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TOWARDS A JUST TRANSITION

Technical Report

February 2024

NET ZERO CO_2 EMISSION PATHWAYS FOR SOUTH AFRICA

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Acknowledgements

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The ESRG would also like to acknowledge the work of Dr Luanne Stevens, who is responsible for the development of the models of the land and agriculture sectors which form an integral part of the SATIMGE framework, and without which this analysis would not have been possible.

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Executive Summary

This report provides a summary of analysis undertaken by the Energy Systems Research Group (ESRG)[1] exploring potential energy and sectoral mitigation pathways through which South Africa could reach net zero CO_2 emissions by mid-century. The project has been undertaken to provide analysis and an evidence base for the Presidential Climate Commission (PCC), to support its objectives of facilitating conversations and building understanding of South Africa's just energy transition. *A separate report has been prepared by the Council for Scientific and Industrial Research (CSIR) on their analysis of some of the scenarios presented here with respect to the resultant air quality and water use impacts. The CSIR study should be read in conjunction with this one.*

The study has developed 40 long-term GHG emissions pathways for South Africa to characterise those pathways which reach net zero CO_2 emissions in 2050 or 2055. The study examines the socio-economic effects of such net zero pathways, and considers the additional effects of key associated measures such as the carbon tax, localisation of parts of the energy infrastructure supply chain, and energy efficiency measures. The conclusion reports key findings on net zero pathways for South Africa, and highlights areas that need further work. The study has been undertaken using SATIMGE, a linked energy/economics/emissions model developed and maintained by the ESRG.

Net zero CO_2 pathways form part of an integrated package of international policy measures decided by Parties to the Paris Agreement (including South Africa) in response to the IPCC's assessments highlighting the features of 1.5 degree GHG emissions pathways. The other parts of the package include a limited global CO_2 budget to 2050 and deep reductions in non-CO_2 gases to 2050, and the scaled-up provision of support to developing countries. Analysis of a net zero CO_2 target should consider both the net zero goal, and a pathway to achieve the goal which is consistent with South Africa's obligations under the UNFCCC and its Paris Agreement and subsequent decisions.

[1] The ESRG would also like to acknowledge the work of Dr Luanne Stevens, who is responsible for the development of the models of the land and agriculture sectors which form an integral part of the SATIMGE framework.

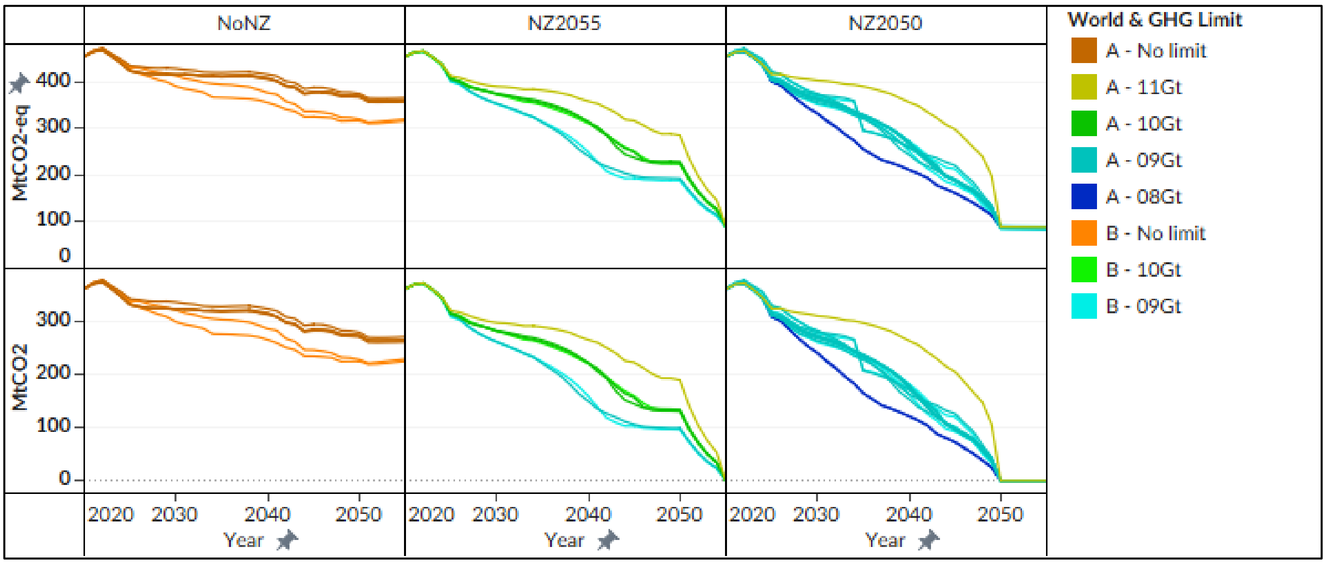

Figure 1: Net GHG (top) and CO2 (bottom) emission pathways by World, GHG limit and net zero year.

