energy efficient appliance rollout, as was the case for the Policy Scenario (see section 4.6 above)

- Localisation of the clean electricity value chain, including construction, operation and equipment and machinery manufacturing, in line with previous ESRG analysis (see Tatham et al., 2024), with local content reaching 85% by 2050 (current levels are estimated at around 47% for machinery and 76% for metal products, although construction is over 90%)
  - Sensitivity analysis: a lower local content target of 60% by 2050 is modelled (IEP_3e_SEN_LOLOCL) to analyse potential trade-offs between localisation and electricity prices
- Endogenous retirement of coal-to-liquids capacity allowed from 2034, as with the Reference Case
  - Sensitivity analyses: allowing endogenous CTL retirement earlier (from 2029 – IEP_3f_SEN_ECTL29) or later (from 2050 – IEP_3g_SEN_ECTL45)
- (DST, 2021)Figure 46Figure 47

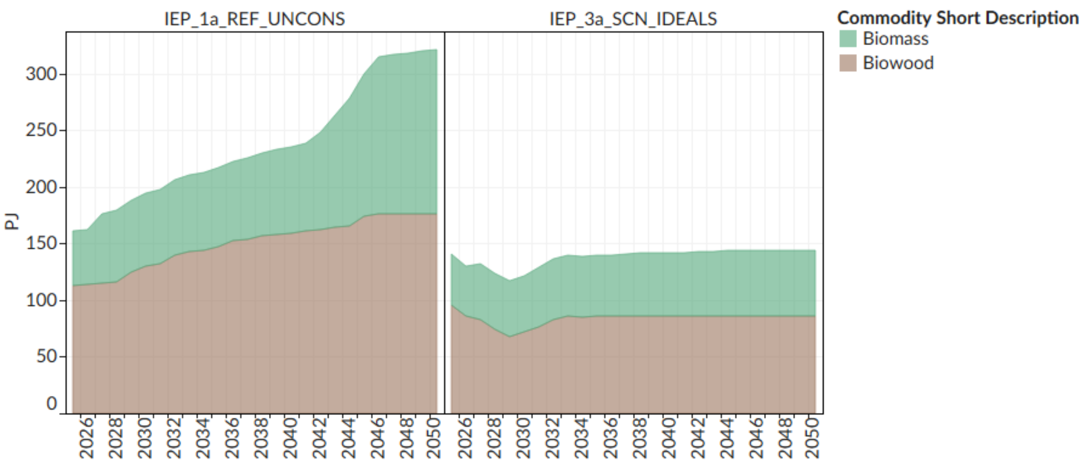


Figure 46: Biomass supply comparing the Ideal Energy Scenario with the Reference Case

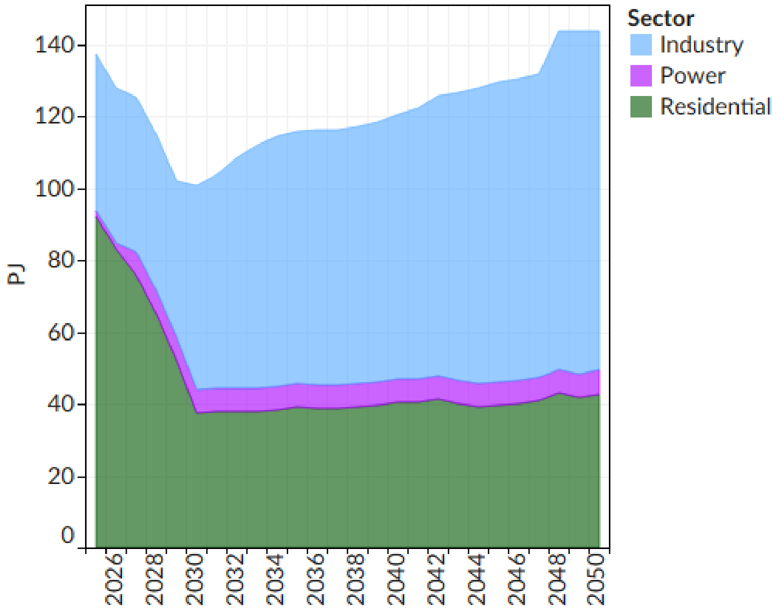


Figure 47: Bioenergy use in the Ideal Energy Scenario

- Energy efficiency ramped up further beyond the Energy Efficiency Policy Scenario, with more ambitious measures modeled particularly for the industry sector (described in the industry results section below)
- Hydrogen as a fuel limited only to existing hard-to-abate industrial sectors, e.g. iron and steel, with no ramp up in 'green' exports such as green-H_2-fueled ammonia
    - Sensitivity analysis: allowing some hydrogen-fueled exports, as was the case for the Hydrogen Policy Scenario (IEP_3n_SEN_HIGGXT)

Additional sensitivity analyses that were run over and above those listed above, include:

- A 'low fossil fuel prices' scenario (IEP_3h_SEN_LOWDRT), where global fossil fuel prices follow the IEA's Net Zero Energy scenario trajectory (IEA, 2024a) which assumes, due to diminished global demand for fossil fuels in a world that transitions globally to net zero CO_2, fossil fuel prices drop significantly. Note that IEA's higher fossil fuel price trajectories, such as for their 'Stated Policies' Scenario, are still lower than the constant assumptions applied in this work (see Table 4 above).
- Two sensitivity runs with varying discount rates: a low (3%) discount rate – IEP_3k_SEN_LOWDRT – and a higher (12%) discount rate – IEP_3m_SEN_HIGDRT. Note that the discount rates here should not be confused with a 'social discount rate' which differentiates how society values current and future money flows based on interpretations of their costs and benefits, with applications primarily in intergenerational equity analysis (an important consideration for long-term integrated energy planning, but one not explored in-depth here).
- An 'optimistic' battery learning sensitivity, where battery overnight costs for renewable energy power follow the more optimistic learning path shown in Figure 8 above (IEP_3p_SEN_LOWBAT).

The following sections present the results of the scenario analysis, beginning, as before, with energy demand, followed by energy supply, greenhouse gas emissions, externalities and, finally, socio-economic indicators.

5.2. Energy demand

Figure 48 shows economy-wide final energy consumption for the Ideal Energy Scenario.

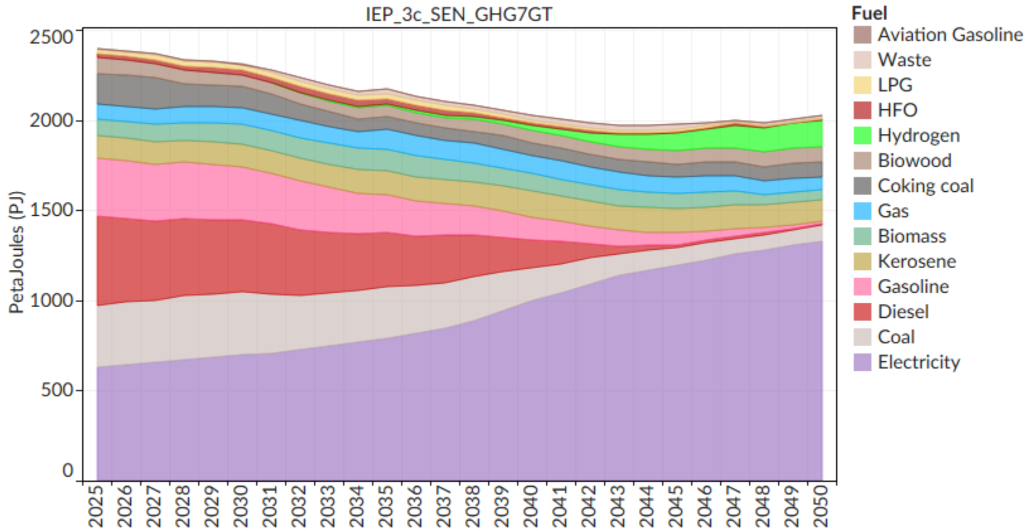


Figure 48: Economy-wide final energy demand for the Ideal Energy Scenario

As was the case with the constrained Reference Case, the Ideal Energy Scenario shows a significant shift away from fossil fuel usage to low-carbon electricity, with some hydrogen use for hard-to-abate industry sectors Figure 49. Residual coal usage still remains for use in sectors such as cement, but liquid fuel usage is even further limited, with significantly reduced and mostly electrified transport demand.

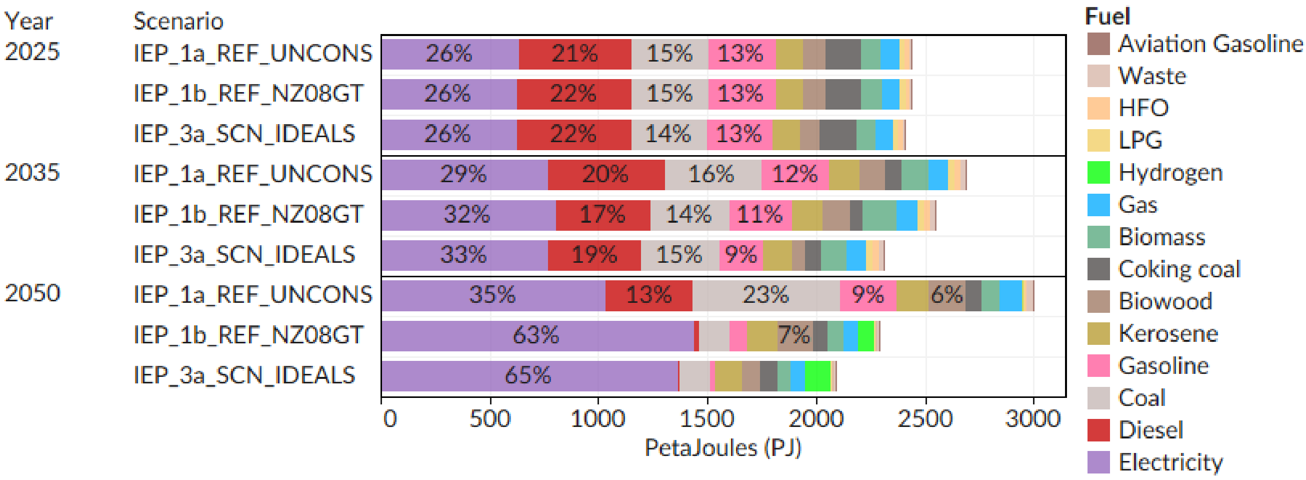


Figure 49: Final energy consumption by fuel comparing the Reference Cases and Ideal Energy Scenario

The following sub-sections unpack energy demand by sector in greater detail.

5.2.1. Households

The Ideal Energy Scenario maintains the drive towards electrification in low-income households that was shown in the Policy Scenario previously, with additional energy efficiency measures across all income groups to reduce overall energy usage.

Electrification and solid fuel phase-down

As shown in Figure 50, aggregate energy consumption for low-income households decreases, as population shifts from the low to middle income bracket, and energy carriers shift from wood to predominantly electricity. Note that energy input for water heating does not show the contribution from solar water heaters, which accounts for the majority of low-income household hot water needs by 2050. Figure 51 shows the corresponding shifts in per capita energy use for low-income households, showing that electricity use per capita increases similar to the Policy Scenario, while wood use reduces even further than was shown in the Policy Scenario. The latter is due to the limit on biomass as part of the Ideal Energy Scenario, which drives further reductions in wood use in households.

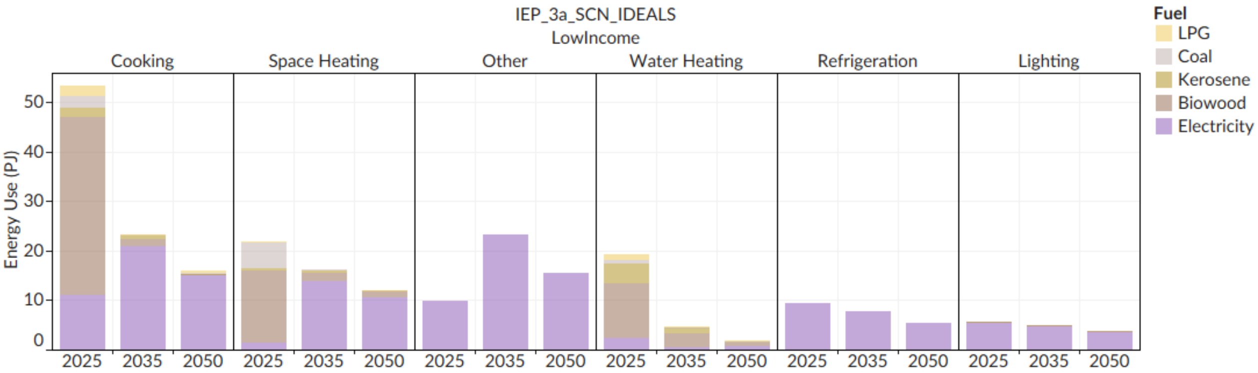


Figure 50: Energy fuel and end-use for low-income households in the Ideal Energy Scenario

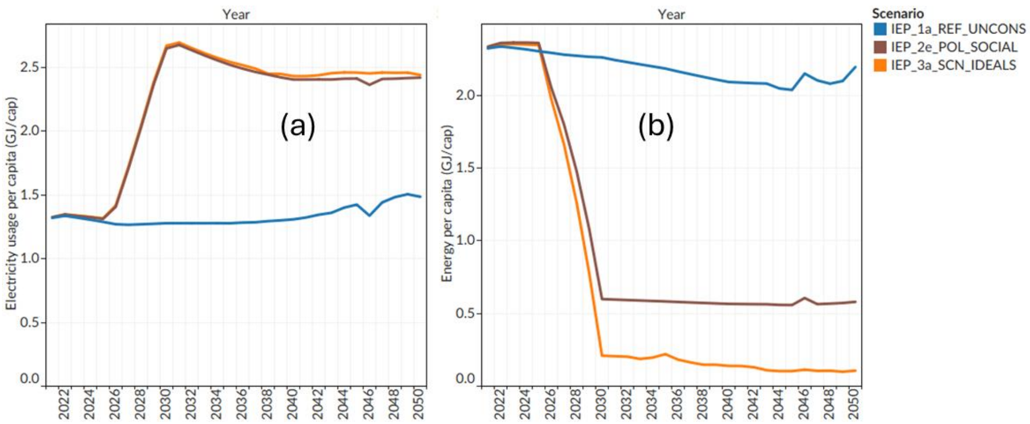


Figure 51: Low-income households: (a) electricity (a) and (b) solid fuel use per capita by scenario

Energy efficiency

Figure 52 shows differences in aggregate energy consumption for the residential sector, comparing the Ideal Energy Scenario with the Reference Case and Energy Efficiency and Social Provisioning scenarios. The Ideal

Energy Scenario combines the FBE measures of the social provisioning scenario with additional rollout of energy efficient appliances across all income groups, which results in energy savings relative to the Reference Case and Policy Scenarios.

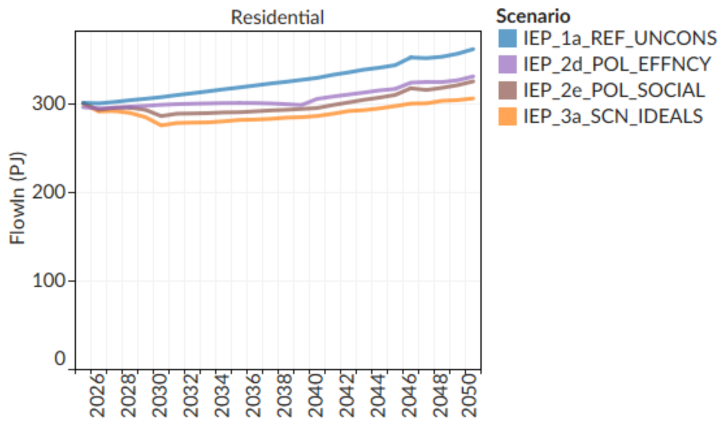


Figure 52: Comparing aggregate residential energy consumption between scenarios

5.2.2. Transport

As with previous scenarios, the Ideal Energy Scenario includes shifts to green transport for both passenger and freight (land-based) transport.

Passenger transport

The following parameters were modelled for passenger transport:

- Private vehicle ownership reduces from base-year levels (see Table 25 in Appendix A) by 2% per annum for middle income road users, and 2.25% for upper income users, from 2025 through 2050 – reflecting declining use and need for private vehicles under a scaled-up integrated transport network
- Annual average private vehicle mileage reduces 25% by 2050 below 2025 levels for all income groups
- Spatial transformation and integrated transport measures are assumed to reduce walking and waiting time for public transport facilities to 30% of total travel-time budget by 2050 (relative to 55% in the base year and Reference Case)
- Bus-Rapid Transit (BRT) usage grows 15% p.a. from 2025 through 2050
- Electric rail usage, in terms of passenger-kilometres, recovers to pre-Covid levels by 2030. Rail usage then grows such that the split between rail, buses (non-BRT) and minibus taxis reaches 40% / 10% / 50% (respectively) by 2050
- On the supply-side, private BEVs are assumed to reach CAPEX cost-parity (excl. tax effects) with ICEs by 2035 (in line with international trends), while public BEVs (including buses and mini-buses) reach the same cost-parity by 2040

Figure 53 shows the resulting growth and shift in passenger transport demand from 2025 levels (near 50:50) to an 80% share of public transport by 2050.

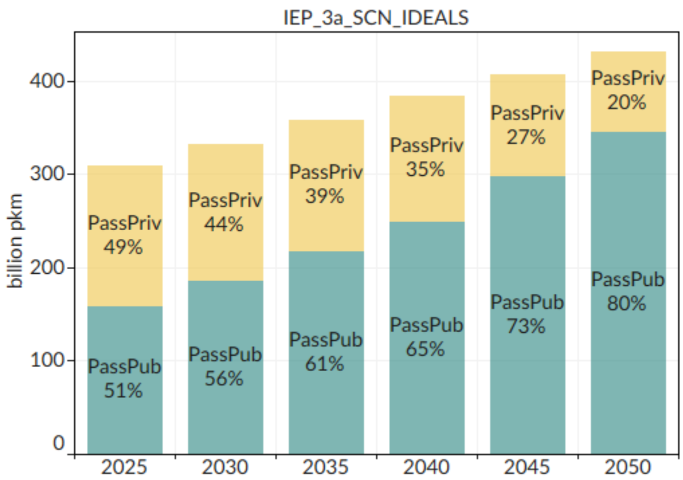


Figure 53: Ideal energy scenario shift from private to public transport

Figure 54 below shows the resulting shifts in passenger-kilometres by vehicle type and fuel for the Ideal Energy Scenario, while Figure 55 shows the shift in vehicle parc in comparison to the Reference Case.

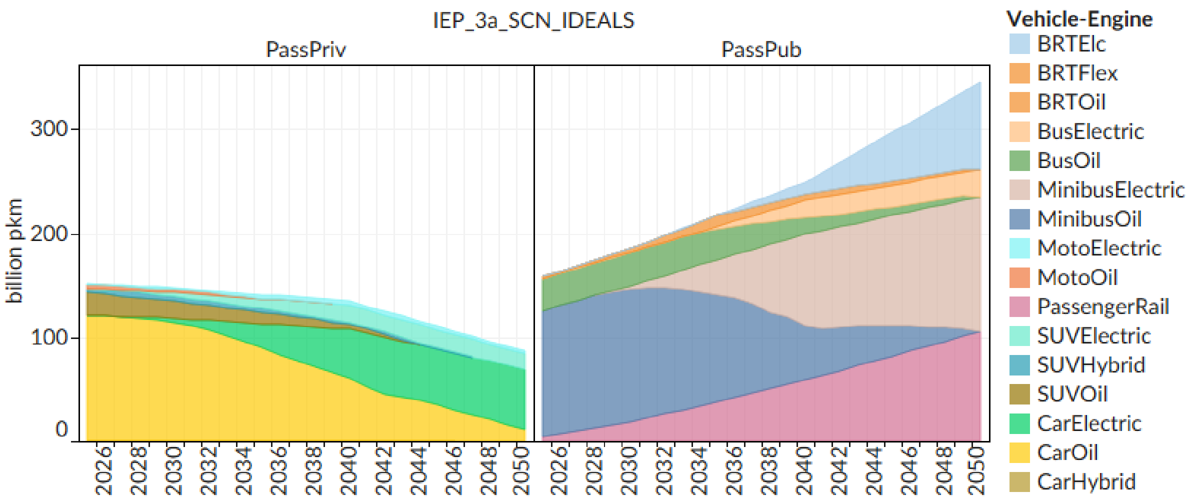


Figure 54: Passenger transport demand by vehicle and fuel type for the Ideal Energy Scenario

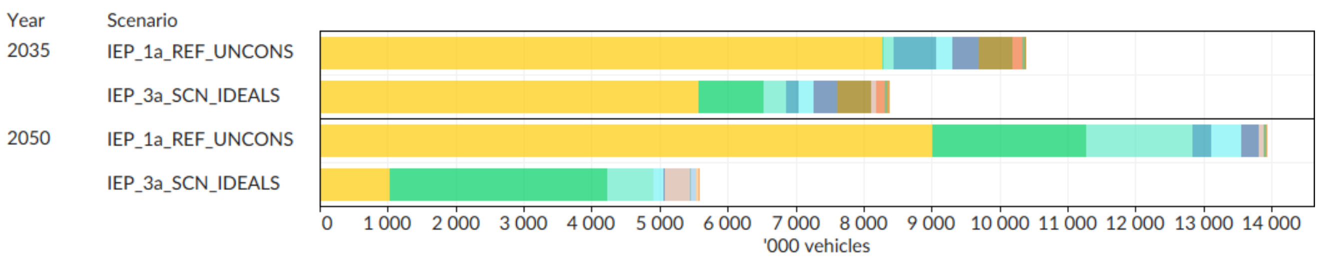


Figure 55: Passenger vehicle parc, comparing the Reference Case and Ideal Energy Scenario

The shifts shown in Figure 54 reflect a transition both to public transport and electrified transport. The former would potentially provide considerable benefits for poorer South Africans, who currently do not have access to any motorised transport options – given that it is estimated that currently more than 40% of household members use walking as their only mode of Transport (StatsSA, 2020).

There are however significant implications of this scenario which cannot be tested in the current SATIMGE model architecture –particularly, the scale of investment in infrastructure necessary to expand public transport on this scale. In order to be fully effective this would require not merely building new bus lanes and rail networks, but also more efficient urban planning and densification. SATIMGE currently does not analyse the spatial characteristics of transport, but, for example, such planning would also need to account for providing equitable rural and long-haul transport access.

The reduced vehicle parc of the Ideal Energy Scenario by 2050 – of mostly electric vehicles (Figure 55) – would result in greatly reduced emissions and air pollution, particularly in urban areas, as well as the reduction in traffic volumes and congestion. This would allow further indirect benefits, such as improvements to national productivity and economic activity, which would potentially partially offset the expenditure on public transport infrastructure. There are however important implications and trade-offs that would need to be considered by policymakers – in particular, the potential losses for the automotive industry, which is a significant employer and contributes a substantial share of South Africa's export revenue.

Freight Transport

The freight transport model for the ideal energy scenario consists of partial shifts from road freight to rail, as well as an accelerated shift to electric vehicles, which are assumed to reach CAPEX cost parity (excl. taxes) with ICEs by 2045. The resulting shifts are shown in Figure 56, where the rail share of freight transport (in tonne-kilometres) rises from 28% in 2025 to 49% by 2050.

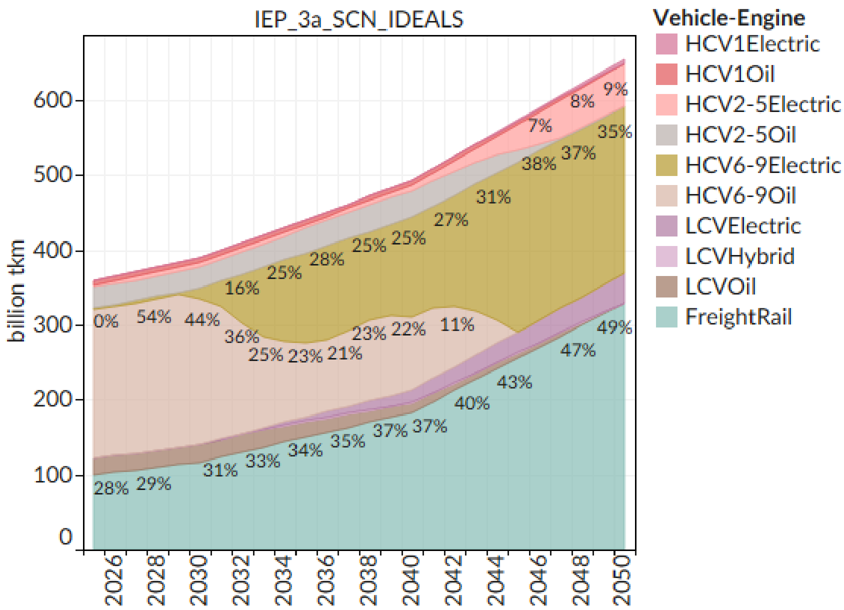


Figure 56: Ideal Energy Scenario freight transport demand, showing growth in rail

Comparison with green transport policy scenario

The transport results of the Ideal Energy Scenario can be usefully contrasted with the Green Transport Policy Scenario (reported in section 4.4), showing how the Ideal Energy Scenario drives towards more sustainable (mostly public) and electrified transport.

Figure 57 shows the comparative growth in private vehicle usage using BEVs (left-hand side) and ICEs (including hybrids – right-hand side). While the green transport policy scenario sees a significant ramp up in BEVs, and corresponding decline in ICEs, the Ideal Energy Scenario shows private BEV usage plateau from 2040, private ICE usage declining even further. The balance of passenger-kilometres in the Ideal Energy Scenario are served by a significant increase in electric public transport (see Figure 58), with rail passenger-kilometres rising to 105 billion pkms by 2050 (nearly fivefold above the green transport policy scenario). Electric public road transport also increases in the Ideal Energy Scenario, to 240 billion pkms by 2050 (compared to 145 billion pkm for the green transport policy scenario, and just 43 billion pkm for the unconstrained reference case). Meanwhile, public transport from ICE road vehicles is fully phased out in the Ideal Energy Scenario by 2050.

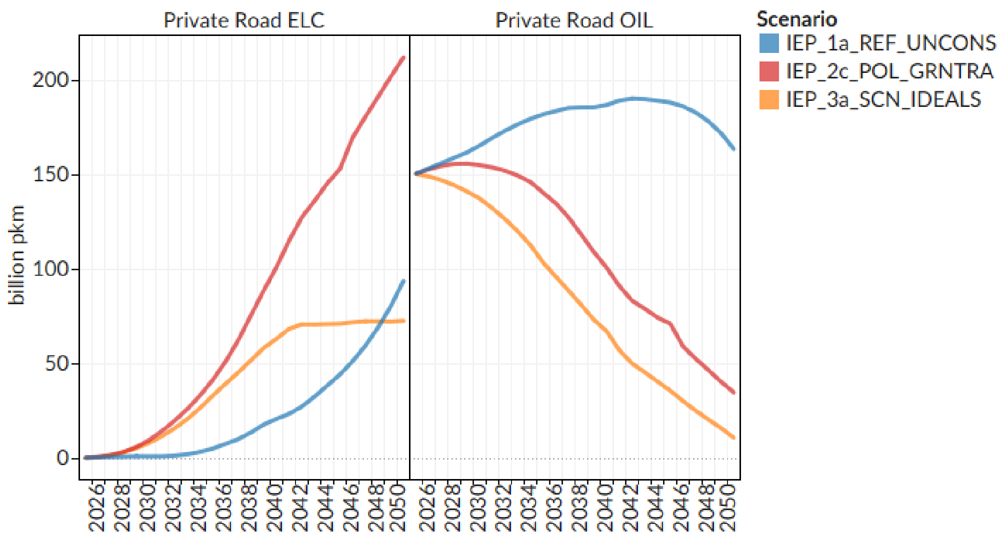


Figure 57: Private vehicle passenger-kilometres comparing BEVs to ICEs

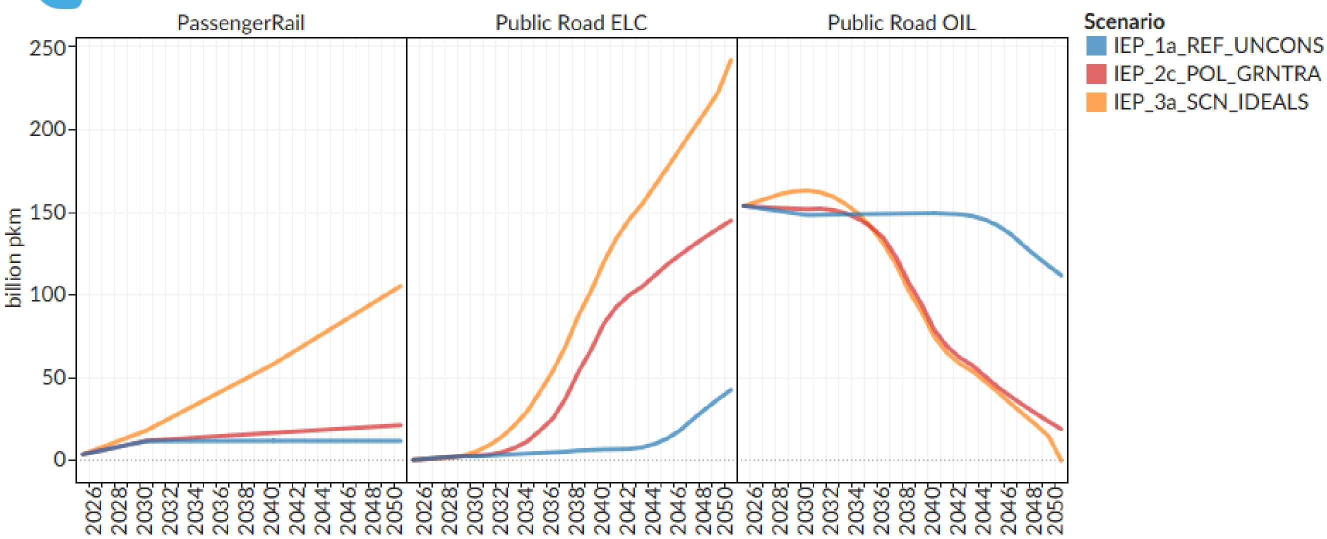


Figure 58: Public vehicle passenger-kilometres comparing BEVs to ICEs

Similar trends and comparisons can be observed in freight transport (Figure 63). Rail freight from electricity is greatly expanded in the Ideal Energy Scenario to be nearly equivalent with road freight, as shown above, reaching 330 billion tonne-kilometres by 2050. This compares to 260 billion tkm for the green transport policy scenario and 179 billion tkm for the unconstrained Reference Case. Freight BEVs show similar growth paths across all scenarios, but are slightly accelerated in the Ideal Energy Scenario, while freight ICEs are almost entirely phased out by 2050.

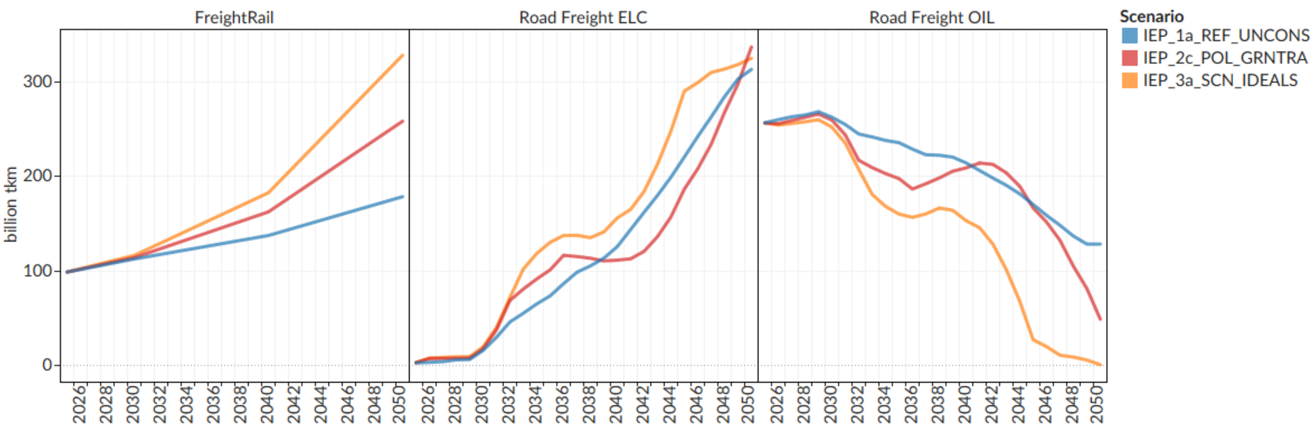


Figure 59: Freight tonne-kilometres comparing rail, BEVs and ICEs

Low fossil fuel price sensitivity

Previous work on net zero pathways for South Africa (Marquard et al., 2024) showed a seemingly odd finding, whereby electrification of public transport occurred more rapidly in South Africa when international fossil fuel prices were high (in a world of high demand) than when they were low (due to reduced global demand). This arises because the SATIMGE model evaluates transport costs on a lifecycle basis and sees that, with lower international fossil fuel prices reducing fuel import prices, it becomes cheaper to persist with ICE vehicles for longer, i.e. 'taking advantage' of the rest of the world's decarbonisation to delay the EV transition.

This effect is mimicked slightly in these results, when one compares BEV and ICE vehicle uptake between the Ideal Energy Scenario and low fossil fuel price sensitivity (Figure 60). The low fossil fuel prices (modelled as the oil price following the IEA Net Zero Energy trajectory rather than the assumed constant trajectory) lead to a slightly reduced transition of passenger transport from ICEs to BEVs (and the same phenomenon occurs more notably in freight road transport).

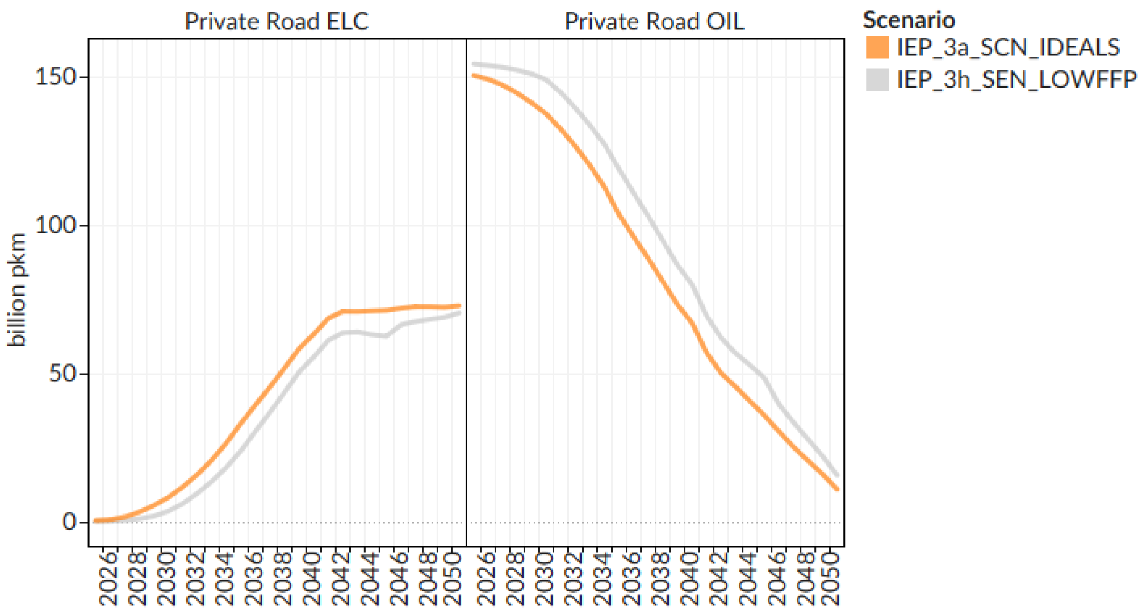


Figure 60: Private vehicle passenger-kilometres for the Ideal Energy Scenario and Low Fossil Fuel Price sensitivity

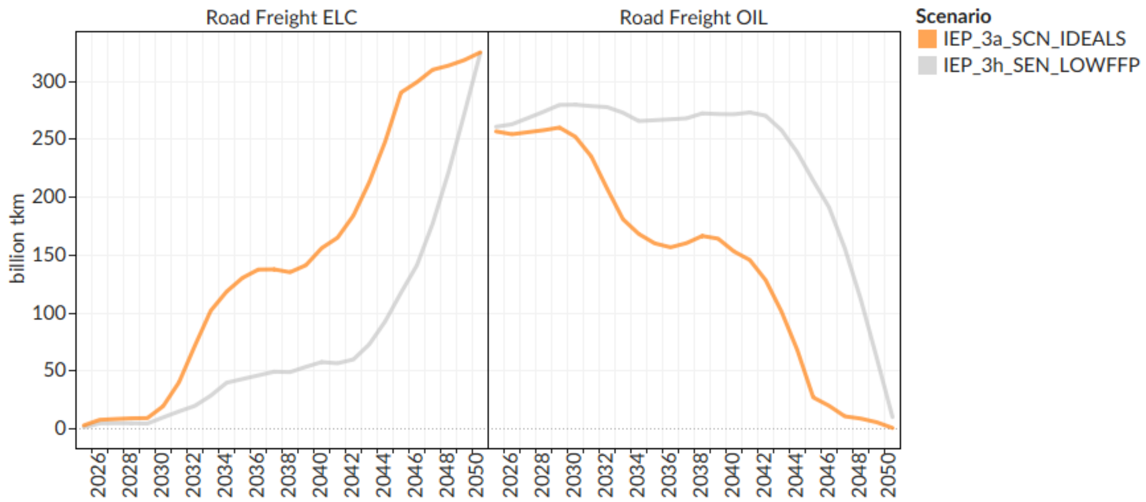


Figure 61: Freight tonne-kilometres for the Ideal Energy Scenario and Low Fossil Fuel Price sensitivity

This result is unlikely to transpire in reality for a couple of reasons: firstly, because in a world with decarbonisation causing lower fossil fuel prices, this would serve to accelerate the (already in motion) global transition from ICEs to BEVs, and South Africa's domestic OEMs would find it increasingly difficult to resist this trend, particularly in order to maintain access to and revenue from their export markets. And, secondly, because the fuel price represented in the model does not reflect the actual fuel price paid by consumers, which includes a series of taxes and levies that greatly increase the price over the base cost of import and production of the raw fuels. This situation is unlikely to cause long-term reductions in petroleum prices for consumers, even if global commodity prices are reduced.

5.2.3. Industry

Figure 62 shows energy carrier shifts for industry under the Ideal Energy Scenario. As with the emissions-constrained Reference Case, the sector shows a shift from coal and diesel usage to a greater than 50% share of electricity, and more than 10% hydrogen. The share of coal use in industry, excluding coking coal, reduces from 30% in 2025 to 12.6% by 2050, while diesel use is entirely phased out. Biomass and wood collectively account for only 8% of final energy in industry by 2050, while natural gas maintains a 6% share. Hydrogen use occurs mainly in the iron and steel, chemicals, and mining sub-sectors. The hydrogen is mainly, but not entirely, green, as the model assumes its production is powered largely from the grid, which still has a small amount of gas generation and a smaller amount of coal generation remaining in the electricity mix in 2050 (see section 5.3.2).

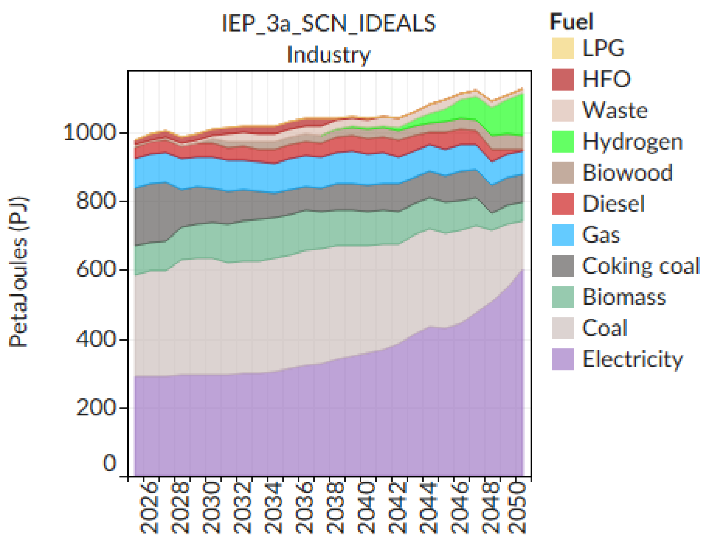


Figure 62: Ideal energy scenario aggregate industry energy demand by fuel

Energy Efficiency

This section shows the additional energy efficiency measures modelled for industry as part of the Ideal Energy Scenario. Specific measures include:

- Lighting: Rollout of LEDs ensure that all lights reach 144 lumens per Watt by 2030 (this applies to the residential and commercial sectors as well)
- Motors (including for cooling, compressed air, HVAC, fans, and pumping): the scenario assumes a rapid decline in the importation or sale of IE0, IE1, and IE2 grade motors by 2030, with only IE3 and IE4 sold thereafter; thus existing stock of motors is fully replaced by the mid-2030s, with a 60:40, share split between IE4 and IE3 by 2050.

- Compressed air: the scenario assumes a rapid uptake by companies in the use of compressed air systems, including reduced leakages and better practice by companies. From 20% of companies in 2030 implementing efficiency measures to 60% by 2040 and almost 100% by 2050.
- Cooling: a rapid uptake of a variety of measures including control systems (and motors) by 20% of companies by 2030 rising rapidly to 85% by 2050.
- Boilers: An uptake between 2030 and 2040 of a variety of boiler system upgrades including steam use to 75% by 2040 and 95% by 2050 of all potential efficiency measures for steam production and use.
- Clinker substitution in cement rising to 30% by 2030, and 40% by 2050.

The resulting reduction in energy consumption for industry is shown in Figure 63, where industry collectively accounts for 22% less energy consumption in 2050 in the Ideal Energy Scenario, relative to the unconstrained Reference Case.

Figure 64 shows the effect of the efficiency measures and emissions constraint on industry production (measured in Gross Value Add – GVA) and energy intensity. While GVA growth is lower for the Ideal Energy Scenario, relative to the Reference Case, energy intensity is also reduced. The 7 Gt sensitivity run shows further decline, showing the sensitivity of the industry to the level of climate ambition required.

It should also be noted that the energy efficiency measures of the Ideal Energy Scenario contribute, along with electrification, to reducing greenhouse gas emissions from industry significantly below baseline levels (see Figure 65).

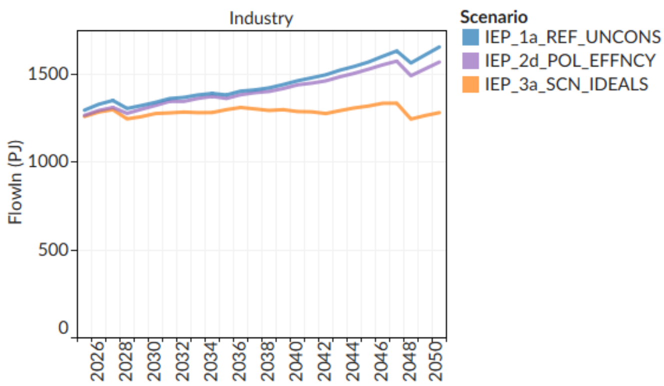


Figure 63: Aggregate energy consumption for industry by scenario

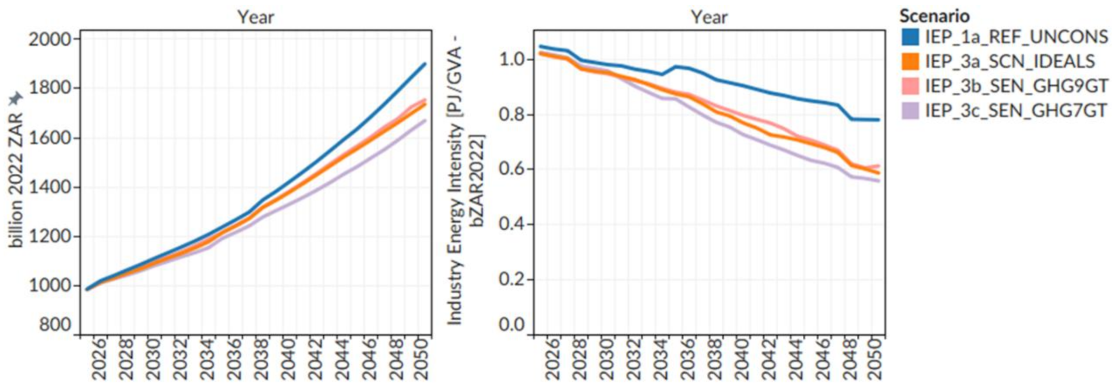


Figure 64: Industry GVA and Energy Intensity comparing the Reference Case, EE Policy Scenario and Ideal Energy Scenario

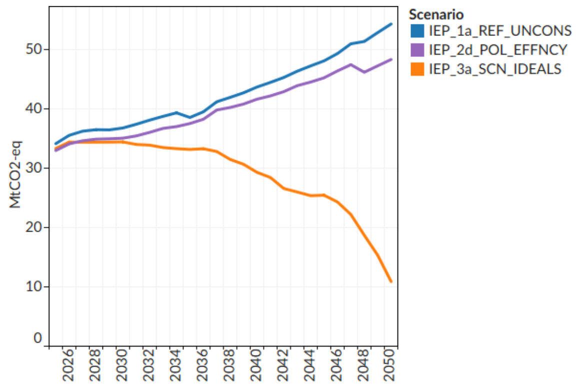


Figure 65: Industry net greenhouse gas emissions comparing the unconstrained Reference Case, energy efficiency policy scenario and Ideal Energy Scenario

This effect is shown further with the example of the iron and steel sector, as shown in Figure 66 below. The more ambitious 7 Gt sensitivity shows a slight reduction in steel output, resulting from lower economic growth reducing overall demand for steel, relative to the Reference Case and Ideal Energy Scenario, while coal use is completely phased out and replaced by electricity and hydrogen (with a small amount of natural gas still in use). Hydrogen use, as noted previously (see section 4.5) is not fully 'green' in SATIM due to the presence of fossil fuels in the electricity mix used to produce hydrogen. However, in practice, where industry can develop their own electrolyser capacity powered only by renewable fuels, this would be *bona fide* green hydrogen.