Figure 1 presents a set of GHG emissions pathways for South Africa, some reaching net zero CO_2 emissions in 2050, others in 2055, and in the panels on the left, without a net zero CO_2 or GHG emissions constraint. Pathways are characterised by their cumulative GHG emissions from 2021 to 2050, and have been modelled with and without a range of key long-term measures, and in two "worlds" – one with a strong multilateral regime, and one with a weak regime. Pathways were explored in detail at a sectoral level, and evaluated economically.

The GHG emissions pathways of three scenarios are presented in Figure 2 to 2055, as well as the share of cumulative emissions for each sector in the same timeframe.

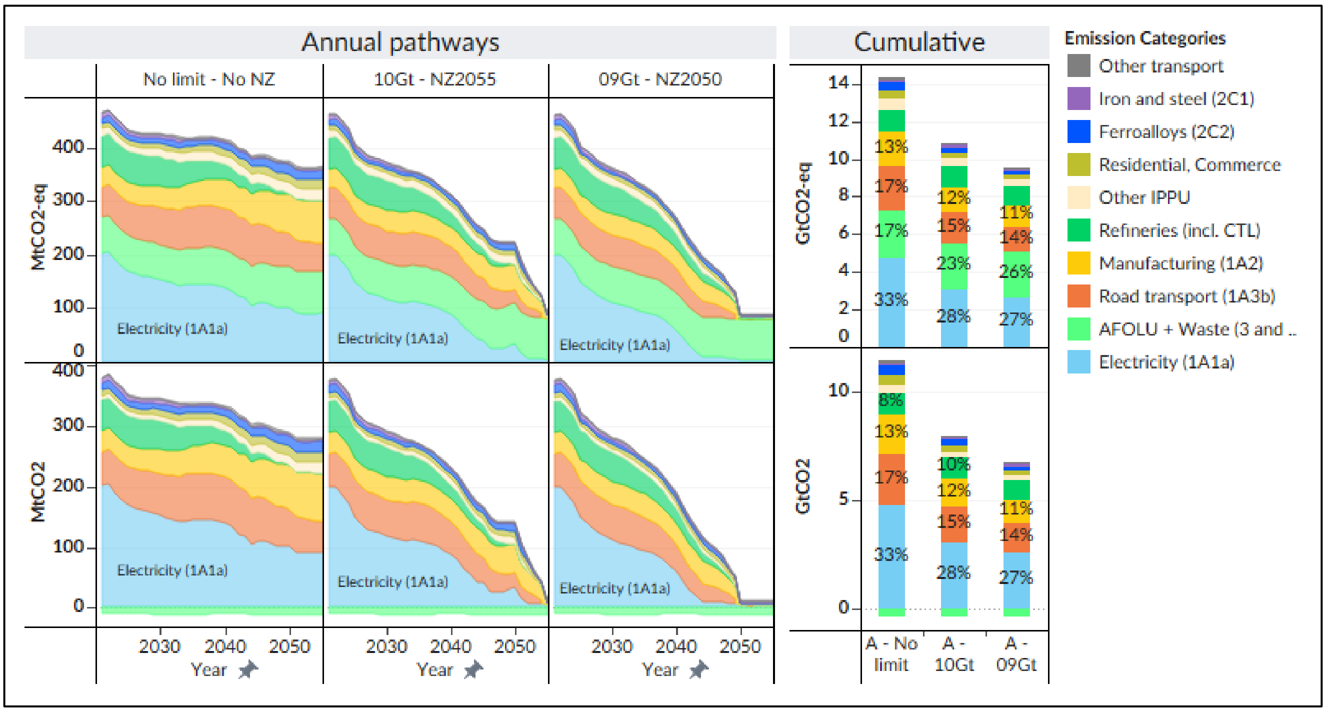

Figure 2: Annual and cumulative GHGs and CO_2 by sector for an unconstrained, 10Gt (NZ2055) and 9Gt (NZ2050) scenario – the pathways in the top row portray all gases, whereas the pathways in the bottom row contain only CO_2.