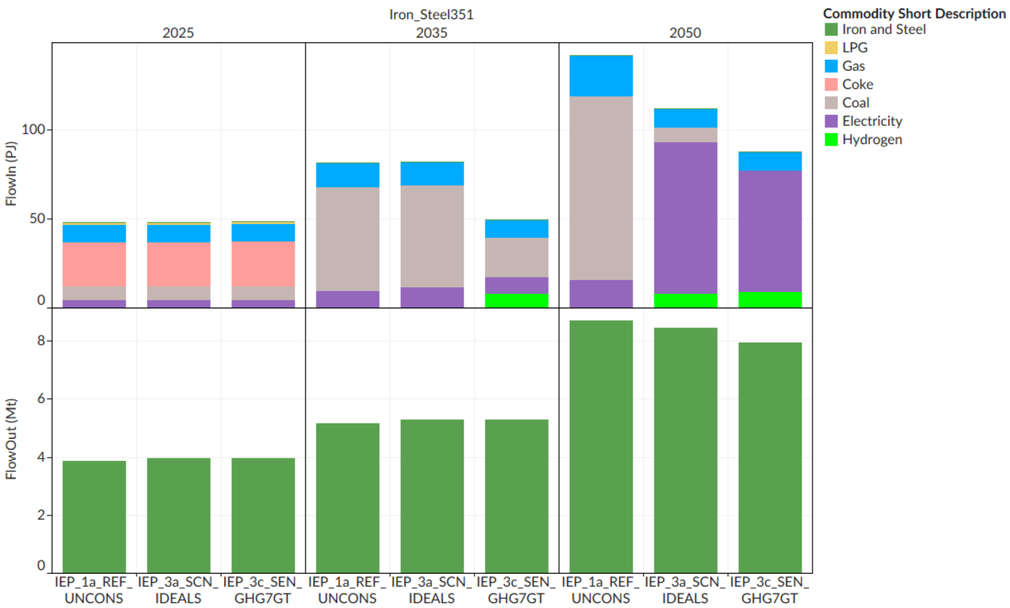


Figure 66: Comparison of energy inputs and product outputs for the iron and steel sector

5.3. Energy supply

The energy transition resulting from the Ideal Energy Scenario is shown in Figure 67 below. The resulting shift from coal dominance to renewable energy is shown in the following Figure 68. Coal is reduced from a 75% share of primary energy in 2025, to 25% by 2050, while wind and solar energy grow to 36% and 21% respectively. The remaining coal use in 2050 mainly occurs in industry, as shown above, as well as some small remaining use in the power sector. Bioenergy use (biomass and wood) is limited to 144 PJ in 2050, as per the definition of the scenario, while imported liquid fuels reduce to 160 PJ (5% of total supply) and natural gas to 200 PJ (7%). As can be seen in both figures, nuclear fuel use is completely phased out following the closure of Koeberg Nuclear Power Station in 2045.

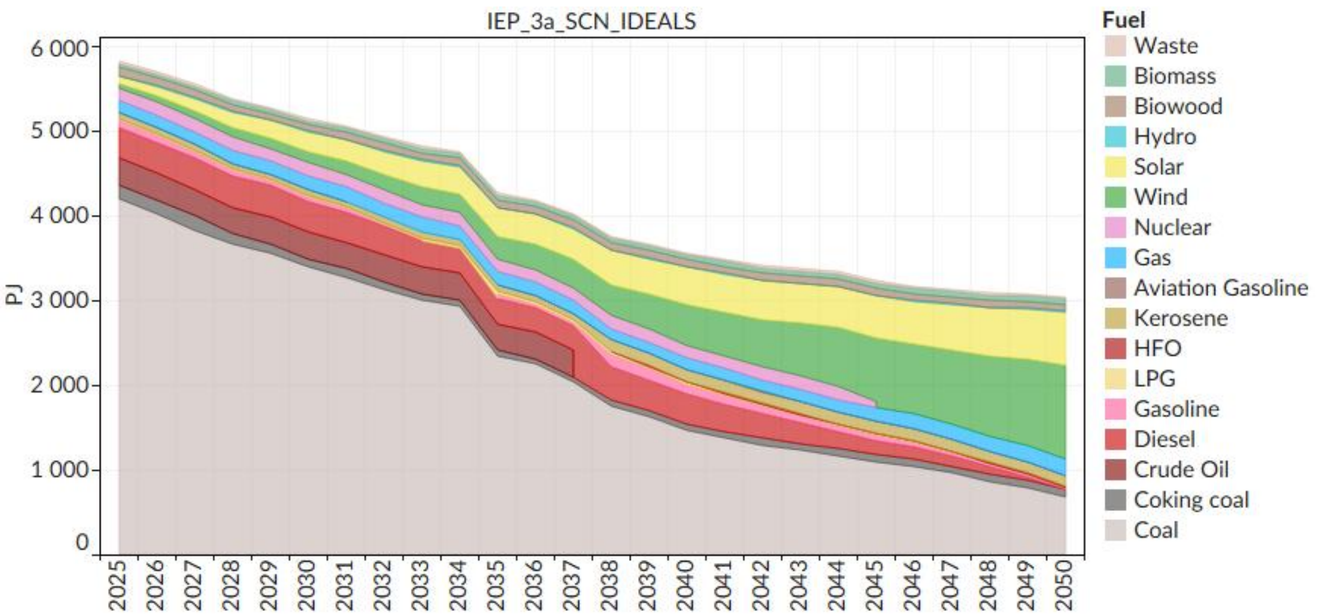


Figure 67: Primary energy supply by fuel type for the Ideal Energy Scenario

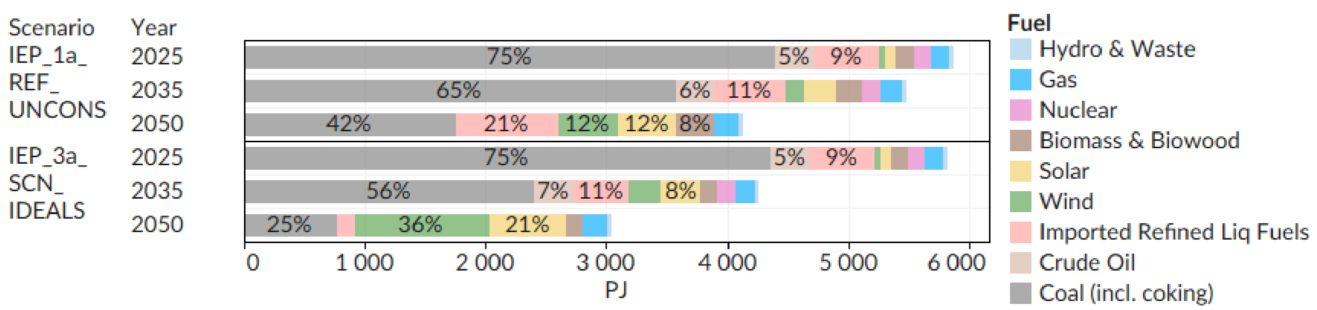


Figure 68: Primary energy shares in selected years comparing the Reference Case and Ideal Energy Scenario

Note that the distinction between 'primary' and 'final' energy is explained above in section 3.2.

5.3.1. Energy imports

Figure 69 and Figure 70 show the pathways for energy imports and shifts in their reliance within the overall energy system, comparing the Ideal Energy Scenario and Reference Cases. Imported energy, mainly in the form of liquid fuels, continue to play a significant role in the energy system in the unconstrained Reference Case, whereas they are largely reduced in the Ideal Energy Scenario by 2050. Natural gas imports (in the form of LNG) remain fairly constant across both scenarios, indicating the potentially limited role natural gas may need to play in the future energy system. Some coking coal imports remain for use in the iron and steel and ferro-alloys sectors, while nuclear fuel imports are phased out as indicated above. Imports maintain a relatively high share of the energy system in the unconstrained Reference Case, whereas they are reduced to14% of total primary energy supply by 2050 in the Ideal Energy Scenario (see Figure 70).

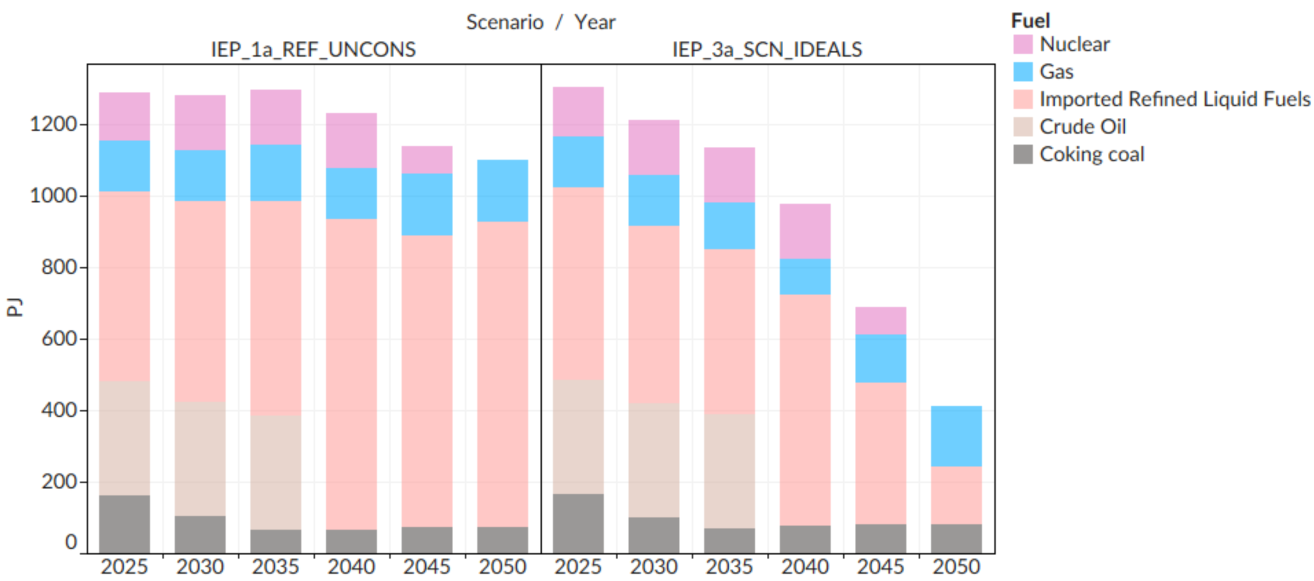


Figure 69: Imported fuels for the Ideal Energy Scenario compared to the Reference Case

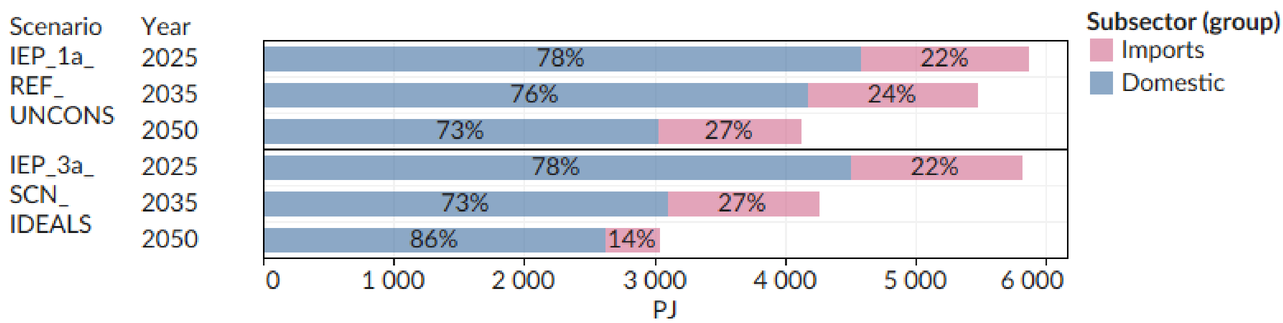


Figure 70: Relative share of domestically sourced and imported energy for the Ideal Energy Scenario compared to the Reference Case

5.3.2. Electricity

The electricity sector for the Ideal Energy Scenario is shown in Figure 71 (total generation capacity by technology) and Figure 72 (total generation capacity by technology). Capacity reaches 250 GW by 2050 in the Ideal Energy Scenario, of which 210 GW (more than 80%) is comprised of wind, grid PV, rooftop PV and battery storage. Nuclear capacity is phased out by 2050, with no new nuclear built in the Ideal Energy Scenario.

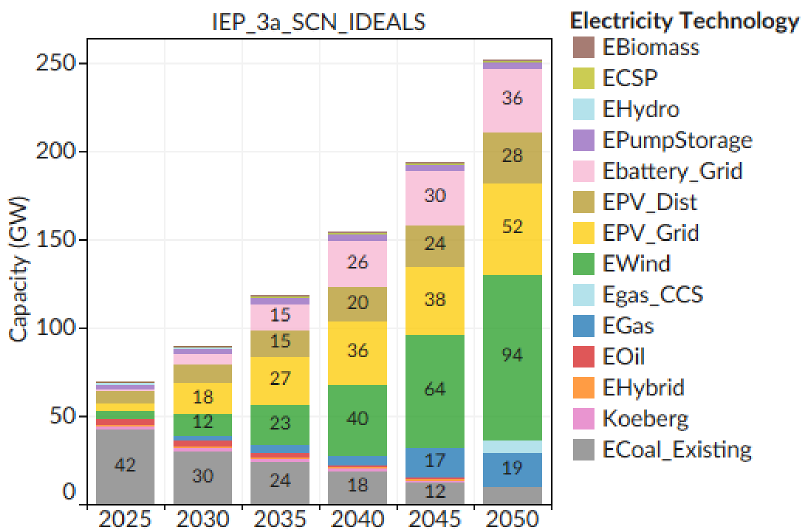


Figure 71: Electricity capacity by technology for the Ideal Energy Scenario

Note the differences between capacity and generation between Figure 71 and Figure 72. While Figure 71 shows that coal and gas (with and without CCS) account for 35 GW in 2050 (the 9 GW of coal from the Medupi and Kusile plants), in combination they account for less than 4% of annual generation, compared with 61% for wind and 35% from PV (grid and rooftop). The gas technologies utilised in this scenario are open-cycle gas turbines (with and without CCS), and are used only in peaking roles, with an average capacity factor of 5%. This is the same for the remaining coal capacity, which is used in a grid 'backup' role for periods where there are insufficient renewable resources for generation or to charge batteries.

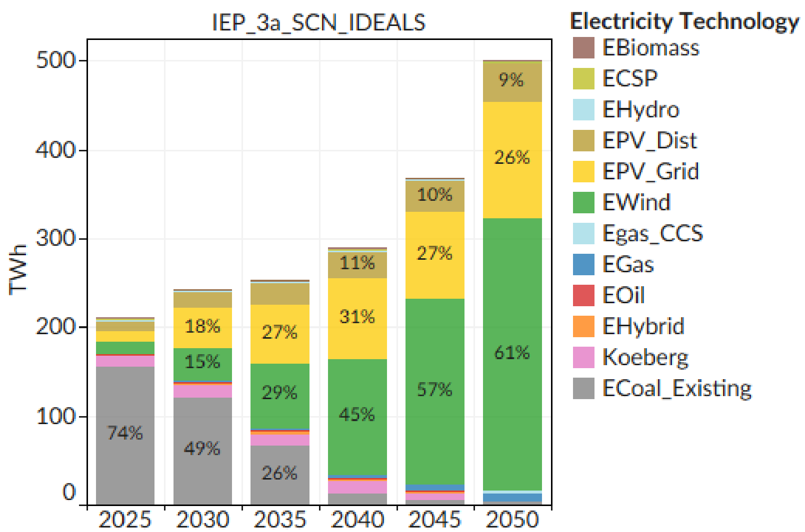


Figure 72: Electricity generation by technology for the Ideal Energy Scenario

Sensitivity analyses

Figure 73 shows electricity generation for coal, nuclear, wind and PV technology by scenario and sensitivity, showing the effects of more or less ambitious GHG budgets as well as higher and lower discount rates. In all scenarios, the use of coal power for generation is greatly reduced, with the rate of phase-out greater with the lower GHG budget (7 Gt) and where the lower discount rate makes alternative zero-carbon technologies more affordable – including nuclear (these are the only scenarios where new nuclear is built and used).

The main trade-off for new build options, depending on discount rate, appears to lie between nuclear and wind power – with the latter greatly reduced under the low discount rate scenario. However, the rate of wind and PV new-build and generation is increased with the more stringent GHG budget (shown by the purple lines in Figure 73).

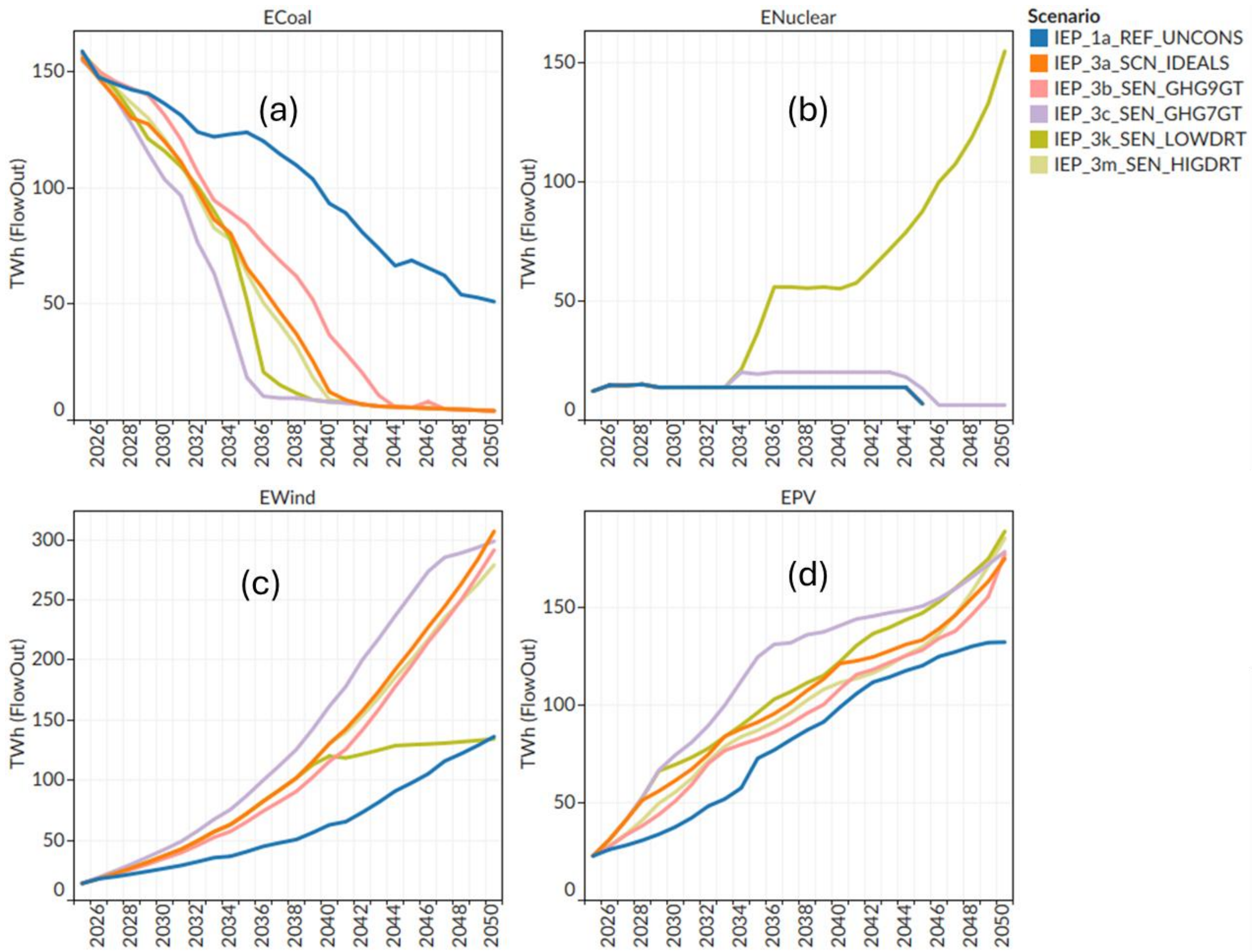


Figure 73: Comparisons of (a) coal, (b) nuclear, (c) wind and (d) PV power generation by scenario

HydraRenewable energy by province

Provincial disaggregation of renewable capacity is shown in this section, with cumulative wind capacity shown by province in Figure 74 and PV capacity in Figure 75. The modelling here tries to replicate the current grid constraints experienced in high-resource areas in the Northern, Eastern and Western Cape, with more 'expensive' (i.e. less-high resource) provinces seeing capacity growth in the short-term – particularly wind in the Hydra (central grid, around De Aar) area, and PV in the North-West, Gauteng, Free State, Limpopo and Mpumalanga. In the long-term, the majority of wind capacity is built in the Northern and Eastern Cape, while the majority of grid-based PV is built in the Northern and Western Cape.

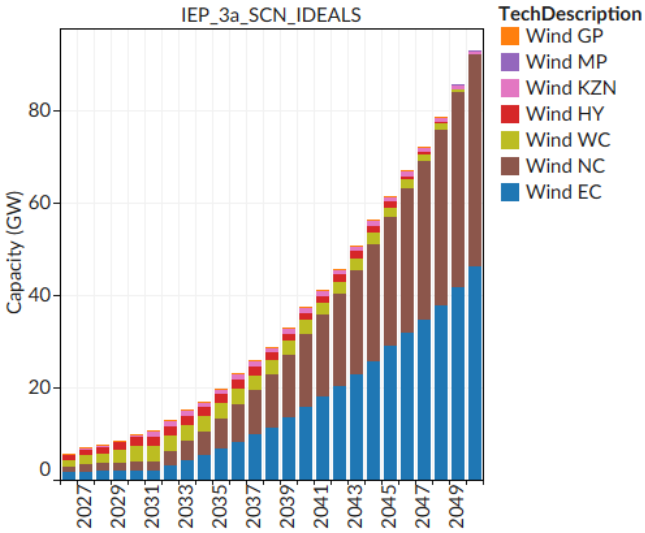


Figure 74: Wind capacity by provincial grid region for the Ideal Energy Scenario

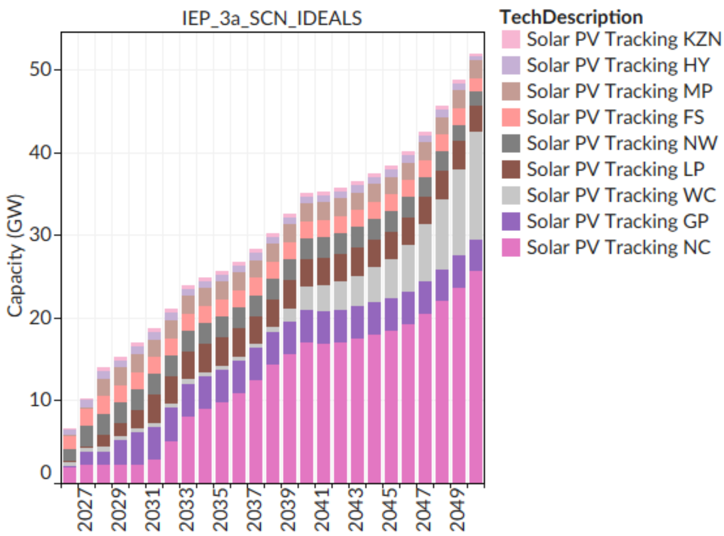


Figure 75: Grid-PV capacity by provincial grid region for the Ideal Energy Scenario

This is further reflected in the assumed land area by province for grid-based renewable energy in Figure 76. The land area estimates were calculated based on an estimated average land requirement of 180m^2 per MW of solar PV, and 4m^2 per MW of wind. The results show, as would be expected, the majority of land area for RE used in the Northern Cape, followed by the Western Cape and then Gauteng.

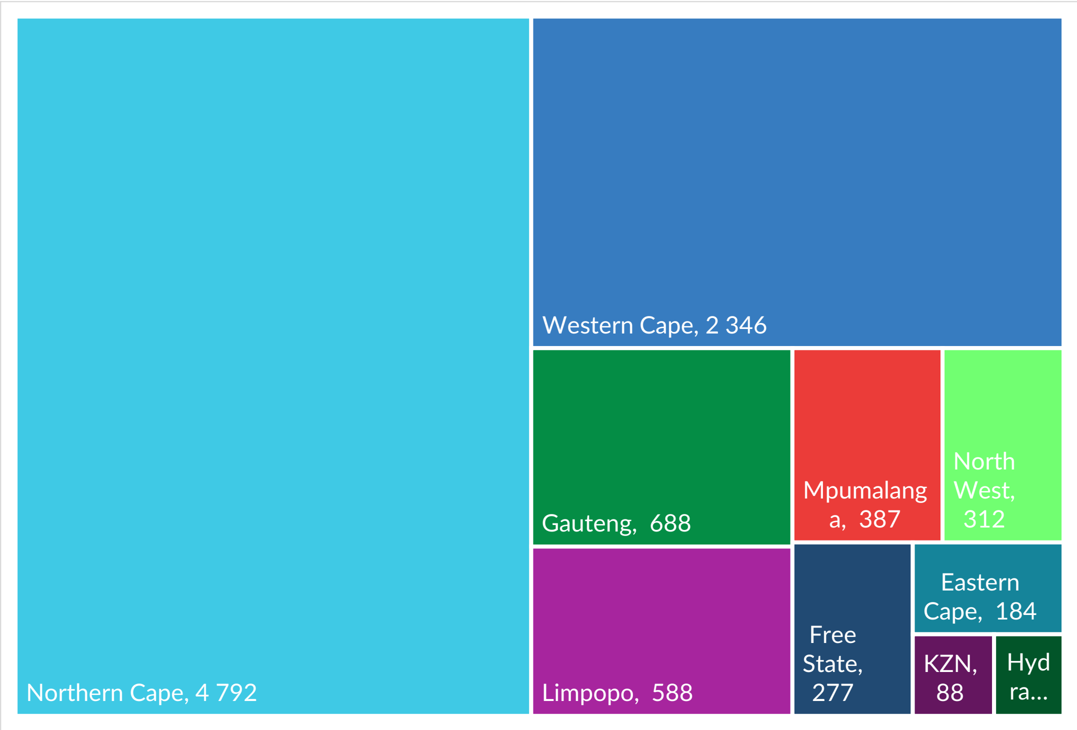


Figure 76: Square-kilometre area covered by grid-based renewable energy for the Ideal Energy Scenario

Battery storage

As shown in Figure 71, battery storage capacity reaches 36 GW in the Ideal Energy Scenario by 2050. Figure 77 shows the effects of different sensitivities – specifically more optimistic battery learning, and different GHG limits – on battery storage pathways. Ultimately, battery capacity reaches similar levels by 2050, but the rate of growth varies in the 2030s. The lower battery prices would allow faster growth of battery storage in the 2030s, but this rate appears more sensitive to the level of GHG ambition as shown by the 7Gt sensitivity.

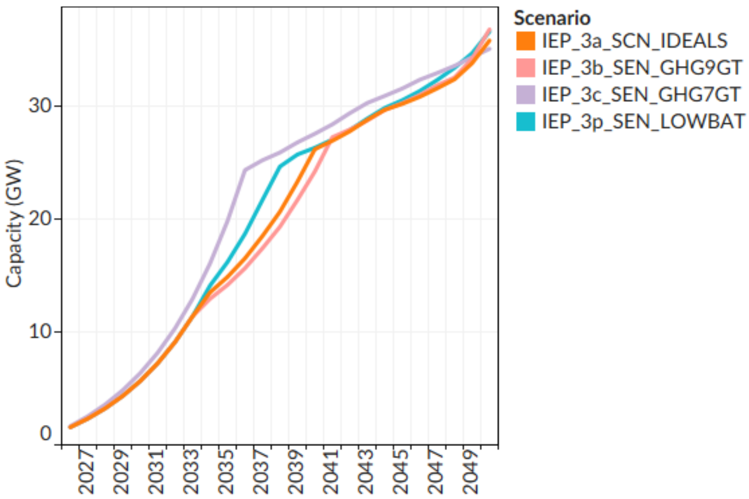


Figure 77: Battery storage by scenario

Electricity costs

Figure 78 shows variation in generation costs by scenario. While SATIMGE cannot model or analyse tariffs, generation costs are a proxy for this as the base cost of generating electricity. As Figure 78 shows, in the long-term electricity generation costs are fairly consistent, and reduce slightly relative to the unconstrained Reference Case. In the medium-term (2030s), there is a slight increase in cost for the more ambitious GHG sensitivity, reflecting the additional zero-carbon electricity build as shown in Figure 73 – and the earlier investment as shown in Figure 79.

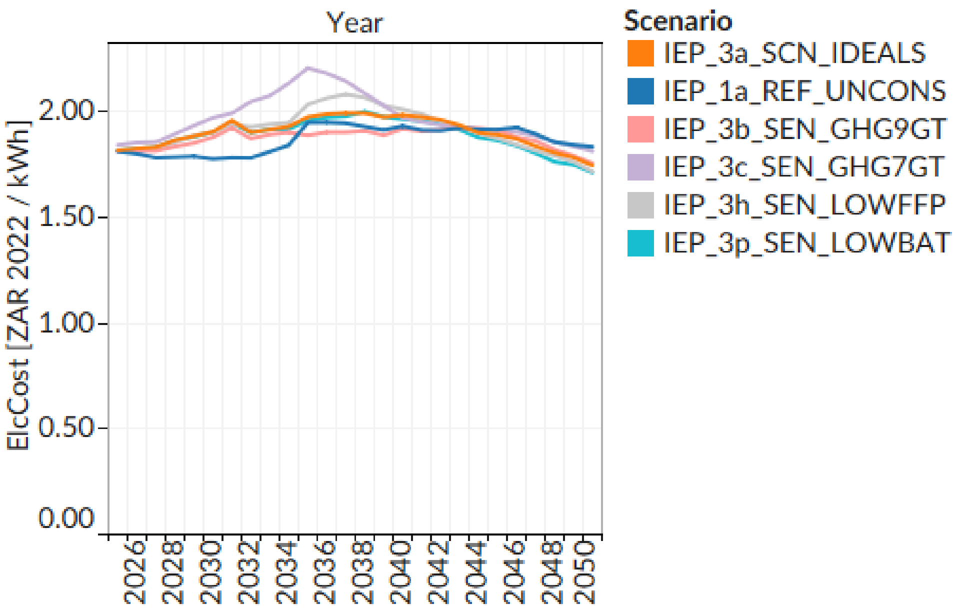


Figure 78: Electricity generation cost comparison by scenario

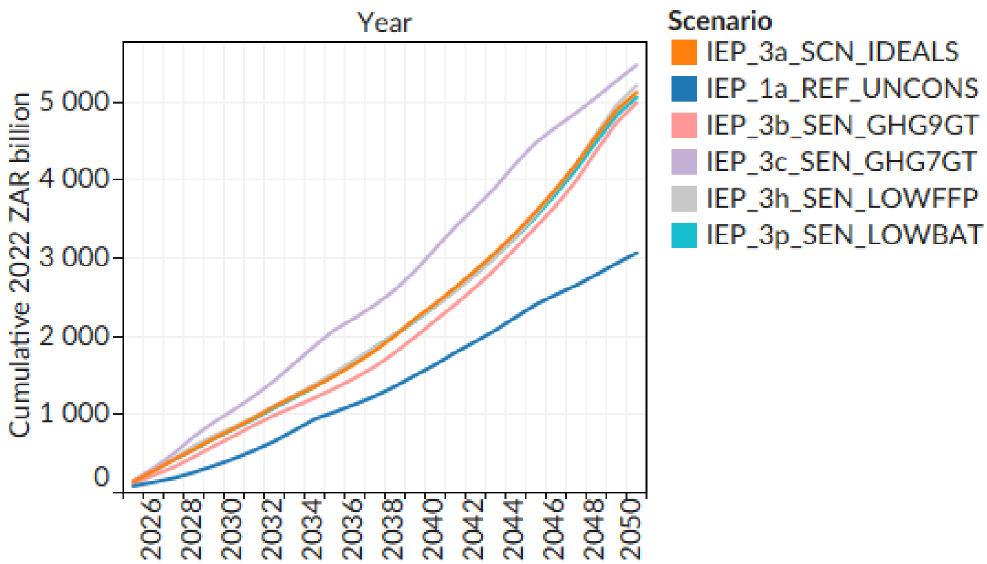


Figure 79: Cumulative investment in electricity infrastructure (incl. transmission and distribution) by scenario

Figure 79 shows cumulative investment in electricity infrastructure by scenario (including generation, as well as transmission and distribution costs). In all set 3 scenarios, cumulative electricity investment between 2025 and 2050 would exceed 5 trillion rand (2 trillion rand more than the unconstrained Reference Case), with higher investment required for the 7 Gt sensitivity. This shows the very high levels of investment that would be required to achieve such a transition in the energy sector.

5.3.3. Liquid fuels

Figure 80 shows different pathways for CTL operations and energy outputs by scenario and sensitivity. As noted in section 3.3.2 above, the analysis of coal-to-liquids and its interconnections with the chemicals sector and other factors are not analysed in-depth in this work. Nevertheless, Figure 80 shows the effects of different GHG budgets and endogenous CTL retirement dates on CTL production. Under the less stringent GHG limit, CTL capacity operates for longer albeit at a slightly lower rate of production relative to the Reference Case, whereas the 7Gt limit causes CTL to be fully retired from 2034.

Where endogenous retirement is allowed earlier (2029), capacity is partially reduced but then continues to operate until 2039; whereas, with the later date (2045), CTL operates at full capacity until that point, whereupon it is fully retired.

Figure 80 shows that, across all scenarios, Sasol's coal-to-liquids capacity retires by 2050. The imposition of any carbon constraint – even a relatively high GHG budget – causes this capacity to close earlier. Sensitivity analyses further show – notwithstanding the caveats about the full representation of Sasol's role in the chemicals industry as mentioned in section 3.3.2 – that keeping the CTL capacity online for longer (in the context of an emissions constrained energy system) has a negative GDP impact, relative to a closure in 2034 – see the ECTL45 sensitivity in Figure 81. Notably, the sensitivity without net zero and CCS (IEP_3d_SCN_NOCCST) shows CTL capacity retiring fully in 2034, in the same manner as the 7 Gt sensitivity.

These results support findings made elsewhere (Crompton et al., 2024) of the necessity of Secunda pivoting to a low-carbon product portfolio.

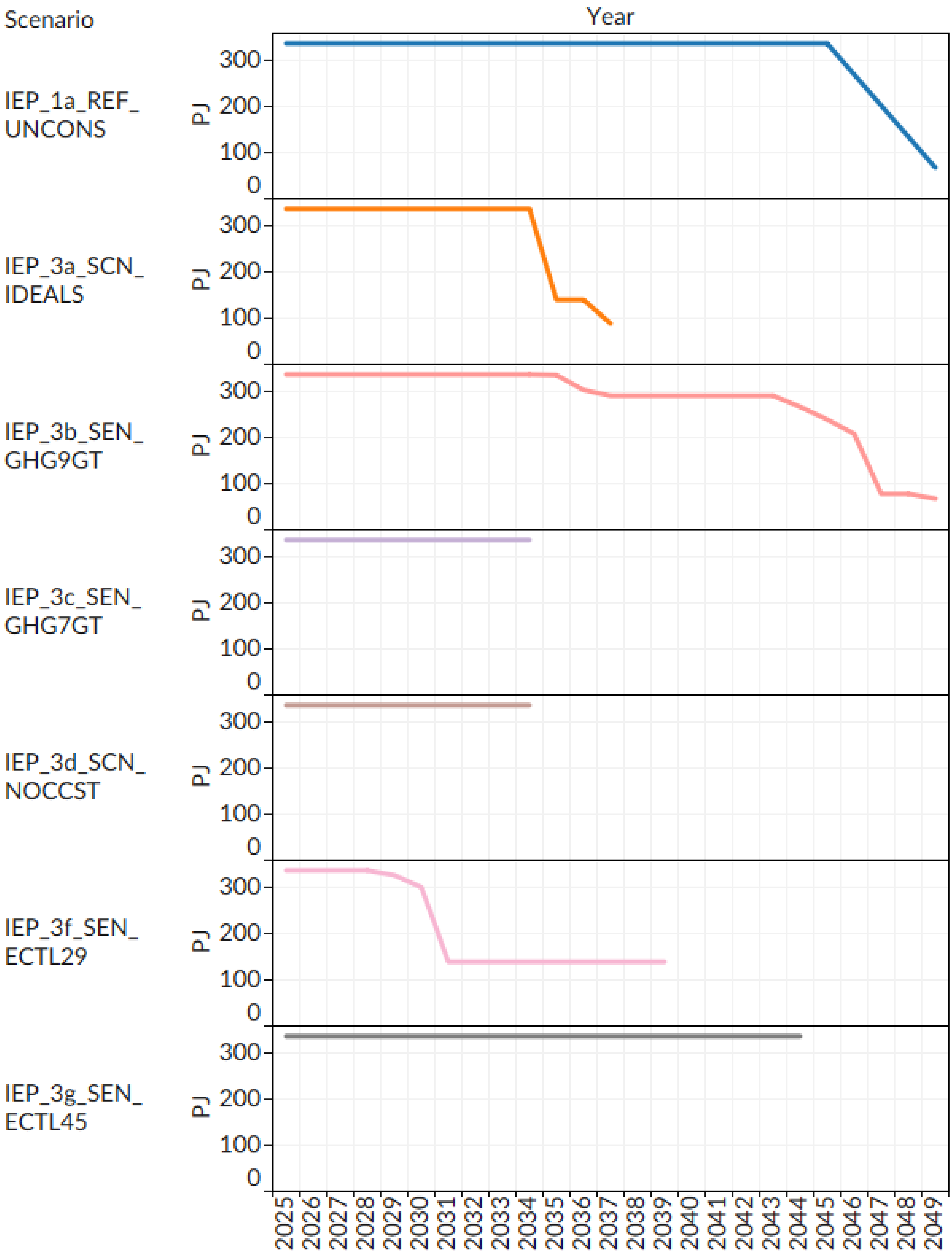


Figure 80: CTL operation and production by scenario

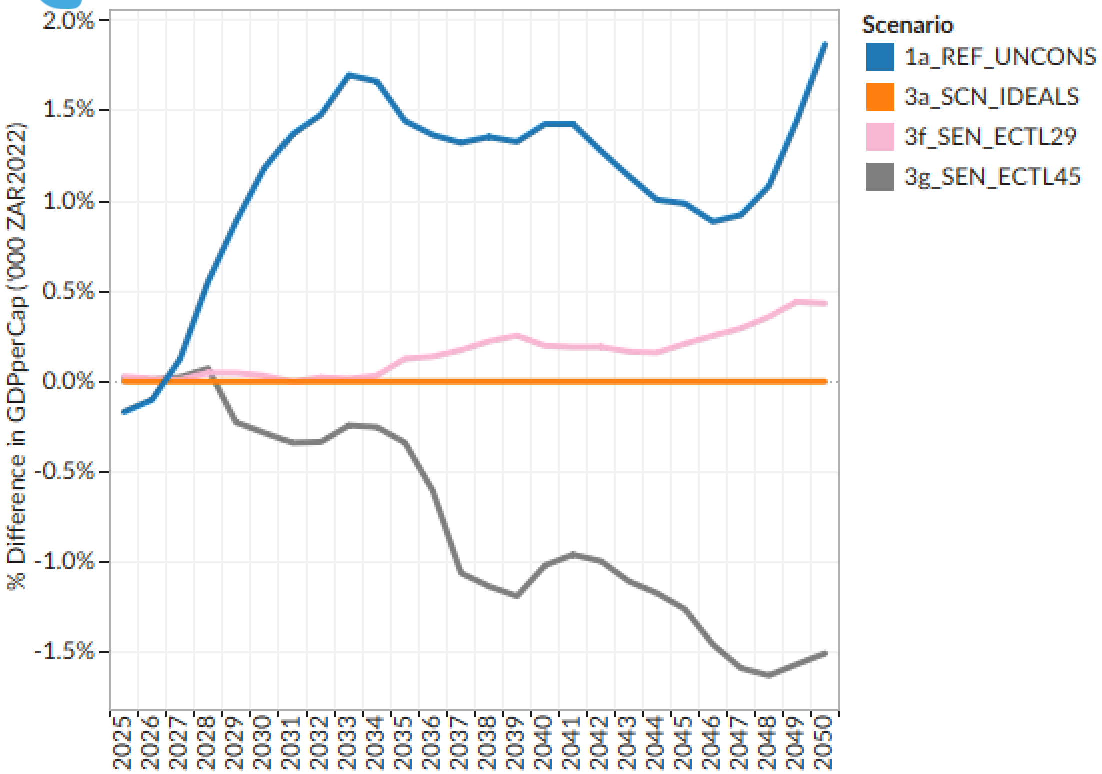


Figure 81: GDP differences for the early and late CTL retirement sensitivities relative to the Ideal Energy Scenario

5.3.4. Overall system investment costs

Figure 82 shows overall system investment costs for each scenario run in this project. Costs are calculated cumulatively over the period 2025 – 2050 for each sector and represent the investment costs in energy (or energy-related) infrastructure required under each scenario. These costs do not include the operating or fuel costs for each scenario, which are more variable across each of the scenarios – and more challenging to track through the SATIMGE modelling architecture. These costs also do not include the costs made into subsidies to support the increased FBE allocation and SWH rollout for the low-income household residential sector – and therefore the costs shown represent an underestimate for the overall system costs for the social provisioning policy scenario and the Ideal Energy Scenario and sensitivity analyses. Limited conclusions can therefore be drawn from this analysis, and it cannot be said that the Ideal Energy System is overall 'cheaper' than either of the Reference Cases.

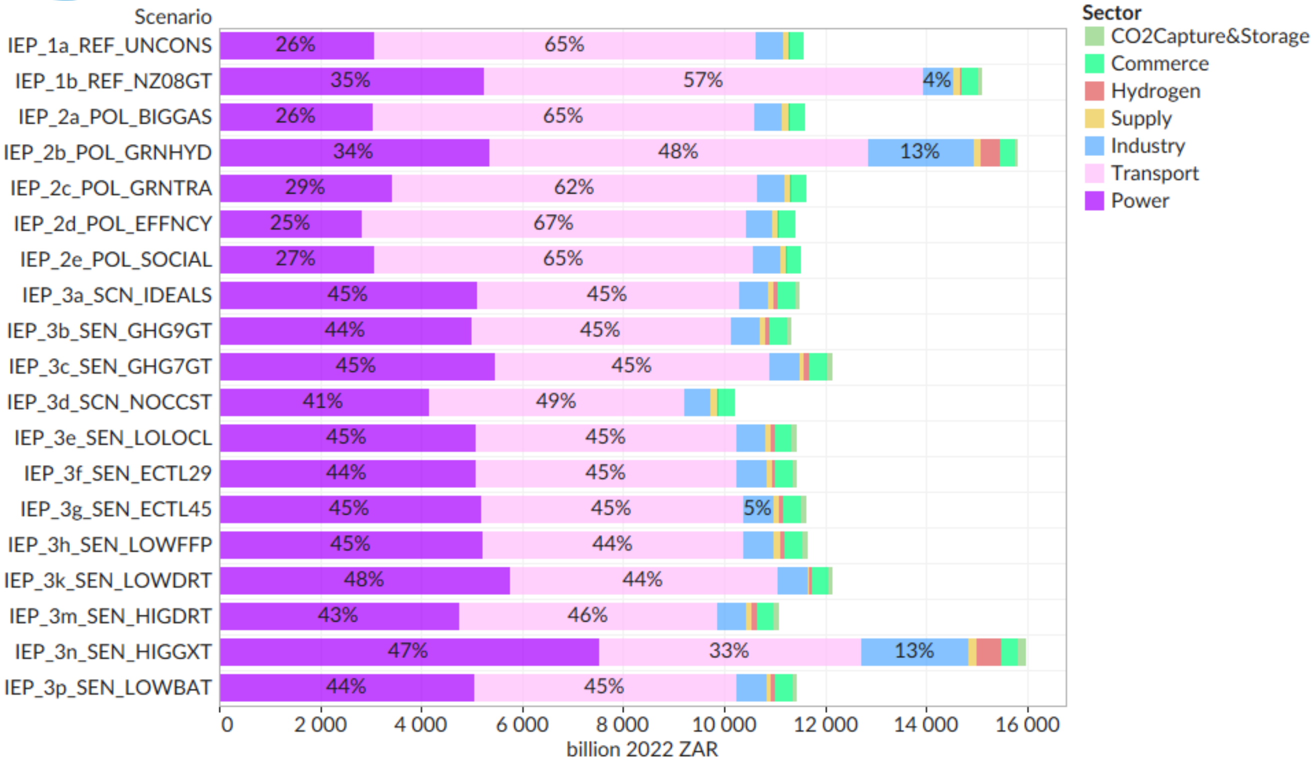


Figure 82: Cumulative (2025 – 2050) system investment costs across all sectors for all scenarios

Table 15: Cumulative (2025 – 2050) energy investment per sector for scenarios (billion 2022 ZAR)

Sector	Transport	Power	Industry	Commerce	Supply	Hydrogen	CCS	Total
IEP_1a_REF_UNCONS	7 549	3 065	545	307	112	2		**11 580**
IEP_1b_REF_NZ08GT	8 683	5 254	610	318	116	46	82	**15 109**
IEP_2a_POL_BIGGAS	7 570	3 040	536	307	135	1		**11 590**
IEP_2b_POL_GRNHYD	7 516	5 346	2 072	302	152	367	49	**15 803**
IEP_2c_POL_GRNTRA	7 230	3 415	547	308	120	2		**11 623**
IEP_2d_POL_EFFNCY	7 617	2 826	493	351	110	2		**11 399**
IEP_2e_POL_SOCIAL	7 501	3 066	542	305	110	2		**11 526**
IEP_3a_SCN_IDEALS	5 169	5 119	592	351	103	68	94	**11 496**
IEP_3b_SEN_GHG9GT	5 143	4 987	569	353	125	63	102	**11 343**
IEP_3c_SEN_GHG7GT	5 424	5 469	596	345	96	103	99	**12 132**
IEP_3d_SCN_NOCCST	5 053	4 166	510	349	124	10		**10 211**
IEP_3e_SEN_LOLOCL	5 153	5 091	581	350	102	66	92	**11 435**
IEP_3f_SEN_ECTL29	5 171	5 084	583	351	104	61	96	**11 450**
IEP_3g_SEN_ECTL45	5 187	5 193	604	348	109	86	90	**11 617**
IEP_3h_SEN_LOWFFP	5 166	5 209	599	356	151	77	96	**11 654**
IEP_3k_SEN_LOWDRT	5 297	5 773	580	345	28	52	72	**12 147**
IEP_3m_SEN_HIGDRT	5 103	4 757	563	348	130	84	101	**11 087**
IEP_3n_SEN_HIGGXT	5 190	7 518	2 114	346	167	485	146	**15 966**
IEP_3p_SEN_LOWBAT	5 178	5 056	593	351	106	68	95	**11 447**

However, what can be observed is that, firstly, absent other measures, the impact of meeting climate mitigation commitments (the constrained Reference Case) greatly adds to the overall energy costs, with additional investment in the power sector and greatly expanded use of private electric vehicles shown by the shares of investment into the power and transport sectors. By contrast, while the Ideal Energy Scenario shows greater investment in the power sector, there is comparatively reduced transport expenditure due to the reduced use of private vehicles, and more efficient public transport system (noting, as above, that this is not fully costed either).