While a long-term net-zero pathway will require challenging shifts away from GHG-intensive activities in all sectors, the analysis confirms the critical importance of the electricity sector in each decade in shifting away from a CO_2-intensive economy, and ultimately reaching net zero CO_2 emissions, on account of its overall contribution to CO_2 emissions, the availability of mature low- and zero-CO_2 generation technologies, and the dependence of other sectors on zero-CO_2 electricity for their decarbonization. The energy transition away from coal is thus at the heart of all GHG emissions pathways for South Africa to net zero; at the same time, a just transition is critical, and coal will still play a central role in the South African energy system over the next decade, including in the more ambitious 9 Gt scenarios.

The effort required in the "last mile" to net zero CO_2 is immense, and rests in all scenarios on both a massive increase in investment in the electricity sector, and extensive use of Carbon Capture and Storage (CCS) technology. CCS is not proven technically or economically in a South African context, and has only been implemented at a very small scale internationally. If CCS is not available at the required scale (30-40 Mt per annum), mitigating the remaining CO_2 emissions (primarily in the cement and ferroalloys sectors) will require the development of new technology, or finding substitutes for products from these sectors, or importing cement and exporting unprocessed ore[2]. The massive investments required in the electricity sector and elsewhere result in a lower GDP/capita in pathways which a) reach net zero, and b) have a GHG emissions constraint of less than 10 Gt. South Africa will require support to achieve a net zero CO_2 target, both for the required level of investment in infrastructure, and in pursuing technological solutions to mitigate CO_2 in 'hard to abate' sectors.

Socioeconomic analysis indicates that, with the right combination of measures, a 10 Gt pathway which does not reach net zero in 2055 results in the same level of GDP/capita as a pathway without any further climate policy. Implementing measures to achieve this pathway is a no-regrets option, and higher GHG emissions have no further economic benefit. The costs of other impacts associated with GHG emissions from fossil fuels (air pollution and water use), which have not been fully factored into this analysis, would possibly result in a worse GDP/capita outcome for scenarios with cumulative GHG emissions above 10 Gt.

Further analysis reveals that with the right combination of accompanying measures, it is possible to reach net zero in 2050 and impose an ambitious long-term GHG budget of 8 Gt on the economy, with a 6% lower GDP in 2050 than in a case without a net zero target or a GHG constraint. This is equivalent to a year and a half of economic growth, and GDP/capita would still be more than double its 2021 value in real terms. Pathways which reach net zero in 2050 or 2055 with a 9 Gt constraint have similar outcomes, with lower GDP losses. The GDP losses occur in modelled pathways with cumulative GHG emissions below 10 Gt, and particularly for those which reach net zero in 2050 or 2055, as a result of the massive investment requirements resulting in a crowding-out effect, relative to pathways with cumulative emissions above this level, due to the re-allocation of investment from other more productive sectors of the economy to where mitigation infrastructure would be required. A combination of long-term measures, especially

[2] This would potentially result in carbon leakage unless other economies had access to either CCS or manufacturing processes which resulted in zero GHG emissions.

energy efficiency measures, can offset some or most of this loss, as can concessional finance and additional foreign direct investment.

This analysis has been undertaken with the assumption that concessional climate finance at the required scale is NOT available. The availability of climate finance at the required scale from the international community will most likely offset GDP losses of ambitious mitigation action and lead to higher economic growth for ambitious mitigation pathways which reach net zero, but this possibility requires further analysis[3].

There are two very significant caveats to these findings. First, there is considerable transition risk in high-GHG emissions pathways (>10Gt) for South Africa that requires further analysis. The first risk is that of having to meet a more stringent target later, as a result of increasing international pressure in a rapidly warming world, which would require a far more rapid and costly transition (in terms of annual financing requirements, and socio-economic impacts). An additional transition risk is posed by the (now very likely) imposition of unilateral trade measures (border tax adjustments) on key exports.