The hydrogen policy scenario, as well as the green exports sensitivity of the Ideal Energy Scenario, show the highest cumulative investment costs, predominantly in the power sector and in industry, to support the rollout and powering of hydrogen to power new export industries. Figure 83 shows that these two scenarios result in lower GDP growth than the Reference Case or Ideal Energy Scenario and show a slight reduction in overall employment – but significant increases in energy sector employment (specifically in the hydrogen, fuel cells and electrolyser subsectors of the eSAGE model). Therefore, such high investments in the green hydrogen industry would provide significant employment opportunities, but the opportunity costs elsewhere in the economy may be greater.

The sensitivity scenario without net zero and CCS (IEP_3d_SCN_NOCCST) has the lowest overall investment cost, largely due to the absence of CCS and other 'last mile' technologies to meet net zero. This sensitivity is explored further in the following section, but the initial indication suggests that significant decarbonisation – without reaching net zero – may represent an affordable pathway for South Africa's energy sector going forward. This also supports a previous finding by the ESRG that an emissions system with GHG budgeting, but not a net zero constraint, may represent a 'no-regrets' pathway for energy development (Marquard et al., 2024).

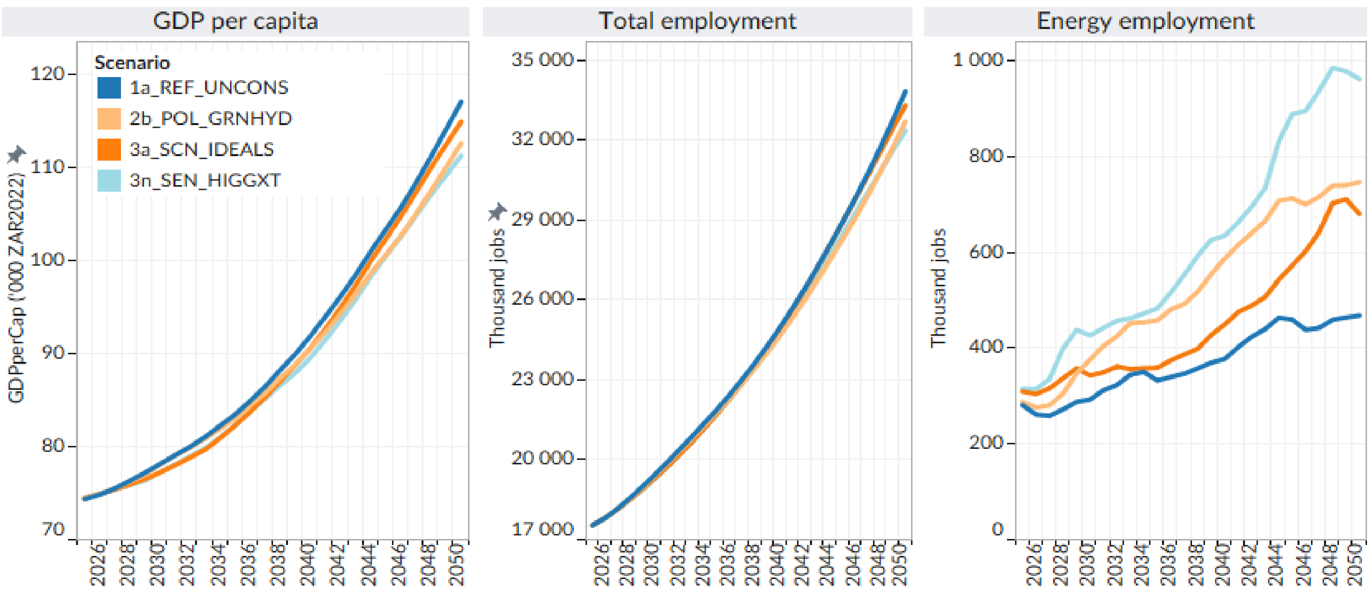


Figure 83: GDP per capita and employment (total and energy-specific) for the unconstrained Reference Case, hydrogen policy scenario, Ideal Energy Scenario and green export sensitivity

5.4. Greenhouse gas emissions

Figure 84 shows the greenhouse gas (GHG) emissions profile by sector (in net GWP_{100} CO_2-eq terms) for the Ideal Energy Scenario, while Figure 85 shows cumulative GHG emissions over the 2021-2050 period for different scenarios and sensitivities. Note that 'Null' in Figure 84 refers to leakages (predominantly methane) from gas and other pipelines.

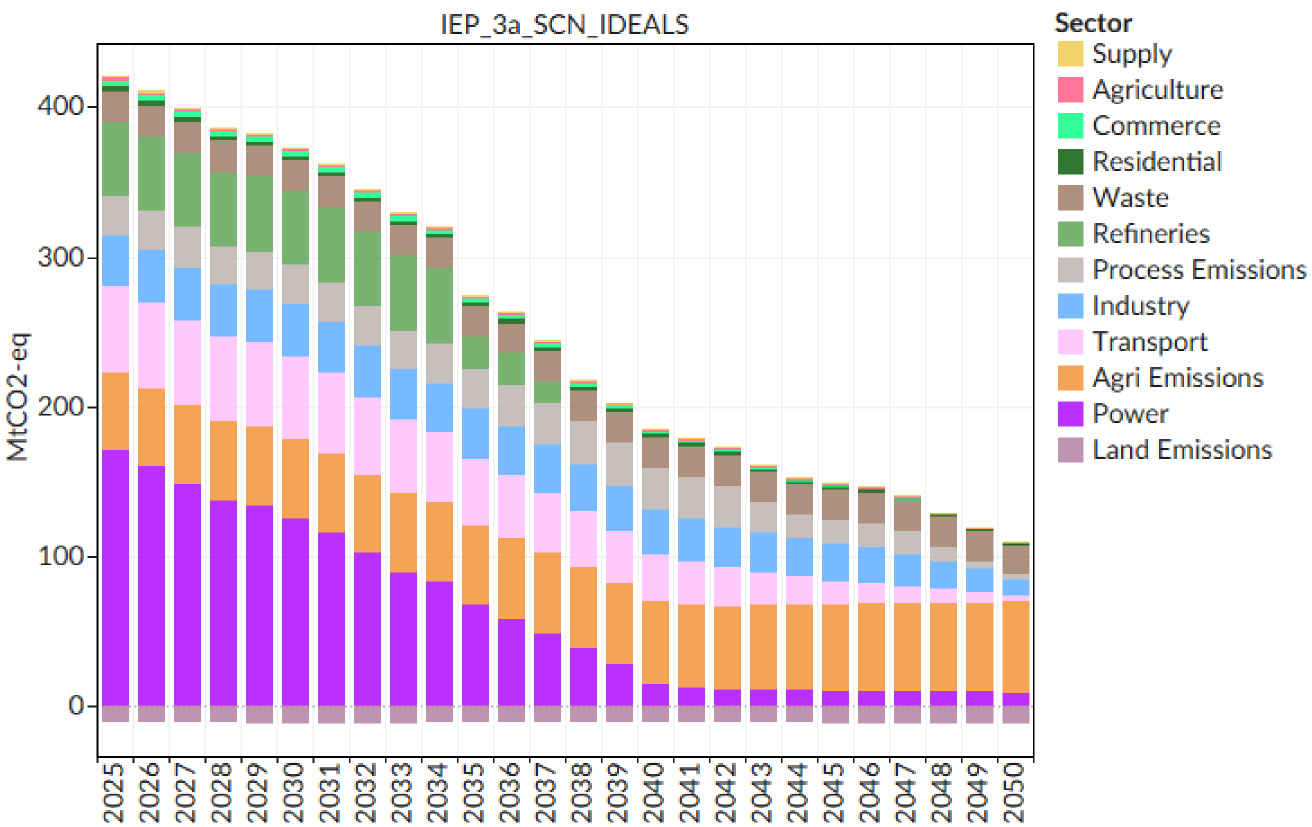


Figure 84: Greenhouse gas emissions for the ideal energy scenario

As was the case with the emissions-constrained Reference Case, by 2050 the remaining GHG emissions are largely from the AFOLU and Waste (non-optimised sectors). There are comparatively few GHG emissions from the power and industry sectors, with transport close to zero, and these are partially offset by the land sink, as well as the use of CCS in power and industry (see below).

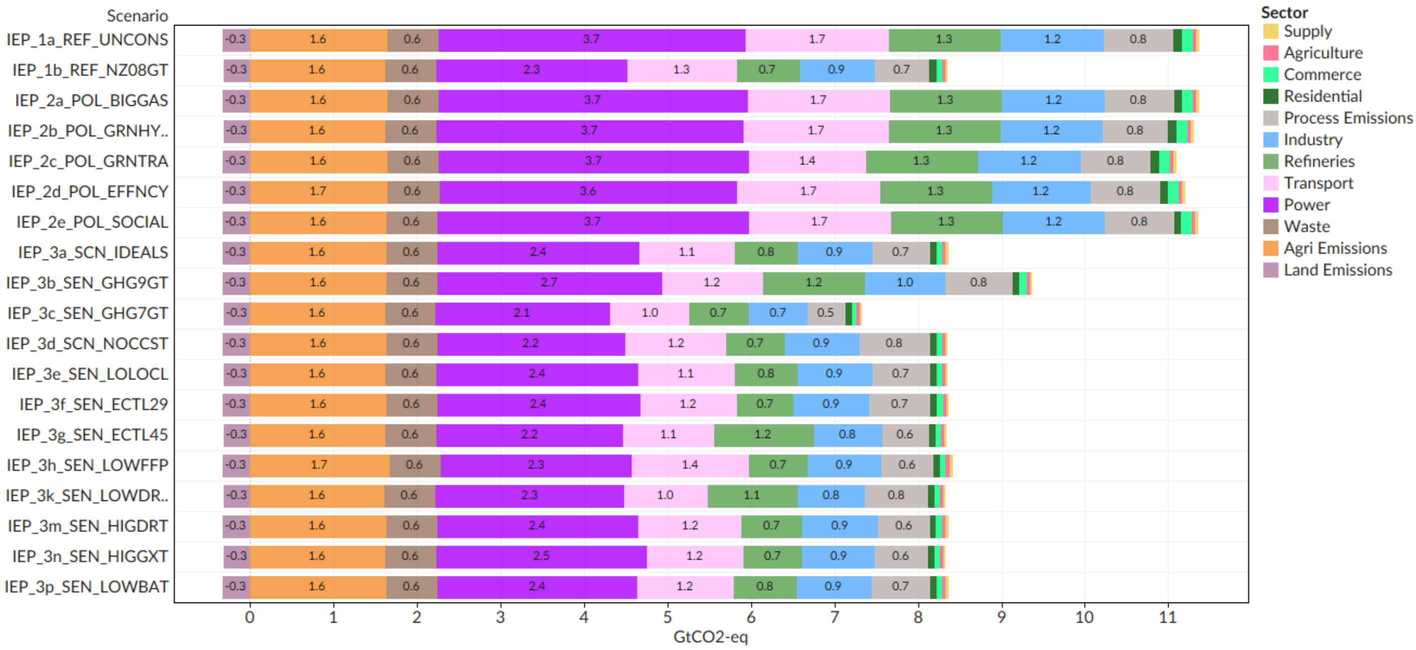


Figure 85: Cumulative GHG emissions (2021 – 50) by scenario (incl. all sensitivities)

Figure 85 shows cumulative emissions by scenario. As was the case with the emissions-constrained Reference Case, the majority of emissions saving potential lies in the power sector – with low-carbon electrification reiterated by these results as the most important available strategy for reaching net-zero – followed by transport and industry. The sensitivities with earlier and later retirement of CTL show the trade-offs between this sector and the power sector under constrained emissions space.

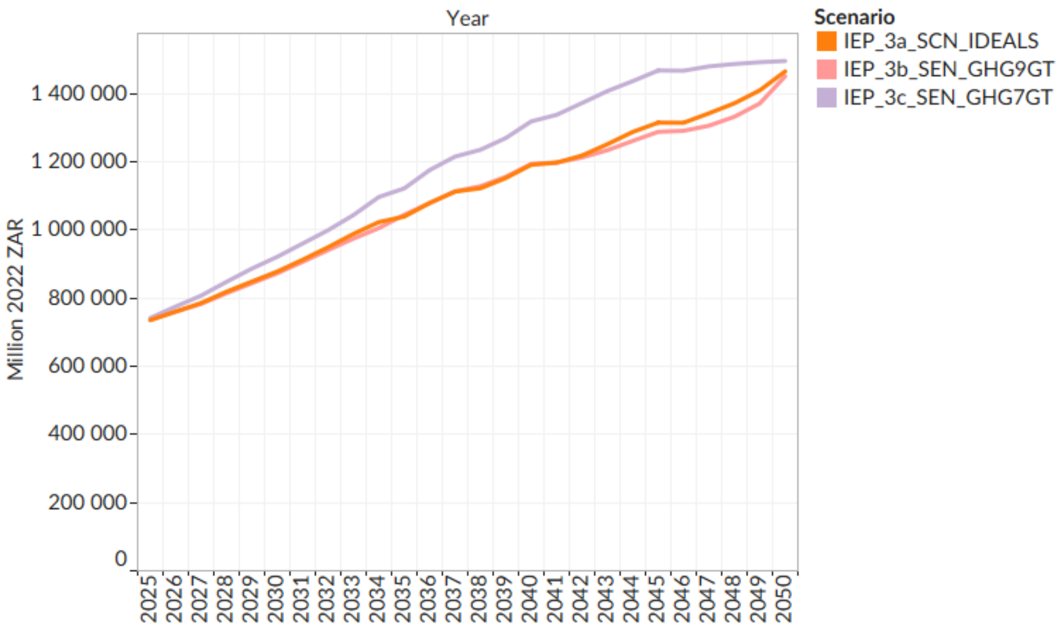


Figure 86: Annualised energy system costs for GHG sensitivities

CO_2 and CCS

Pathways to net zero CO_2 emissions for different GHG ambition are shown in Figure 87, along with the sensitivity that excludes CCS as a technology option and does not reach net zero. The latter, under an 8 Gt GHG limit, shows that, in the absence of CCS technology, residual net CO_2 emissions in 2050 reach about 80 Mt CO_2. This is due to the absence of CCS, as well as the earlier shutting down of CTL capacity in this sensitivity – as shown in Figure 80 – which 'allows' greater emissions in other industry sectors over the modelling period up to 2050 (and again indicates that prolonged CTL activity is not compatible with significant decarbonisation). The majority of those remaining emissions arise from industry – particularly cement, iron and steel and ferro-alloys – as well as some emissions remaining from the power and transport sectors. This sensitivity also sees reduced investment in hydrogen, due to a reduced 'need' to further decarbonise industry, which further explains why investment costs are comparatively low (see Figure 79 and Table 15).

Captured CO_2 in the Ideal Energy Scenario reaches 30 MtCO_2 in 2050, equivalent to slightly less than 10% of CO_2 emissions in 2025. However, for context, this is still three times higher than the land sink. Figure 88 shows cumulative CO_2 emissions by scenario, showing the role of CCS particularly in industry, which increases with increasing GHG mitigation ambition. Given the uncertainty of CCS technology – and that, as of 2024, the IEA estimates only 50 Mt CO_2 carbon capture projects operational worldwide (IEA, 2024b) – its use as part of a strategy to reach net zero CO_2 emissions in the energy sector remains a considerable risk. The trade-off, in the absence of such technology, would – absent other new technology developments, such as scale-up and cost reduction of green hydrogen – require reductions in cement and other industry production, and reliance on imports for these materials to support the scale-up of wind energy to meet the scale of low-carbon electrification indicated above – along with other developmental infrastructural needs.

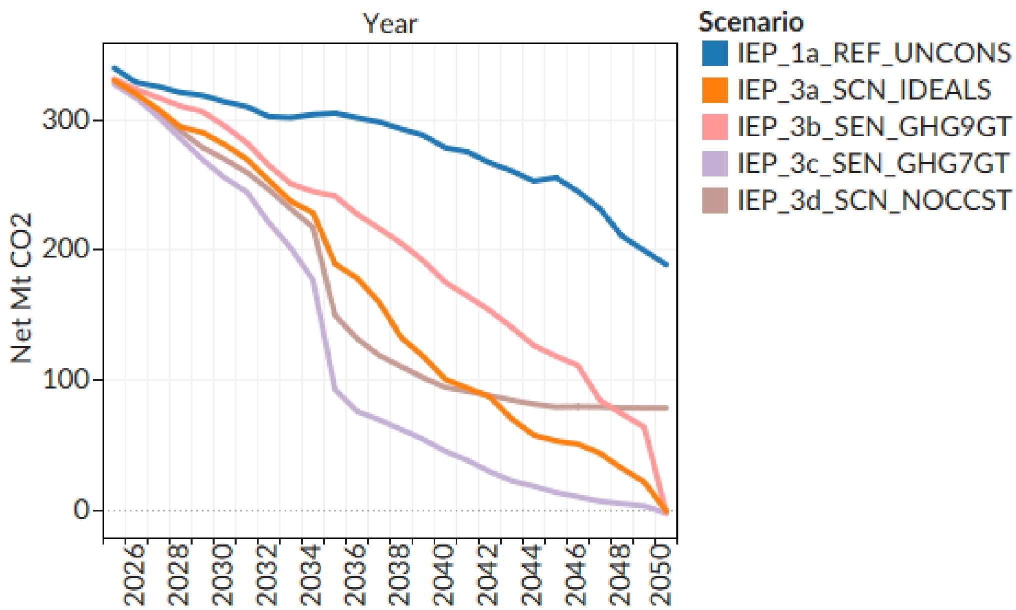


Figure 87: Net CO_2 pathways by scenario (selected sensitivities)

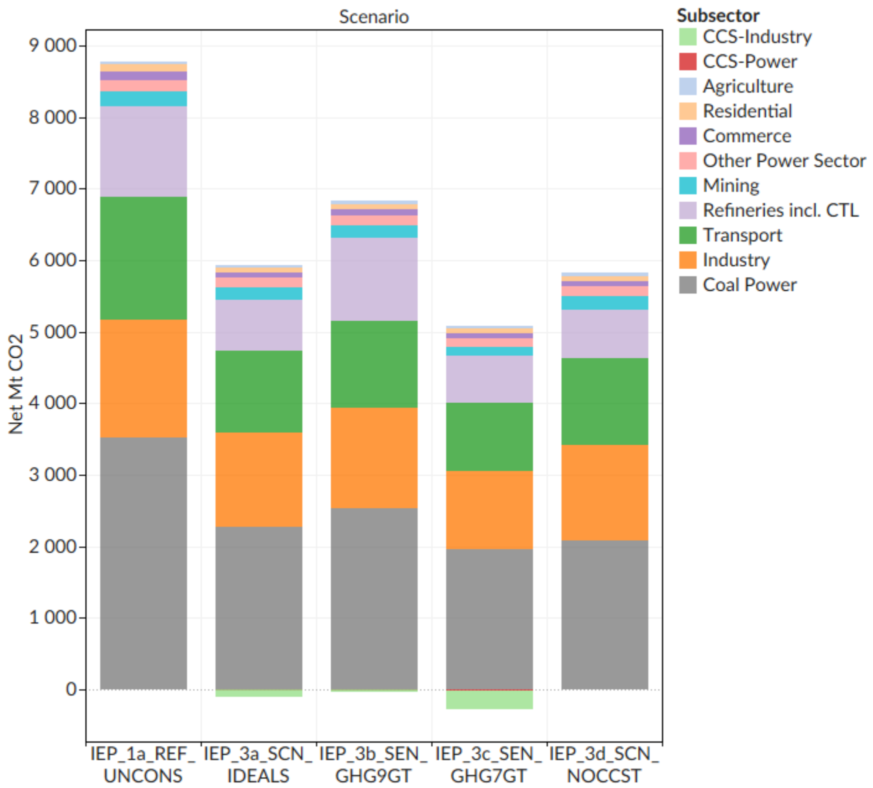


Figure 88: Cumulative CO_2 emissions by scenario (2021 – 2050)

5.5. Environmental externalities

This section provides high-level indications in the reduction of SATIMGE measurable externalities – air pollution (see Figure 89) and water consumption in coal mining, coal power and gas power (see Figure 90) – in the Ideal Energy Scenario relative to the Reference Case.

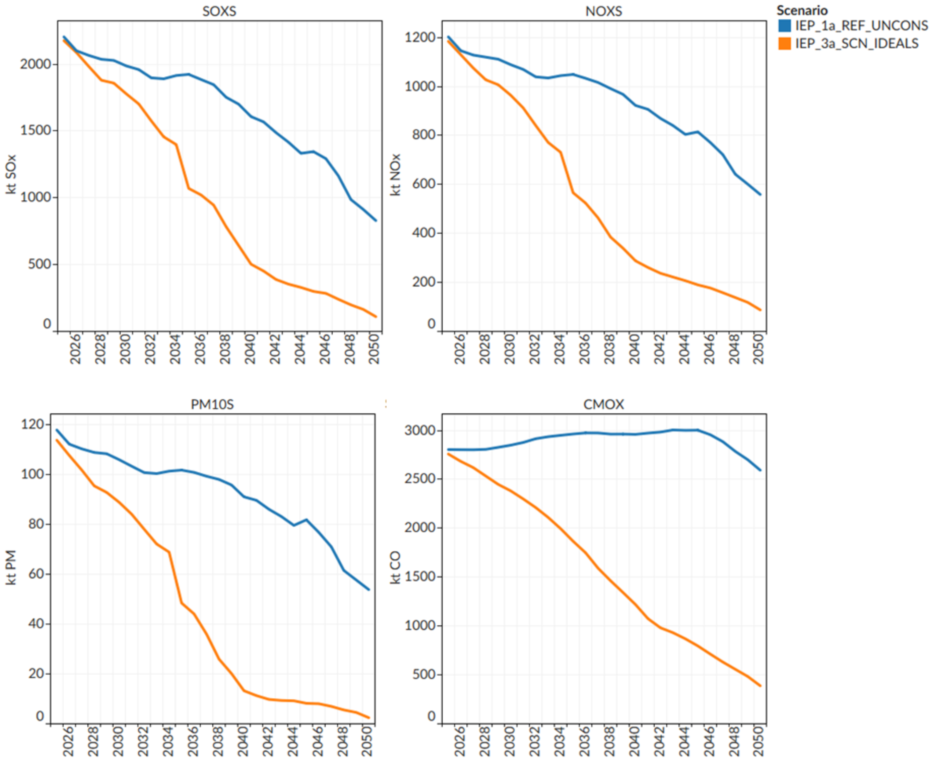


Figure 89: Comparing emissions of (a) SOx, (b) NOx, (c) PM10 and (d) CO between the Reference Case and Ideal Energy Scenario

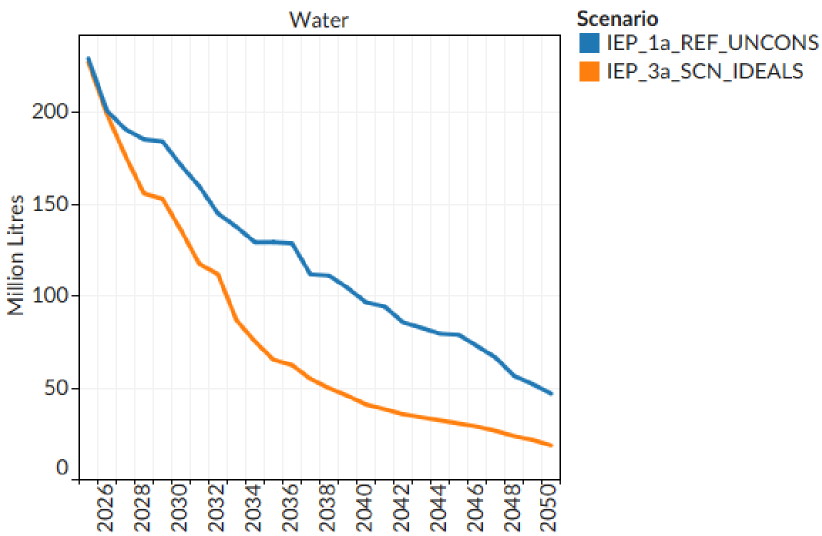


Figure 90: Water consumption in the energy sector comparing the Ideal Energy Scenario to the Reference Case

5.6. Socio-economic indicators

This section provides a summary of high-level socio-economic indicators for the Ideal Energy Scenario as well as sensitivity analyses, in comparison to the unconstrained Reference Case.

5.6.1. Employment

Figure 91 compares economy-wide employment numbers between the Reference Case and the Ideal Energy Scenario, as well as the sensitivity with low localisation.

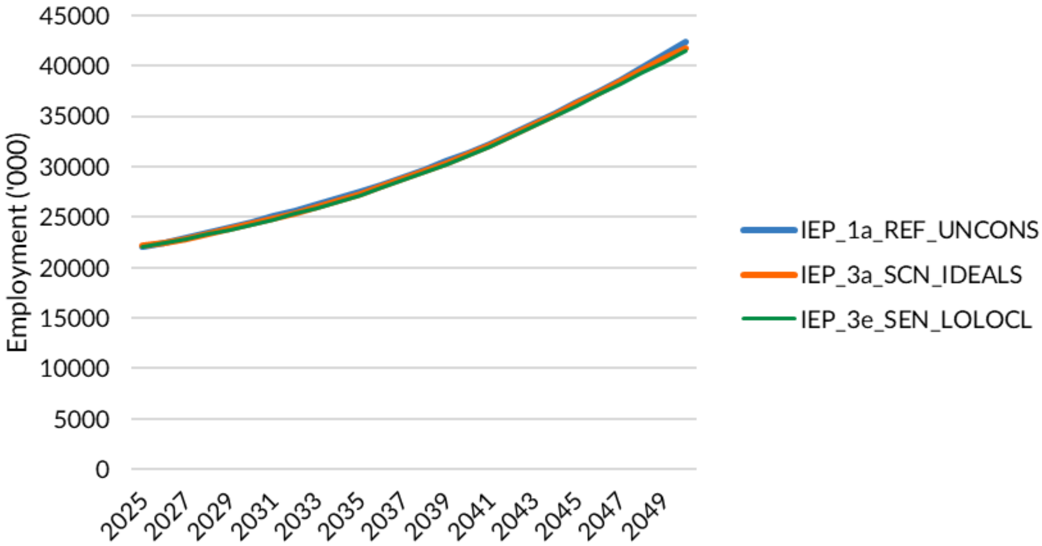


Figure 91: Total employment by scenario

The results show comparatively little difference in employment results. This may however arise at least in part due to the limited sophistication of the CGE model, particularly at disaggregate levels of employment modelling, and therefore further work would likely be needed to establish potential impacts. This is particularly relevant, given the just transition imperatives for the energy sector and the immense challenge of overcoming existing high levels of unemployment. This challenge is partially reflected in the reduction in coal mining jobs shown in Figure 92. While the figure shows that such job losses may be largely offset, in numerical terms, by electricity construction and operation, there are important implications in terms of the location of these jobs – given, as shown above, the majority of renewable energy projects are likely to be located in the Northern and Western Cape, while most coal jobs are naturally located in Mpumalanga and Limpopo.

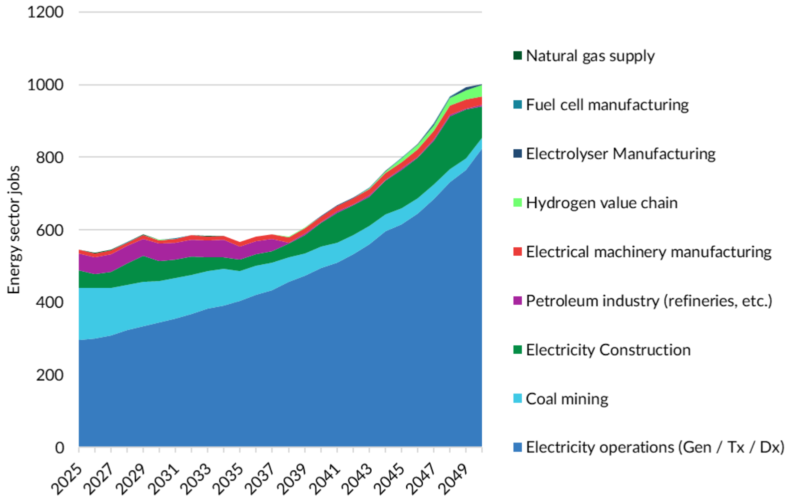


Figure 92: Energy sector jobs for the Ideal Energy Scenario

Sensitivity analyses

The following is a comparison of employment results from all scenarios and sensitivities. Figure 93 shows economy-wide employment results by sector in 2050, while Figure 94 shows energy sector specific employment, and Table 16 provides aggregate data from both figures. The results show that the green exports sensitivity has the high energy sector employment – mainly in electricity operation and hydrogen – but the lower overall employment, while the inverse is shown for the no net zero/CCS sensitivity (higher total employment and lower energy employment).

The lower discount rate results in the highest energy employment and lowest overall employment, while the inverse is not reflected in the higher discount rate sensitivity. This is perhaps a reflection of the low discount rate leading to significantly increased build of nuclear energy, as well as other capital-intensive technology (wind and solar), as shown in Figure 73 above under the low discount rate scenario. The lower discount rate favours nuclear technology with its high capital prices spread over a long period of time, but this also appears to cause a 'crowding out' of investment and job creation elsewhere in the economy.

Notably, relative to all other sensitivities, the low localisation sensitivity seems to have a relatively small impact on overall employment and a small negative impact on energy sector employment (due mainly to a reduction in local electrical machinery manufacturing).

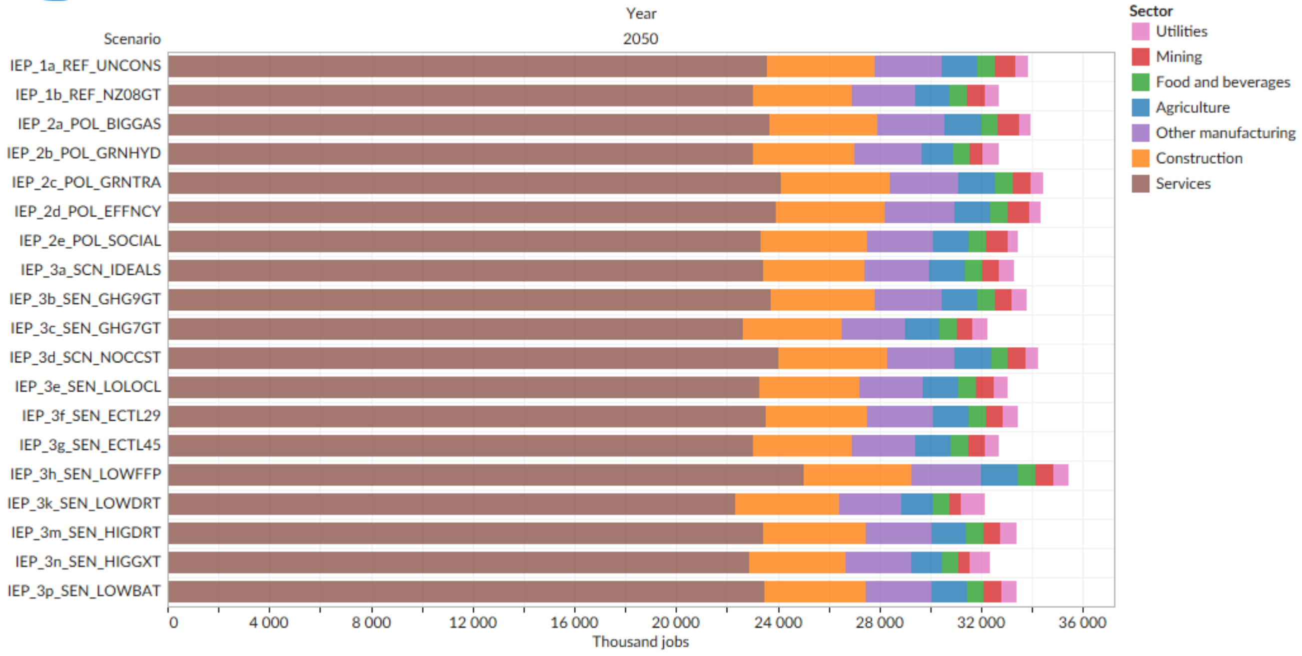


Figure 93: Economy-wide employment for all scenarios and sensitivities in 2050

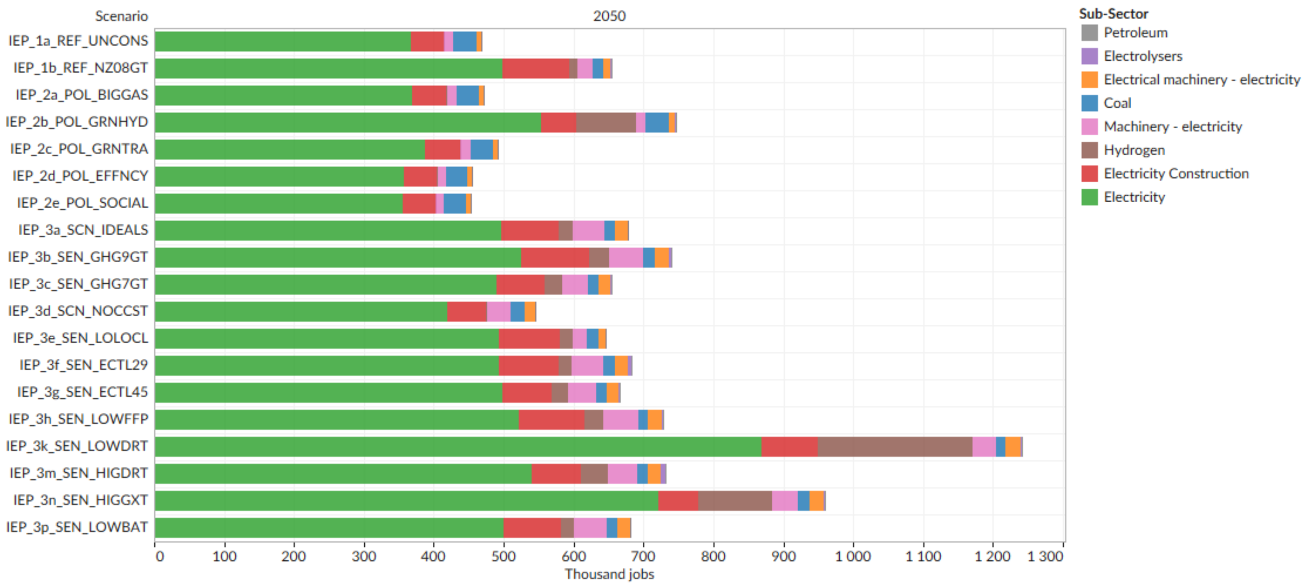


Figure 94: Energy-sector specific employment by scenario and sensitivity in 2050

Table 16: Total economy-wide and energy sector employment by scenario ('000 jobs)

Scenario	Economy-wide employment	Energy sector employment	Energy as percent of total
IEP_1a_REF_UNCONS	33 817	468	1.38%
IEP_1b_REF_NZ08GT	32 712	656	2.01%
IEP_2a_POL_BIGGAS	33 944	471	1.39%
IEP_2b_POL_GRNHYD	32 687	746	2.28%
IEP_2c_POL_GRNTRA	34 435	492	1.43%
IEP_2d_POL_EFFNCY	34 330	455	1.33%
IEP_2e_POL_SOCIAL	33 460	453	1.36%
IEP_3a_SCN_IDEALS	33 286	680	2.04%
IEP_3b_SEN_GHG9GT	33 794	740	2.19%
IEP_3c_SEN_GHG7GT	32 219	656	2.03%
IEP_3d_SCN_NOCCST	34 245	546	1.59%
IEP_3e_SEN_LOLOCL	33 052	647	1.96%
IEP_3f_SEN_ECTL29	33 420	684	2.05%
IEP_3g_SEN_ECTL45	32 709	667	2.04%
IEP_3h_SEN_LOWFFP	35 452	729	2.06%
IEP_3k_SEN_LOWDRT	32 125	1 241	3.86%
IEP_3m_SEN_HIGDRT	33 371	733	2.20%
IEP_3n_SEN_HIGGXT	32 344	961	2.97%
IEP_3p_SEN_LOWBAT	33 371	683	2.05%

5.6.2. GDP

Figure 95 shows GDP projections by scenario, and Figure 97 shows Palma ratio projections comparing the unconstrained Reference Case and Ideal Energy Scenario. The Ideal Energy Scenario performs better in terms of GDP in the long-term than the emissions-constrained Reference Case, potentially showing positive impacts of the energy efficiency and social provisioning measures of this scenario. The more ambitious 7 Gt scenario shows lower GDP growth than other scenarios, reflecting the greater investment amounts required to transition the energy sector more rapidly.

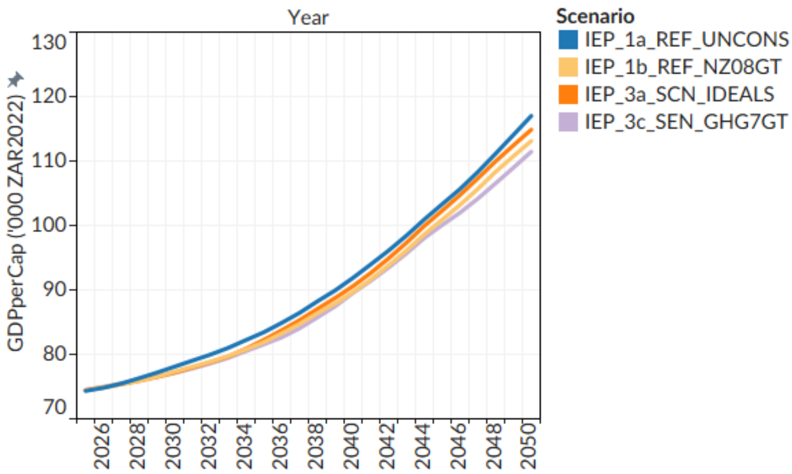


Figure 95: GDP per capita for Ideal Energy Scenario and Sensitivity Analyses

Sensitivity analyses

Figure 96 compares GDP growth of the Ideal Energy Scenario to a selection of other sensitivities, showing the percentage difference in GDP level between the sensitivity and the scenario for each year. Corresponding to what was shown above, the low discount rate – which allows for a significant nuclear build – results in lower GDP growth, as the nuclear build causes a 'crowding out' effect in the broader economy. Similarly, as shown previously, the green export scenario has a negative impact on GDP projections, despite providing an additional export revenue, due to the higher levels of investment required in electricity and hydrogen which, again, cause a crowding out effect in the CGE model.

In the absence of the last mile push to net zero, the no net zero/CCS sensitivity shows more positive GDP growth projections in the latter years of the modelling horizon up to 2050. Notably, the low localisation scenario shows a decline in GDP below the Ideal Energy Scenario – suggesting that localisation is a 'win-win' strategy in terms of providing both employment and economic growth.

Finally, the low fossil fuel price sensitivity run shows the most positive end effect for GDP growth. However, as discussed in section 5.2.2, this finding is not definitive and likely reflects a particularly unrealistic scenario in which South Africa somehow maintains access to fossil fuels at low prices while the rest of the world decarbonises.

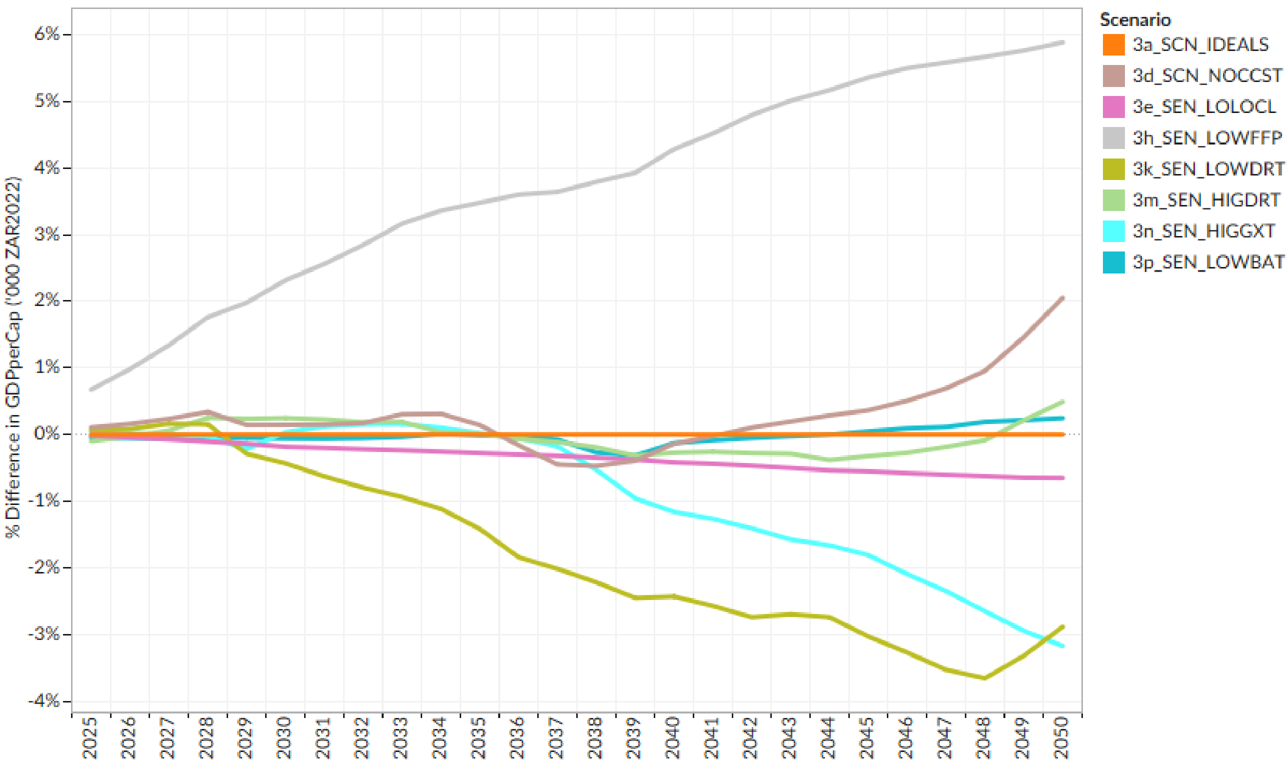


Figure 96: GDP growth of selected sensitivities relative to the Ideal Energy Scenario

5.6.3. Income distribution

Social provisioning also has a greater (albeit still limited, in the context of SATIMGE's modelling) effect on mitigating inequality, as reflected in Figure 97. The same limitations, as described in section 3.6 above, remain applicable here, and are an important caveat in the context of these results.

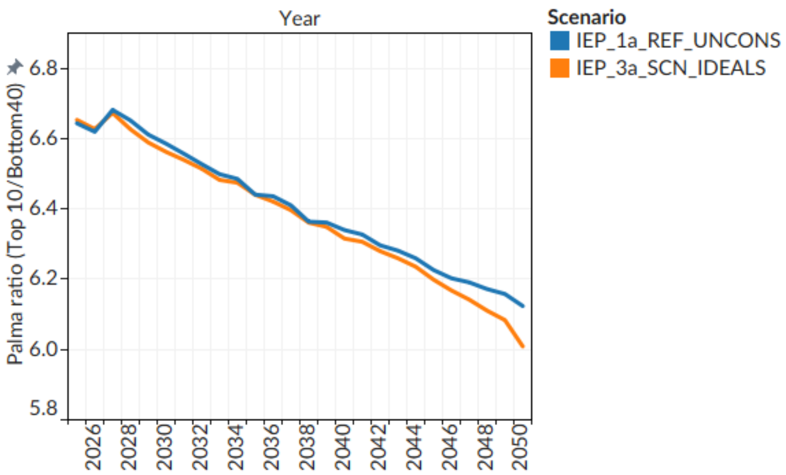


Figure 97: Palma ratio for the Ideal Energy Scenario compared to the Reference Case

Such limitations are reflected in Figure 98, which shows income distribution by decile for the Ideal Energy Scenario and all sensitivity runs.