In addition, the immense cost of air pollution associated with the use of fossil fuels (and analysed in detail in the CSIR's companion study) is NOT fully integrated with the economic analysis in this study. The high costs of continued air pollution are both a national liability in high-carbon scenarios, and an opportunity to achieve considerable co-benefits by pursuing a low-GHG pathway.

[3] Preliminary analysis in this regard has been undertaken in the World Bank's Country Climate and Development Report for South Africa (World Bank Group. 2022. South Africa Country Climate and Development Report. CCDR Series;. World Bank Group. http://hdl.handle.net/10986/38216)

Introduction and objectives

This report provides a summary of analysis and findings from a research project undertaken by the Council for Scientific and Industrial Research (CSIR) in collaboration with the Energy Systems Research Group (ESRG), exploring potential energy and sectoral mitigation pathways, and their co-benefits, through which South Africa could reach net zero CO_2 emissions domestically by mid-century. The project has been undertaken to provide research analysis and an evidence base for the Presidential Climate Commission (PCC) of South Africa, to support its objectives of facilitating conversations and building understanding of South Africa's just energy transition.

This report addresses the findings of the ESRG's energy/economy/emissions systems modelling, whilst a separate report has been prepared by the CSIR's Climate and Air Quality Modelling group to report their air quality and water use co-benefits analysis.

The goal of this analysis is to explore potential energy and industrial mitigation pathways to achieve long-term decarbonisation and net zero CO_2 emissions, in the context of contributing a South African "fair share" to global climate change mitigation, achieving a just and equitable transition which addresses South Africa's development challenges, in the context of the latest science, due regard for South Africa's treaty obligations and an assessment of the current status and future direction of the multilateral climate regime. The specific objectives of this analysis are to:

- Provide a clear definition of "net zero" pathways consistent with the latest science and more specifically requirements and institutional arrangements expressed in the Paris Agreement and elaborated on in subsequent decisions;
- Develop and characterise long-term emission pathways for South Africa to reach net zero CO_2 emissions by or around mid-century (2050 or 2055), in terms of the timing and shifts of energy supply technologies and end-use consumption in key demand sectors, and the potential costs and socio-economic effects associated with these pathways;
- Characterise potential socio-economic impacts and effects of a net zero transition, as well as potential known and unknown risks that would influence South African policymaking and decision making on the just energy transition towards net zero
- Explore the extent to which existing or future policies and measures could mitigate some of the negative socio-economic effects of such implementation and maximise uptake of key opportunities and benefits;
- Draw conclusions on common features of net zero pathways that may lead to potential 'no-regrets' options, and highlight areas that require further in-depth analysis and discussion in order to better inform the policy space around climate mitigation in concert with other pressing socio-economic priorities and imperatives.

Separately, the CSIR are conducting analysis on potential improvements to air quality, and associated health impacts, and water conservation, that may be attained under a long-term decarbonisation transition to net zero CO_2.

Net zero targets in the international scientific, legal and policy context

The concept of "net zero" GHG emissions has both a scientific and a policy context. Net zero targets have been referenced in a variety of contexts, including at a global and national scale (UNFCCC/PA), at sub-national scales including provinces/states and cities, and at firm level (Net Zero Tracker, 2023). While all these are relevant, the focus here will be on net zero targets at a national level in the context of the Paris Agreement.

The term "net zero" is a shorthand for reaching either net zero CO_2 by a specific date (in most cases 2050, but with important exceptions), or net zero GHGs as contained in Article 4.1 of the Paris Agreement (2015). Both of these goals have important scientific and conventional elements which will be discussed below.

From a scientific standpoint, anthropogenic CO_2 emissions result in increased concentration of CO_2 in the atmosphere which declines only over centuries. Other GHGs by contrast (CH_4 and N_2O, the second most common anthropogenic GHGs, have lifetimes of 12 and 109 years respectively) have relatively short lifetimes. Global warming is a result of the concentration of GHGs in the atmosphere; hence, on the scale of human lifetimes, stopping the emission of anthropogenic CO_2 will result in the stabilization of CO_2 concentration in the atmosphere. A stable concentration of CO_2 implies that no additional warming due to CO_2 will take place. Stabilization will thus prevent further warming (with a gradual decline over centuries), whereas stopping or reducing the emissions of other GHGs with shorter lifetimes in the atmosphere will result in a drop in global temperature.