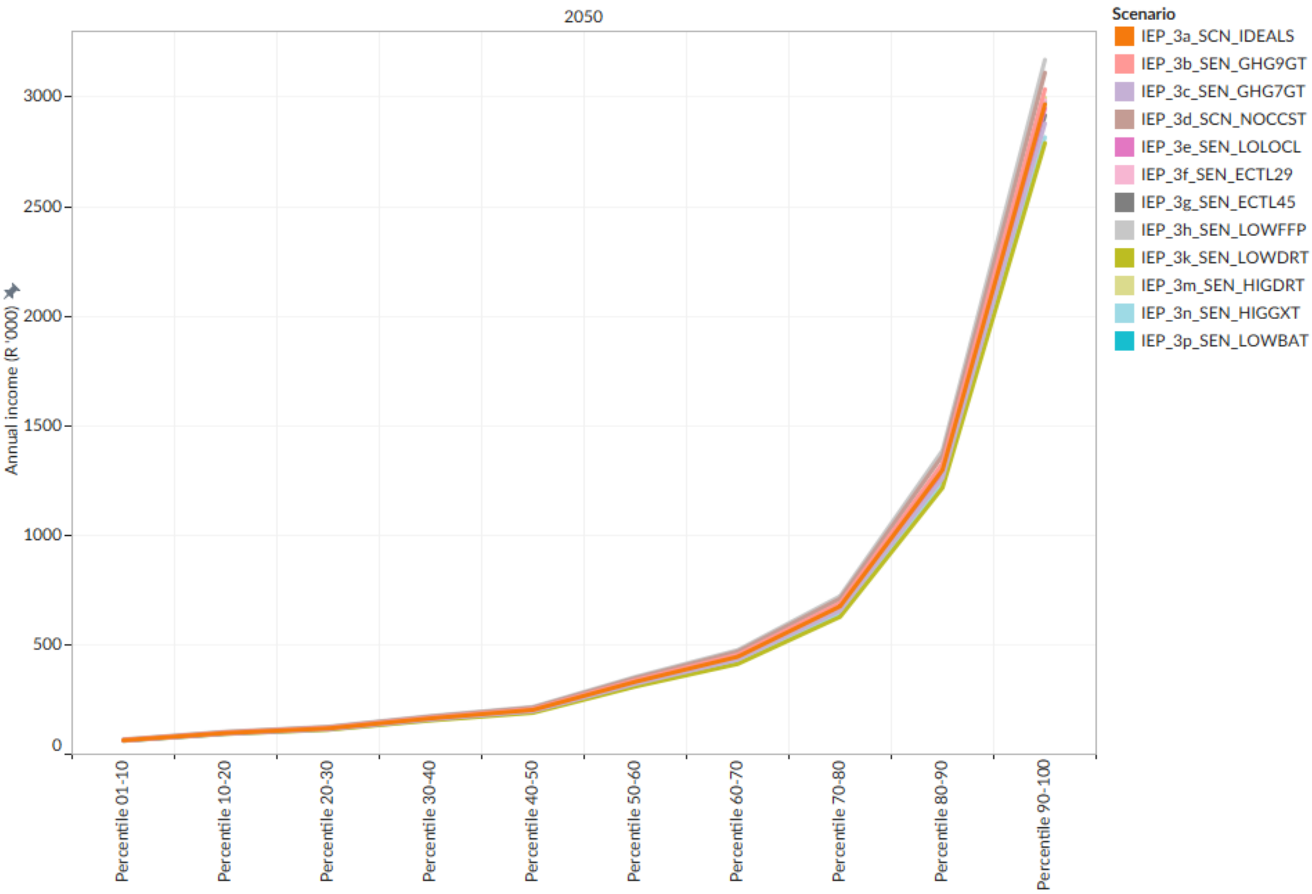


Figure 98: Income distribution by decile for the Ideal Energy Scenario and all sensitivities

While there is a small range of variation for income levels in the higher deciles, there is negligible difference in the bottom deciles. Furthermore, the Palma ratio varies from the lowest level – 6.63 for the low discount rate and high green export sensitivities – to the highest level – 6.71 for the low fossil fuel price sensitivity. These results are thus inverse to the GDP growth results shown for these sensitivities in the previous section, suggesting existing inefficiencies in the distribution of higher levels of income – but also, that the current representation of income distribution in eSAGE is not fully articulated to enough of an extent to provide fully reliable analysis.

6. Discussion

6.1. Stakeholder-led energy planning

The development of Scenario 3—the "Ideal Energy Scenario"—was shaped through a collaborative process that integrated technical modelling with structured stakeholder engagement. The process was initiated by co-designing the overall scenario development approach in partnership with key project stakeholders and collaborators. This collaborative planning phase led to the articulation of three distinct scenario sets, each intended to progressively deepen the analysis and policy relevance of the SATIMGE modelling exercise.

To support the development of the initial scenarios, the project team collected data and insights from subject matter experts across energy, climate, and economic areas, in order to enhance the SATIMGE modelling framework. This informed the initial modelling analysis of the Reference Cases and Policy Scenarios, the results of which were presented and discussed at a multi-stakeholder workshop in January 2025.

At this workshop, participants reviewed the outputs from Scenarios 1 and 2, providing feedback on the assumptions, results, and broader implications. Importantly, the discussions also surfaced early indications of stakeholder priorities and values that could inform the design of Scenario 3. Building on this feedback, the project team developed a proposed framework for Scenario Set 3, characterised as an "Ideal Energy Scenario" that reflects a more aspirational but technically grounded vision of the future energy system. This scenario was supplemented with sensitivity analyses to explore key uncertainties and trade-offs.

The draft scenario design was circulated to stakeholders for input, and their feedback played a crucial role in shaping the final scenario parameters. Once these inputs were integrated and the scenario design finalised, the team undertook detailed modelling analysis. The results, as presented in this document, were again shared with stakeholders to gather their feedback on the plausibility, coherence, and relevance of the scenario outcomes.

Through this process, several important learnings and opportunities for improvement emerged. Stakeholders indicated a desire for more regular and sustained engagement throughout the modelling process, rather than at a few discrete moments. They also highlighted the need for a clearer definition of the scope and limitations of the modelling framework, particularly to manage expectations about what the scenarios can and cannot capture. Finally, participants expressed the importance of allowing sufficient time for consultation and reflection, especially around key assumptions, input choices, and modelling results that shape decision-making and narrative framing.

These insights will inform future iterations of scenario development and stakeholder engagement. Strengthening the process in these areas will help build greater trust, transparency, and co-ownership among stakeholders—ultimately supporting more inclusive and robust policy outcomes.

6.2. Going beyond modelling

In the course of stakeholder engagements and feedback sessions, several additional areas of concern were raised that, while beyond the immediate scope and capabilities of the SATIMGE model, are nonetheless critical for advancing a more holistic, equitable, and participatory approach to energy planning in South Africa.

One key area highlighted was the need for more detailed socio-economic analysis. While the current work includes elements such as access to electricity and the rollout of solar water heaters (SWHs), stakeholders emphasised that these are only part of a much broader socio-economic picture. South Africa continues to grapple with entrenched poverty and inequality, which are deeply interwoven with the structure and evolution of the energy system. Stakeholders noted the unequal burdens borne by women, young people, and rural communities, and called for future energy planning efforts to explicitly account for these disparities through targeted socio-economic assessments and inclusive policy design.

Another critical concern was the importance of just transition planning. As the country undertakes a major transition away from fossil fuels—particularly coal—toward a cleaner and more sustainable energy system as outlined in the Ideal Energy Scenario, it is critical to ensure that this shift is fair and inclusive. In particular, social protection measures—such as income support, retraining programs, and job placement services—are essential to help affected workers and communities navigate the transition without falling into deeper poverty or exclusion. Stakeholders urged that future work should build more directly on the foundations laid by the Just Transition Framework, with particular attention to supporting vulnerable workers, affected communities, and regions whose economies have historically depended on fossil fuel-based industries. Without deliberate and inclusive planning, the transition risks deepening existing inequalities

Lastly, stakeholders pointed to the need for a Community Participation Framework that would provide structured, accessible, and meaningful opportunities for a broader range of public actors—including ordinary community members—to engage in energy decision-making processes. Current consultation processes often remain limited to technical stakeholders, leaving out voices from civil society, youth organisations, labour groups, and frontline communities. Developing a robust participation framework would be a key step toward democratising energy planning and ensuring that the energy transition reflects the values, needs, and aspirations of all South Africans.

Together, these insights highlight the importance of complementing quantitative modelling with broader social and participatory dimensions. Addressing these concerns in future work will help ensure that energy planning is not only technically sound and economically efficient but also socially just and genuinely inclusive.

7. Conclusions

The analysis presented in this report demonstrates that a decarbonised and equitable energy future for South Africa is not only technically feasible but also economically within reach. The Ideal Energy Scenario shows that it is possible to meet ambitious climate and development objectives simultaneously, through a coherent package of interventions that foreground energy access, system affordability, and social equity. While this transition requires higher upfront investment and deliberate planning choices, the overall trajectory is implementable and lies well within the bounds of what the South African economy can accommodate, particularly when long-term benefits are considered.

At the same time, the results make clear that different energy development pathways involve important trade-offs. These trade-offs manifest across several dimensions — economic costs, employment outcomes, emissions trajectories, and the structure of the energy system. The modelling highlights, for example, how expanding fossil gas supply in the Big Gas scenario delays decarbonisation and locks in emissions-intensive infrastructure, while scenarios focused on hydrogen or energy efficiency can accelerate transformation but require greater initial investment and institutional alignment. These trade-offs are not simply technical; they reflect differing social, political and economic priorities, and therefore require open and participatory engagement to navigate responsibly.

Perhaps most critically, the choices made today will have long-term and potentially irreversible effects on the structure and performance of the energy system. Because energy infrastructure is capital-intensive and long-lived, decisions about new investments — whether in refineries, public transport, or distributed renewables — shape not only emissions and costs, but also patterns of energy access, employment and economic inclusion for decades to come. This underscores the urgency of integrated planning that takes full account of both near-term constraints and long-term consequences.

One of the key insights from the modelling is that prioritising equitable access to energy services — as opposed to simply expanding final energy demand — can deliver meaningful improvements in welfare while containing system costs. The Ideal Energy Scenario demonstrates that it is possible to raise access and quality of service, particularly for low-income households, without driving up total energy demand or overburdening the system. This is achieved by scaling up interventions such as free basic electricity, solar water heaters, thermal insulation and efficient lighting, alongside structural shifts in transport and industry. In this way, the scenario aligns improved developmental outcomes with a more efficient and climate-compatible energy system.

A further conclusion from this work is that the application of equity-oriented assumptions in energy modelling substantially changes the picture of system costs and benefits. By shifting the focus from purely least-cost supply expansion toward social provisioning and inclusive access, the Ideal Energy Scenario leads to a different system configuration. This includes earlier deployment of public transport infrastructure, distributed solar and household-level interventions, with co-benefits for health, affordability and resilience. While such a scenario may not reflect a single optimal solution, it does demonstrate that values-based modelling can help expand the space of policy possibility, and surface otherwise neglected options.

Finally, the process underpinning this work reaffirms the critical role that people — stakeholders, communities and citizens — must play in shaping South Africa's energy future. The Ideal Energy Scenario is not a technocratic abstraction; it is the product of deliberative engagement with a diverse range of actors, expressing their aspirations for a system that is clean, inclusive and fair. While not every input could be modelled in detail, the exercise demonstrates the value of participatory modelling in helping to clarify choices, build consensus, and promote transparency in long-term energy planning.

Additional insights arising from the analysis include:

- Beyond the core findings above, the modelling and stakeholder engagement also highlight several additional considerations for future planning processes:
- Public transport transformation emerges as a key enabler of a low-cost and low-carbon energy future. The shift to 80% public transport by 2050 — electrified and accessible — reduces liquid fuel dependency, lowers household energy costs, and contributes significantly to cumulative emissions reductions. The modelling suggests that the investment required for this transition is justified by long-term system-wide benefits.
- Localised energy systems and domestic manufacturing offer opportunities for economic development and job creation. The Ideal Energy Scenario shows that decentralised generation (e.g., rooftop PV) and support for local manufacturing in renewable and battery value chains can partially offset employment losses in fossil sectors and enhance resilience.
- Enabling policies and institutions are essential to realise the modelled pathways. The modelling assumes coherent planning and implementation across multiple domains — industrial policy, public procurement, energy regulation, transport planning and local governance. Without these enablers, the benefits identified may not materialise in practice. Such potential policy measures are explored in more depth in the accompanying policy paper for this work.
- The model has limitations that must be acknowledged in policy application. While the SATIMGE framework provides powerful insights into energy-economy linkages, it cannot account for spatial differentiation, localised environmental impacts, climate resilience needs, or ownership structures. These are critical dimensions for a truly just and sustainable transition, and future iterations of modelling and planning should aim to incorporate them.

In sum, this work contributes to building an evidence base for an inclusive, transparent and future-oriented energy planning process. It reinforces the importance of combining rigorous modelling with stakeholder engagement, and it demonstrates that placing people and equity at the centre of energy planning can lead to better outcomes — not only for the climate, but for society as a whole.

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Appendix A: Assumptions

Electricity

Table 17 shows base assumptions for the existing coal power fleet, including capacity and coal-to-electricity conversion efficiency. Historic assumptions for capital costs are used to determine averaged levelised costs of generation. Figure 99 shows the coal capacity retirement schedule assumed for all scenarios. The schedule is based on the IRP 2019 with various adaptations by Eskom and does not reflect the more recent schedules indicated in the recent work on the new IRP. Table 18 shows constant assumptions for coal fleet availability per plant, based on and derived from Eskom EAF historic data and projections as of the 2024 Medium Term System Adequacy Outlook (MTSAO) 2025-2029 report (Eskom, 2024b). Table 19 shows costing, efficiency, lead time, life and availability assumptions for non-renewable new build power plants, derived from EPRI (2017) and the 2019 IRP (DMRE, 2019). Fuel costs are linked to fuel assumptions as shown above in Table 4.

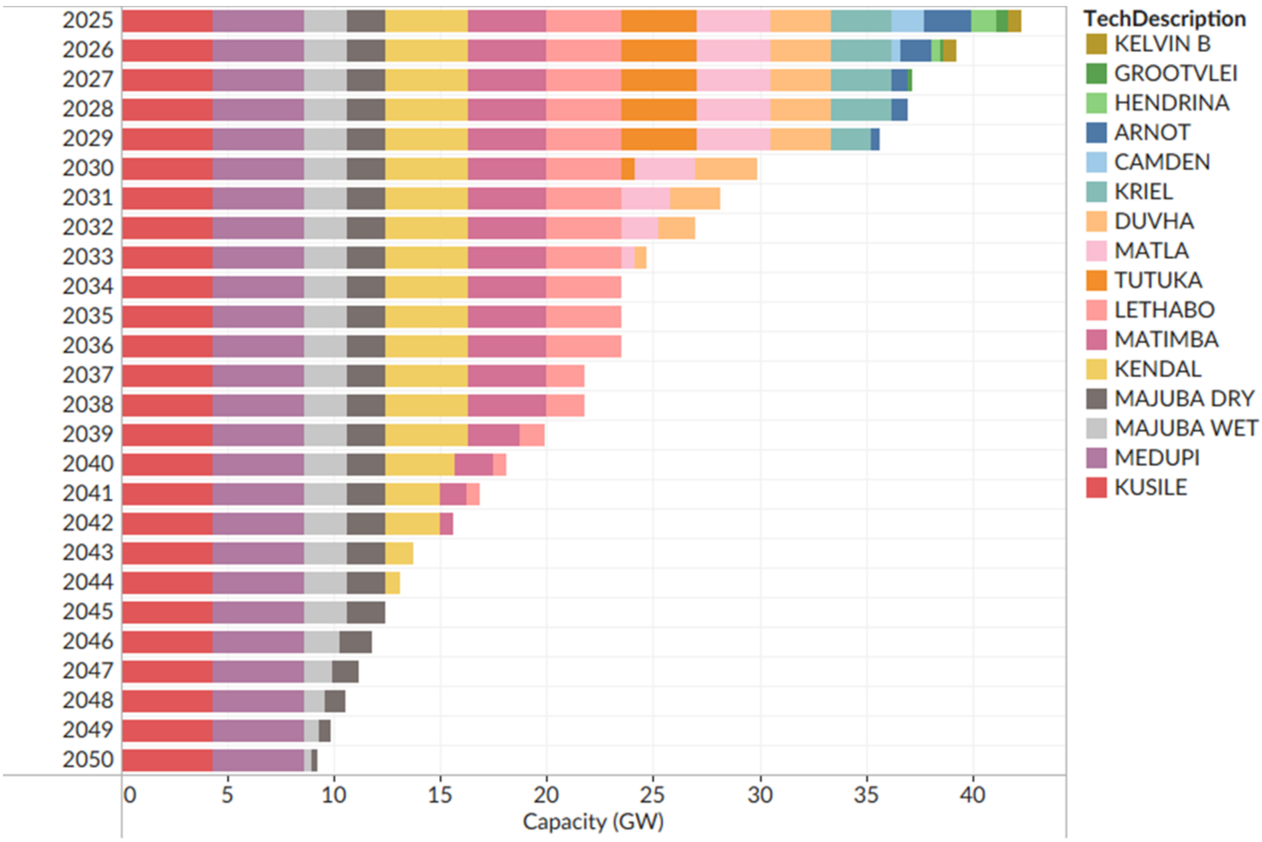

Figure 99: Coal power plant retirement year assumptions

Table 17: Existing coal power plant assumptions

Plant	Capacity (MW)		Conversion Efficiency (%)		Investment (overnight) Cost (R/kW)		Fixed O&M Cost (R/kW)				Variable O&M Cost (R/kW) (excl. fuel cost)			
	2017	2025	Value	Source	Value	Source	2017	Source	2021	Source	2017	Source	2021	Source
ARNOT	2.232	2.232	0.280	Derived from historic Eskom data	11 042.37	Calibrated to historic SAM, used to scale the capital intensity of the electricity sector in the CGE over time	552.87	Assumed constant per plant, calibrated to Eskom Reporting)	635.80	Assumed 15% increase, in line with coal prices	13.27	Assumed constant per plant, calibrated to Eskom Reporting)	15.26	Assumed 15% increase, in line with coal prices
CAMDEN	1.481	1.520	0.273		11 042.37		552.87		635.80		13.27		15.26	
DUVHA	2.875	2.875	0.298		11 042.37		552.87		635.80		13.27		15.26	
GROOTVLEI	1.120	0.570	0.272		11 042.37		552.87		635.80		13.27		15.26	
HENDRINA	1.638	1.140	0.269		11 042.37		552.87		635.80		13.27		15.26	
KENDAL	3.840	3.840	0.306		11 042.37		552.87		635.80		13.27		15.26	
KOMATI	0.904	0.000	0.242		11 042.37		552.87		635.80		13.27		15.26	
KRIEL	2.850	2.850	0.277		11 042.37		552.87		635.80		13.27		15.26	
LETHABO	3.558	3.558	0.340		11 042.37		552.87		635.80		13.27		15.26	
MAJUBA DRY	1.833	1.833	0.300		11 042.37		552.87		635.80		13.27		15.26	
MAJUBA WET	2.010	2.010	0.310		11 042.37		552.87		635.80		13.27		15.26	
MATIMBA	3.690	3.690	0.327		11 042.37		552.87		635.80		13.27		15.26	
MATLA	3.450	3.450	0.321		11 042.37		552.87		635.80		13.27		15.26	
TUTUKA	3.510	3.510	0.311		11 042.37		552.87		635.80		13.27		15.26	
MEDUPI	1.444	4.332	0.371		51 359.85	Meridian data	635.80		731.17		13.27		15.26	
KUSILE	0.711	4.266	0.367	EPRI 2017	51 359.85		635.80		731.17		13.27		15.26	
KELVIN B	0.600	0.600	0.249	IRP 2019	11 042.37		552.87		635.80		13.27		15.26	

Table 18: Existing coal fleet availability assumptions

PLANT	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
CAMDEN	0.50	0.40	0.38	0.36	0.33	0.38	0.42	0.42	0.42	0.40	0.38
GROOTVLEI	0.74	0.64	0.55	0.49	0.46	0.53	0.59	0.60	0.60	0.56	0.54
KOMATI	0.73	0.62	0.54	0.48	0.45	0.52	0.58	0.59	0.59	0.55	0.53
ARNOT	0.54	0.45	0.40	0.34	0.33	0.39	0.46	0.45	0.41	0.34	0.33
DUVHA	0.45	0.35	0.37	0.31	0.33	0.36	0.44	0.43	0.40	0.38	0.37
HENDRINA	0.51	0.40	0.43	0.38	0.36	0.41	0.46	0.46	0.46	0.44	0.42
KENDAL	0.57	0.51	0.40	0.40	0.36	0.44	0.50	0.47	0.53	0.46	0.44
KRIEL	0.45	0.45	0.34	0.28	0.34	0.38	0.43	0.46	0.34	0.38	0.39
LETHABO	0.68	0.62	0.61	0.55	0.54	0.60	0.57	0.57	0.57	0.60	0.59
MAJUBA	0.67	0.64	0.61	0.56	0.57	0.61	0.58	0.60	0.60	0.58	0.57
MATIMBA	0.76	0.69	0.66	0.63	0.62	0.63	0.66	0.66	0.64	0.65	0.64
MATLA	0.62	0.59	0.57	0.55	0.53	0.56	0.58	0.58	0.58	0.57	0.56
TUTUKA	0.47	0.41	0.33	0.33	0.29	0.36	0.38	0.38	0.42	0.37	0.35
MEDUPI	0.69	0.68	0.68	0.65	0.65	0.65	0.71	0.72	0.66	0.67	0.65
KUSILE	0.66	0.66	0.68	0.63	0.62	0.66	0.65	0.69	0.68	0.65	0.64

Table 19: Assumptions for non-renewable new build electricity

Tech	Conversion Efficiency (%)	Variable OM (R/GJ)	Fixed OM (R/kW)	Overnight (R/kW)	Lead time (years)	Life (years)	Annual Avail (%)
Generic Waterberg Coal Plant	0.438	31.50	1 311.26	55 306.83	4	50	0.80
Generic Waterberg Coal Plant with CCS	0.326	58.12	2 235.68	106 982.81	4	50	0.80
Fluidised Bed Combustion Coal	0.360	68.17	881.71	66 757.53	4	50	0.80
Nuclear Mid	0.348	14.57	1 373.44	96 386.01	8	60	0.85
Open Cycle Gas Turbine - LNG	0.313	0.94	227.34	12 746.64	2	30	0.85
Hydrogen Turbine or FuelCell	0.500	110.34	0.00	34 758.64	2	30	0.85
Combined Cycle Gas Turbine - LNG	0.487	8.62	234.87	13 996.99	2	30	0.85
Combined Cycle Gas Turbine - LNG with CCS	0.405	13.40	557.66	30 757.18	2	30	0.85
Gas Engines - LNG	0.450	27.56	597.86	19 886.75	2	20	0.85

Existing renewable power capacity data, for both utility-scale and embedded generation, is derived largely from Meridian Economics, Eskom, and the DoEE Renewable Energy Data and Information Service (REDIS). All scenarios assume fixed distributed rooftop PV capacity additions annually from current levels ramping up to 900 MW from 2031 onwards, split evenly across five demand sectors (residential, commercial, industry, mining and agriculture). Learning rates for PV and wind are based on data collected from UNEP, NREL and the Fraunhofer research institutes – see cost projections shown in Table 20.

Table 20: Renewable costing data

	Overnight Costs (R/kW)								Assumed FOM as % of Overnight	Fixed Cost (R/kW)						
Utility	**2017**	**2020**	**2023**	**2025**	**2030**	**2040**	**2050**	**Source**		**2017**	**2020**	**2023**	**2025**	**2030**	**2040**	**2050**
Solar Central Receiver 09 hrs stor	81 279	81 280	73 999	61 863	49 727	49 727	49 727	CSIR learning applied to IRP	2%	1 626	1 626	1 480	1 237	995	995	995
Solar PV Fixed	48 763	19 505	13 810	12 963	12 179	10 819	9 558	Based on PV learning	2%	975	390	276	259	244	216	191
Solar PV tracking	51 983	20 793	14 722	13 820	12 983	11 533	10 189		2%	1 040	416	294	276	260	231	204
Wind	32 296	28 019	17 575	17 422	17 270	16 969	16 674	Wind learning	2%	646	560	352	348	345	339	333
On-site	**2017**	**2020**	**2023**	**2025**	**2030**	**2040**	**2050**	**Source**		**2017**	**2020**	**2023**	**2025**	**2030**	**2040**	
Solar PV rooftop Agriculture	56 565	22 626	16 020	15 038	14 127	12 550	11 087	Empirical project data (e.g. Black River Park)	2%	1 131	453	320	301	283	251	222
Solar PV rooftop Mining	56 565	22 626	16 020	15 038	14 127	12 550	11 087		2%	1 131	453	320	301	283	251	222
Solar PV rooftop commercial	56 565	22 626	16 020	15 038	14 127	12 550	11 087		2%	1 131	453	320	301	283	251	222
Solar PV rooftop residential	85 334	34 134	24 168	22 686	21 313	18 933	16 727		2%	1 707	683	483	454	426	379	335
Solar PV rooftop Industry	56 565	22 626	16 020	15 038	14 127	12 550	11 087		2%	1 131	453	320	301	283	251	222

Battery learning costs

As shown in Figure 8 in Section 2.2.2 above, two battery learning rate assumptions were applied in this analysis, derived from IRENA analysis: a default "conservative" assumption, as well as a more optimistic accelerated learning rate. Annual battery costs, in ZAR per kW, are thus assumed as follows:

Table 21: Battery Learning Costs assumed in this study

Year	IRENA Conservative (ZAR/kW)	IRENA Optimistic (ZAR/kW)
2025	900	900
2030	830	730
2035	760	560
2040	690	400
2045	620	250
2050	550	200

Transport

Assumptions on base level vehicle costs for internal combustion engine (ICE), hybrid (HEV) and battery electric vehicles (BEVs) by different vehicle classes – see cars (sedans and hatchbacks) in Figure 100 (and Table 22), SUVs in Figure 101 (and Table 23) and commercial vehicles in Figure 102 (Table 24).

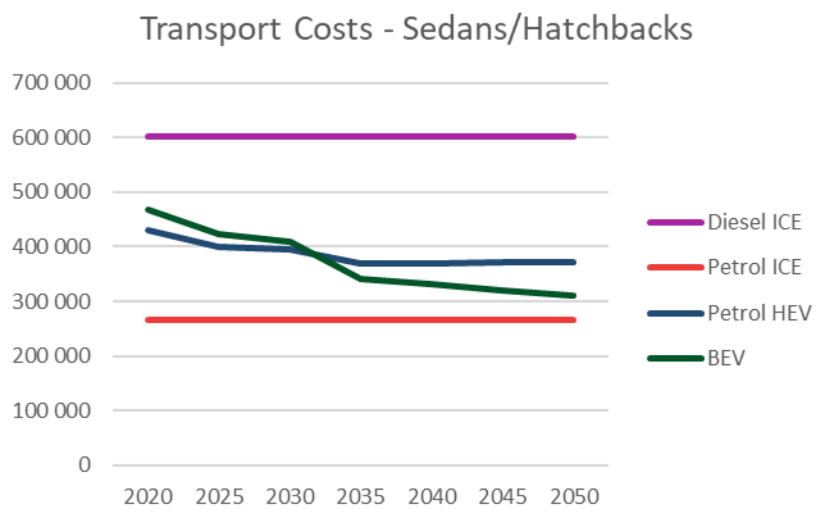

Figure 100: Base assumptions for price trajectories for private cars – ICEs and EVs

Table 22: Base assumptions for price trajectories for private cars – ICEs and EVs (2022 ZAR)

Year	Diesel ICE	Petrol ICE	Petrol HEV	BEV
2020	600 000	270 000	430 000	470 000
2025	600 000	270 000	410 000	420 000
2030	600 000	270 000	390 000	400 000
2035	600 000	270 000	370 000	340 000
2040	600 000	270 000	370 000	320 000
2045	600 000	270 000	370 000	310 000
2050	600 000	270 000	370 000	300 000

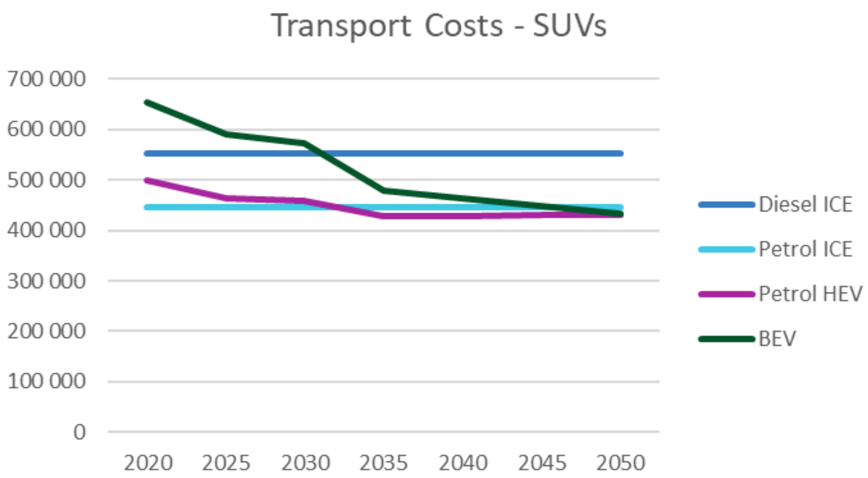

Figure 101: Base assumptions for price trajectories for private SUVs – ICEs and EVs

Table 23: Base assumptions for price trajectories for private SUVs – ICEs and EVs (2022 ZAR)

Year	Diesel ICE	Petrol ICE	Petrol HEV	BEV
2020	550 000	500 000	490 000	650 000
2025	550 000	480 000	470 000	600 000
2030	550 000	470 000	460 000	580 000
2035	550 000	440 000	430 000	500 000
2040	550 000	440 000	430 000	460 000
2045	550 000	440 000	430 000	440 000
2050	550 000	440 000	430 000	430 000

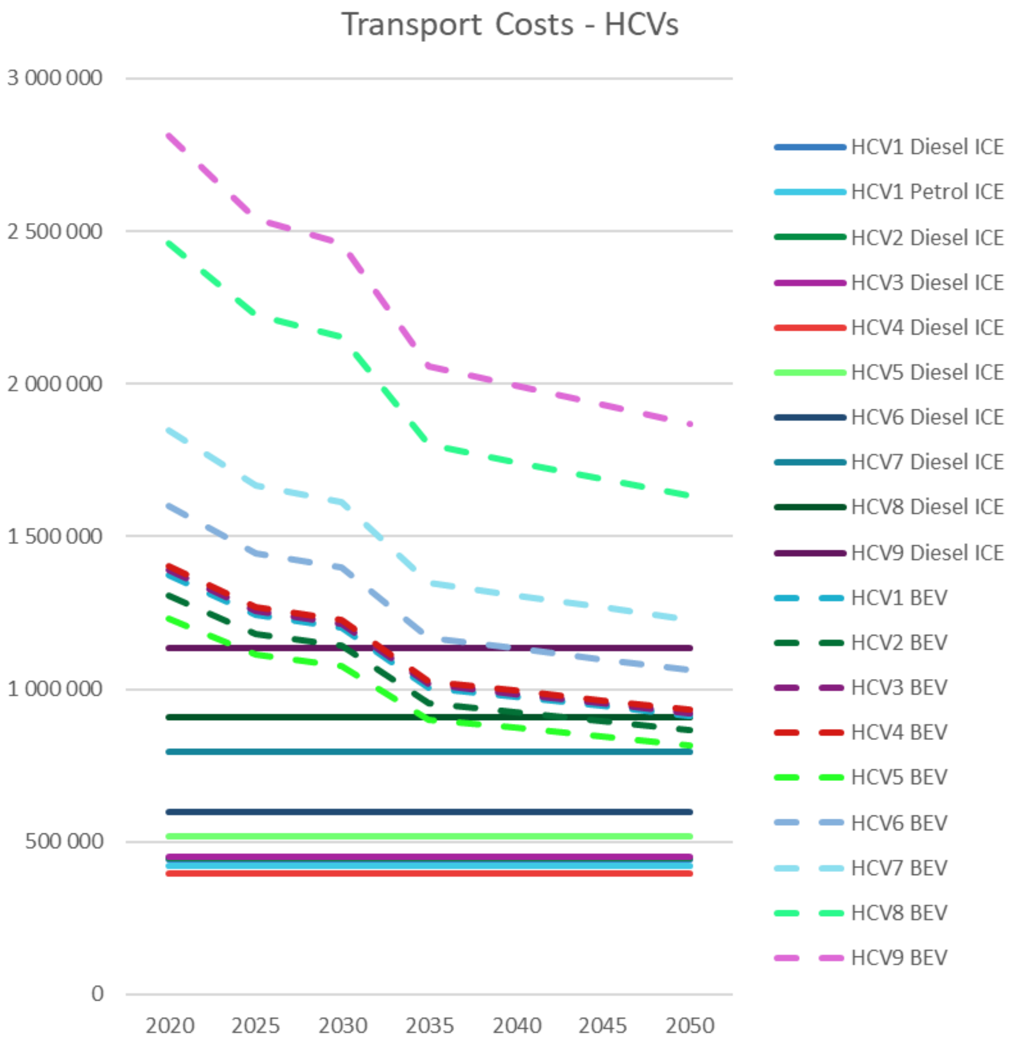

Figure 102: Base assumptions for price trajectories for HCVs – ICEs and EVs

Table 24: Base assumptions for price trajectories for HCVs – ICEs and EVs (2022 ZAR)

Vehicle Type	2020	2025	2030	2035	2040	2045	2050
HCV1 Diesel ICE	1 300 000	1 250 000	1 200 000	1 100 000	1 050 000	1 030 000	1 000 000
HCV1 Petrol ICE	1 400 000	1 350 000	1 300 000	1 150 000	1 100 000	1 070 000	1 050 000
HCV1 BEV	900 000	900 000	900 000	850 000	850 000	850 000	850 000
HCV2 Diesel ICE	1 800 000	1 700 000	1 600 000	1 400 000	1 350 000	1 300 000	1 250 000
HCV2 BEV	950 000	950 000	950 000	900 000	900 000	900 000	900 000
HCV3 Diesel ICE	1 300 000	1 250 000	1 200 000	1 150 000	1 100 000	1 050 000	1 000 000

Vehicle Type	2020	2025	2030	2035	2040	2045	2050
HCV3 BEV	900 000	900 000	900 000	850 000	850 000	850 000	850 000
HCV4 Diesel ICE	1 400 000	1 350 000	1 300 000	1 200 000	1 150 000	1 100 000	1 050 000
HCV4 BEV	950 000	950 000	950 000	900 000	900 000	900 000	900 000
HCV5 Diesel ICE	2 000 000	1 900 000	1 800 000	1 600 000	1 550 000	1 500 000	1 450 000
HCV5 BEV	1 000 000	1 000 000	1 000 000	950 000	950 000	950 000	950 000
HCV6 Diesel ICE	1 100 000	1 050 000	1 000 000	950 000	900 000	900 000	900 000
HCV6 BEV	600 000	600 000	600 000	600 000	600 000	600 000	600 000
HCV7 Diesel ICE	1 250 000	1 200 000	1 150 000	1 100 000	1 050 000	1 000 000	950 000
HCV7 BEV	850 000	850 000	850 000	850 000	850 000	850 000	850 000
HCV8 Diesel ICE	1 100 000	1 050 000	1 000 000	950 000	900 000	900 000	900 000
HCV8 BEV	600 000	600 000	600 000	600 000	600 000	600 000	600 000
HCV9 Diesel ICE	2 800 000	2 500 000	2 300 000	2 100 000	2 000 000	1 950 000	1 900 000
HCV9 BEV	1 200 000	1 200 000	1 200 000	1 100 000	1 100 000	1 100 000	1 100 000

Table 25: Base assumptions for private passenger transport demand

Household Income Group - Private Veh Ownership		2017
Low Income		2%
Middle Income		53%
High Income		78%
Veh/pers for pers with priv.veh.		**2017**
Low Income		0.25
Middle Income		0.32
High Income		0.42
Priv.veh.Occupancy for pers with priv.veh		**2017**
Low Income	pers/veh	1.39
Middle Income	pers/veh	1.39
High Income	pers/veh	1.39
Other priv.veh(gov, rental, company)	pers/veh	1.36
Priv.veh.mileage per veh for pers with priv.veh		**2017**
Low Income	'000 km/yr	7.39
Middle Income	'000 km/yr	12.34
High Income	'000 km/yr	13.33
Other priv.veh(gov, rental, company)	'000 km/yr	13.50
Other priv. veh (gov/companies/car rentals)		
Elasticity to GDP		0.50
Number of priv (gov etc.) Veh	veh million	0.82
Time budget for travelling		**2017**
Total travel time per household	hours/year	330.00
Average Speed by Mode		
Priv veh	km/hr	33.50
BRT	km/hr	25.50
Gautrain	km/hr	43.00
MBT/Bus/metrorail	km/hr	21.50

https://dataportal.opendataforafrica.org/nbyenxf/afdb-socio-economic-database-1960-2021

Time budget split by Mode and Income group	
Walking/waiting time for public transport of total travel time by public	55%

Table 26: Assumed base year public passenger transport modal shares

Proportion of travel by public transport for people with a priv veh		
Low Income	million pers	0.52
		2017
Priv.veh.	%	23.28%
BRT	%	**0.50%**
Gautrain	%	**0.00%**
Bus, minibus, metro rail	%	76.22%
Middle Income	million pers	9.23
Priv.veh.	%	49.80%
BRT	%	**1.00%**
Gautrain	%	**0.20%**
Bus, minibus, metro rail	%	49.00%
High Income	million pers	10.46
Priv.veh.	%	70.43%
BRT	%	**1.00%**
Gautrain	%	**0.50%**
Bus, minibus, metro rail	%	28.07%

pers without a priv. veh		
Low Income	million pers	25.24
BRT	%	**0.50%**
Gautrain	%	**0.00%**
Bus, minibus, metro rail	%	99.50%
Middle Income	million pers	8.19
BRT	%	**0.50%**
Gautrain	%	**0.20%**
Bus, minibus, metro rail	%	99.30%
High Income	million pers	2.89
BRT	%	**0.50%**
Gautrain	%	**0.50%**
Bus, minibus, metro rail	%	99.00%

Table 27: Assumed base year passenger transport modal shares

Split between priv pkm		**2017**
Car		80.00%
SUV		**17.00%**
Motorbikes		**3.00%**

Split between Bus, minibus, metro rail pkm		**GHS 2018**
Bus		**12.78%**
MBT		**80.30%**
Metro rail		6.92%

Public Road Veh. Occpancy		
Bus	pers/veh	**25.00**
MBT	pers/veh	**14.00**
BRT	pers/veh	**25.00**

Table 28: Freight transport average vehicle loading and base year mileage assumptions

Average Loading - direct input into model		VEDA	2017
TFLCV	Freight LCV	ton	0.40
TFHCV1	Freight HCV1	ton	1.48
TFHCV2	Freight HCV2	ton	2.50
TFHCV3	Freight HCV3	ton	5.01
TFHCV4	Freight HCV4	ton	7.92
TFHCV5	Freight HCV5	ton	10.89
TFHCV6	Freight HCV6	ton	19.52
TFHCV7	Freight HCV7	ton	17.89
TFHCV8	Freight HCV8	ton	18.40
TFHCV9	Freight HCV9	ton	21.91

Base year vehkm demand			BY-DMD 2017
TFLCV	Transport Freight - LCV	b vehkm	47.58
TFHCV1	Transport Freight - HCV1	b vehkm	3.65
TFHCV2	Transport Freight - HCV2	b vehkm	1.00
TFHCV3	Transport Freight - HCV3	b vehkm	3.30
TFHCV4	Transport Freight - HCV4	b vehkm	0.60
TFHCV5	Transport Freight - HCV5	b vehkm	0.30
TFHCV6	Transport Freight - HCV6	b vehkm	6.66
TFHCV7	Transport Freight - HCV7	b vehkm	2.23
TFHCV8	Transport Freight - HCV8	b vehkm	0.12
TFHCV9	Transport Freight - HCV9	b vehkm	0.03
TFRCO	Transport Freight - Rail Corridor	b tonkm	22.00
TFROT	Transport Freight - Rail Other	b tonkm	27.14
TFREX	Transport Freight - Rail Export (bulk mining)	b tonkm	88.67

Other

Emissions factors

Table 29: Emissions factors used in SATIM (kilotonne native unit per PJ)

Emission	Coal	Gas	AvGas	Diesel	Gaso-line	HFO	Kero-sene	LPG	Biomass (incl. wood)
Carbon dioxide (CO_2)	96.250	56.100	70.000	74.067	69.300	77.400	72.900	63.100	0.000
Methane (CH_4)	0.001	0.001	0.003	0.003	0.003	0.003	0.003	0.003	0.015
Nitrous Oxide (N_2O)	0.001	0.000	0.001	0.001	0.001	0.001	0.001	0.000	0.001
Sulphur gases (SO_x)	0.626	0.000	0.047	0.253	0.047	1.529	0.046	5.409	0.030
Nitrogen gases (NO_x)	0.300	0.150	0.300	0.200	0.600	0.200	0.200	0.012	0.150
Carbon monox-ide (CO)	0.020	0.020	0.100	0.015	8.000	0.010	0.010	0.182	2.600
Non-methane volatile organic compounds (NMVOCs)	0.005	0.005	0.050	0.005	1.500	0.005	0.005	0.024	0.040
Particulate Mat-ter 10µm (PM10)	0.046								0.120

Refineries

Existing refinery production slates and timelines (assuming no endogenous retirement for CTL) – see Figure 103:

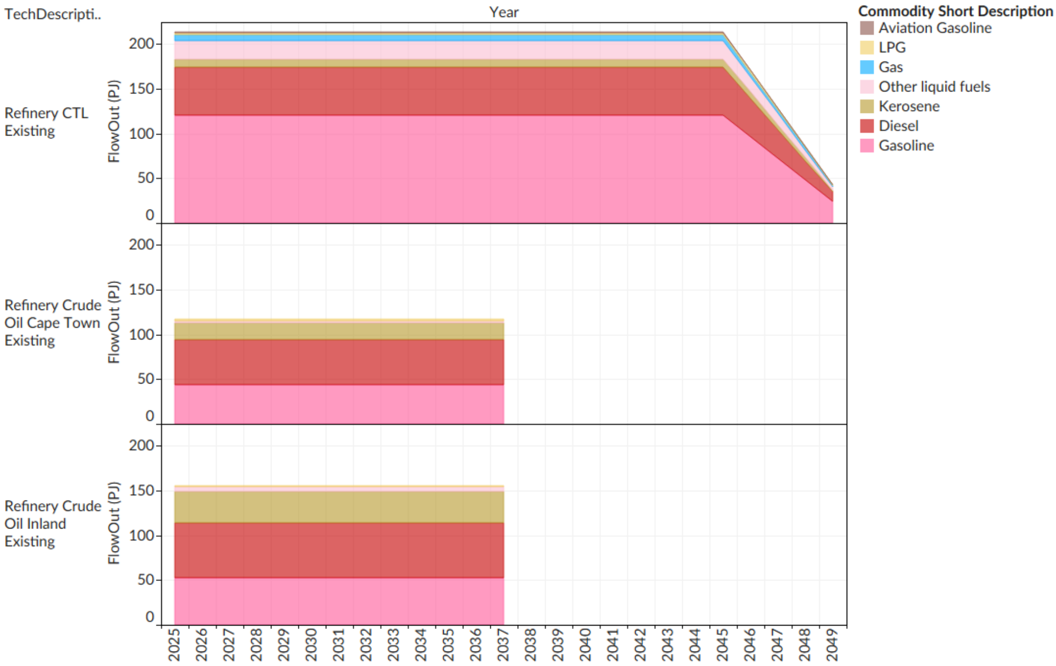

Figure 103: Assumptions about refinery liquid fuel productions (output shown in PJ)

Economic growth

Economic growth is endogenous in the model and adjusts in response to economic "shocks". A reference GDP growth trajectory is however, imputed into the model by adjusting total factor productivity over the time horizon. This in combination with a simple capital allocation step in the CGE will determine the base growth trajectories for each sector.

These base growth trajectories are then kept constants for all scenarios (except in cases that force higher or lower reference growth). In the short term (up to 2031) GDP growth in the CGE is calibrated to match the growth projections in the 2024 budget review's economic outlook (National Treasury, 2024). Beyond this economic growth is assumed to gradually increase to 3.5% in the mid-2030s and then hover around this percentage to 2050.

In each scenario the CGE is exposed to various shocks which differ from the reference scenario (e.g. more investment in the power sector to achieve more CO2 emission reductions). These shocks come from processing results of the SATIM model, that is endogenously itself responding to, for example, a CO_2 reduction cap ('shock') applied to the power sector. SATIM is able to provide a more robust picture of what the power sector should look like given a particular CO2 trajectory, than the CGE would be able to achieve by itself.

In this way the model provides an estimate of the GDP impact of policy interventions applied to the model, and in the context of other given assumptions (e.g. fixed amount of capital, a particular trajectory for FDI, a different mix of local vs imported components for the RE build-out, etc.).