Addressing climate change therefore requires a global response which will result in an outcome which reduces anthropogenic GHG emissions at a scale and pace which will avoid dangerous climate change. Agreeing on and implementing such a response globally is one of the core functions of the multilateral climate regime, as described below. International policy goals (contained in the UNFCCC (1992) and its Kyoto Protocol (1997) and Paris Agreement (2015), and associated decisions) have been set over the last three decades (since the negotiation of the UNFCCC in 1992) which specify two key elements of international climate policy:

- The level of global warming above pre-industrial levels beyond which anthropogenic climate change will be considered "dangerous"; and
- What needs to be achieved globally in order to prevent dangerous anthropogenic climate change.

Both the threshold for dangerous climate change and what action will be required to prevent it are policy goals decided by Parties to the UNFCCC/KP/PA, but are strongly informed by scientific research, and in particular by the work of the Intergovernmental Panel on Climate Change (IPCC).

The IPCC was set up in 1988 by UNEP and the WMO, and consists of country representatives who make decisions from time to time on what work the IPCC will undertake. The goal of the IPCC is to provide policy-relevant, but not policy prescriptive, assessments of the state of scientific knowledge on climate change (on the physical science, adaptation and impacts and on mitigation of climate change). This is primarily achieved via periodic Assessment Reports on the state of the science, but the IPCC also responds to requests from the UNFCCC/KP/PA to produce Special Reports. The work of the IPCC is very influential in informing the multilateral process, both in setting global goals and elaborating on these. Evidence presented in its Assessment and Special Reports has a high degree of political credibility due to the institutional arrangements underpinning the IPCC and the actual assessment process itself, and is difficult but certainly not impossible for the multilateral process to ignore.

This evidence is an important basis to inform the setting of international policy goals.

The science of net zero emissions goals

The "net zero" goal is closely linked to the long-term goal of limited global warming to a specific temperature level, and net zero CO_2 emissions by 2050 has been specifically linked to the 1.5 degree goal. This is important to emphasise, since the "net zero" shorthand only partially describes the characteristics of global emissions pathways necessary to achieve this goal (Rogelj et al, 2021).

There has been a long-standing dispute in the multilateral climate process regarding what global temperature increase would constitute "dangerous" climate change. This has been informed by both a scientific understanding of the potential climate impacts at various temperature levels, and the willingness of countries to trade off climate damage against other interests – i.e. what level of climate damage the international community has been willing to accept. Different groups of countries have had different interests in this regard – for instance, small island states face an existential threat even at low levels of global warming, and countries very in their ability to adapt (IPCC Chapter 15, 2022). Up to 2015, 2 degrees was the generally (but certainly not universally) accepted "guardrail". Very strong pressure by a large majority of countries resulted in the inclusion of a 1.5 degree goal in the Paris Agreement in 2015.

The UNFCCC COP in Paris, 2015, also requested the IPCC to produce a Special Report on 1.5 degrees, to provide evidence on the risks of global warming to 1.5 and 2 degrees, and evidence on the features of global emissions pathways necessary to limit global warming to 1.5 and 2 degrees. The Special Report was published in 2018 and contained two critical pieces of evidence. The first was an assessment of the additional loss and damage due to impacts of climate change which would occur if the global temperature rose by more than 1.5 degrees, to 2 degrees. The Report's conclusion – that there is a very significant rise in loss and damage from 1.5 to 2 degrees – provided a strong basis to focus on what action would be necessary to remain within 1.5 degrees.

The Special Report, based on an analysis of assessed modelled global GHG emissions pathways, concluded that pathways capable of limiting global warming to 1.5 degrees (and some which overshoot this goal and return to it by the end of the century), found that global pathways which will achieve the long-term 1.5 degree goal reach net zero CO_2 emissions around mid-century, a

45% reduction in 2030 from 2010 levels, along with "deep reductions" in non-CO_2 GHGs, and in almost all cases net negative CO_2 emissions from mid-century on. These findings were confirmed and elaborated in the report from Working Group III of the IPCC's 6th Assessment Report[4], and were as follows (global pathways): a 45% reduction in GHG emissions (all gases) by 2030 from 2019 levels, and an 84% reduction in GHG emissions by 2050 and net zero CO_2 emissions by 2050-55. "Net zero" CO_2 is therefore meaningful as a policy goal as one of the characteristics of global emissions pathways which are consistent with the long-term goals of the Paris Agreement. These pathways are characterised in terms of key points on the trajectory (2030, 2040, 2050), a net zero CO_2 point, and cumulative CO_2 emissions. The characteristics of these pathways have informed international climate policy, and qualified the long-term goals of the Paris Agreement via decisions taken at each COP (specifically COPs 26, 27 and 28) as referenced below.

Net zero and the multilateral climate regime

The international legal and policy framework for addressing climate change was negotiated in 1992 as the United Nations Framework Convention on Climate Change (UNFCCC), which has the international legal status of a treaty, i.e. is legally binding. Over the next 23 years institutional features of the multilateral regime have been decided and implemented, including reporting infrastructure requiring all countries to report on their GHG emissions and other climate-related aspects of their national circumstances, including the Kyoto Protocol and subsequent Cancun Agreement to establish and implementing GHG emissions limitation and/or reduction targets, and the Green Climate Fund to provide support to developing countries for implementation of climate-related measures; but these developments were not sufficient in themselves to achieve the goals of the Convention. In 2015, the Paris Agreement (PA) was concluded, and ratified by enough countries to come into force in 2016. The core of the mitigation architecture of the PA is a combination of a clear long-term temperature goal combined with an "ambition cycle" whereby countries commit to "nationally determined contributions" (NDCs), based on each country's assessment of what their "fair and ambitious" contribution would be, with guidance from an increasingly detailed set of considerations (the most important being the respective obligations of developed and developing countries), followed by a "global stocktake" to assess progress against the global goals of the PA. Countries are then required to take the outcome of each GST into account when determining their next NDC.

The key features of the Paris Agreement (2015) relevant to net zero pathways consist in:

- Its long-term goals stated in Article 2 which include the goal of "holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5 °C above pre-industrial levels" (2.1(a)), fostering low greenhouse gas development (2.1(b)) and "making finance slows consistent with a pathway towards low greenhouse gas emissions and climate-resilient development" (2.1(c))

[4] Table SPM.2 of the WGIII Summary for Policymakers, 6th Assessment Report [[ref]]

- Its Article 4 which specifies that:
  - Countries should collectively aim to reach global peaking of GHG emissions as soon as possible, and thereafter to undertake rapid reductions "in accordance with best available science" to reach a "balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century", while recognizing this will take longer for developing countries and should be accomplished "on the basis of equity and in the context of sustainable development and efforts to eradicate poverty" (Article 4.1)
  - Countries shall submit successive "nationally determined contributions" (NDCs), and shall "pursue domestic mitigation measures, with the aim of achieving the objectives of such contributions" (Article 4.2). Each NDC will be more ambitious than the last, and represent each country's "highest possible ambition, reflecting its common but differentiated responsibilities and respective capabilities, in the light of different national circumstances" (Article 4.3).
  - Developed country targets should be defined as "economy-wide absolute emissions targets" (in other words including all sectors and all GHGs) and developing countries should move to "economy-wide emission reduction or limitation targets";
  - Support shall be provided to developing countries to implement Article 4 (Article 4.5).
  - Article 4.19 specifies that countries "should strive to formulate and communicate long-term low greenhouse gas emission development strategies"
- Article 9-11, which provide for support to be provided to developing countries for the implementation of the Agreement;
- Article 13, which provides for biennial reporting on implementation and achievement of NDCs, and for reporting a GHG inventory, both of which will be reviewed by a technical expert review team';
- Article 14, which provides for a "global stocktake" (GST) which assesses global progress in meeting the long-term goals in Article 2, the outcome of which countries must take into consideration when 'updating and enhancing, in a nationally determined manner, their actions and support in accordance with the relevant provisions of this Agreement, as well as in enhancing international cooperation for climate action".

These core provisions have been implemented via a series of CMA[5] decisions. (UNFCCC, 2018). Notably, decisions 4/CMA1, 18/CMA.1 and 19/CMA.1 requires countries to provide "information to facilitate clarity, transparency and understanding" with their NDCs, including information on how their NDCs are "fair and ambitious", and how these contribute to the long-term goals of the

[5] The Conference of the Parties serving as the meeting of the Parties to the Paris Agreement (CMA) is the decision-making body for the Paris Agreement.

Paris Agreement, provide the modalities, procedures and guidelines for biennial reporting of GHG inventories and progress in implementing NDCs, and elaborate details on the conduct of the GST respectively. Decision 5/CMA.3 specifies electronic formats for reporting GHG information and information on implementation and achievement of NDCs, and decision 6/CMA.3 specifies a common timeframe for NDCs of 5 years.

The overarching decisions from COPs 26-28 (CMA3-5) significantly qualified the relevant provisions of the Paris Agreement, including decision 1/CMA.5, which comprised the outcome of the first GST. The conclusions to the GST both recognized the level of insufficient implementation to reach the PA's long-term goals and underscored the urgency of accelerated action, and an affirmation, based on both the Special Report and on the 6th Assessment Report, of the importance of the 1.5 degree temperature goal[6]. There was also a clear recognition of the findings of the reports of the IPCC's 6th Assessment Report (2023) and formal recognition of the analysis in the Working Group 3 Summary For Policymakers regarding the characteristics of global GHG pathways capable of keeping global warming within the 1.5 degree threshold (or with limited overshoot), specifically a reduction of 43% of GHG emissions by 2030, 60% by 2035 (both in relation to 2019 levels) and reaching net zero CO_2 around 2050 (IPCC, 2023).

1/CMA.5 also contained further calls for countries to contribute to specific "global efforts" to achieve "deep, rapid and sustained reductions in greenhouse gas emissions" to achieve the 1.5 degree limit, which include tripling global renewable energy capacity and energy efficiency efforts by 2030, accelerating the "phase down" of coal power, "accelerating efforts globally towards net zero emission energy systems, utilizing zero- and low-carbon fuels well before or by around mid-century", transitioning away from fossil fuel energy systems in line with a global net zero CO_2 goal, accelerating investment in zero- or low-emissions technologies including renewables, nuclear, CCS/CCUS/DAC, and low carbon hydrogen production, phasing out fossil fuel-powered transport and phasing out fossil fuel subsidies, urging countries that have not done so to communicate long-term low emissions development strategies towards "just transitions to net zero emissions by or around mid-century" (IPCC, 2023).

All of these decisions place these increasingly detailed global mitigation goals within the context of the differentiation between obligations of developed and developing countries fundamental to the architecture of the UNFCCC and its Paris Agreement, "in the light of national circumstances", which include the obligation on developed countries to take the lead, and to provide support to developing countries, and an overall recognition of the importance of meeting development goals, just transitions and equity. However, even given this leeway for developing countries, the need to both reduce CO_2 emissions to net zero in 25-30 years, and bring about "deep reductions" in other GHGs, ambitious climate action will be required from all countries. This will in turn inevitably be accompanied by dramatic shifts in energy, transport, industrial and agricultural systems, amongst others, and concomitant shifts in the global economy. There is little doubt that developing countries, as contemplated in the UNFCCC and PA, will require considerable support

[6] Decisions 1/CMA.3, 1/CMA.4 and 1/CMA.5 concerning the importance of the 1.5 degree temperature goal qualified Article 2.1(a), and validated the 1.5 degree goal as THE long term temperature goal.

and international cooperation to achieve these transformations and the required sustainable development gains. The alternative global future (in which global warming exceeds 1.5 or 2 degrees, or a higher temperature level) will potentially result in very severe and in cases cataclysmic and existential[7] climate damage, which will impact developing countries far more severely than developed countries.

Specifications for national 1.5-degree pathways in the context of the Paris Agreement

1.5-degree pathways have two quantifiable elements – the first is the year in which net zero CO_2 emissions will be reached, and the trajectory of the pathway to this point. Equally important qualitative elements are which gases are accounted for in the target, and the inclusion of other features, such as the just transition.

Two types of net zero target exist in the PA framework – a net zero CO_2 target (referenced in decisions 1/CMA.3-1/CMA.5) in the context of long-term pathways associated with the 1.5 degree temperature goal, and the text in Article 4.1 which refers to a net zero GHG target ("balance of sources and sinks"). Here we consider only net zero CO_2 targets, which means that in the net zero target year, GHG emissions as a whole will not necessarily have reached net zero.

It is important to understand how the shift from a global target to national targets is represented in the multilateral regime. Decision 1/CMA.3 moves from a global level in paragraph 22 which ties the long-term temperature goal to the IPCC's Special Report's (IPCC 2018) analysis of the key features of global pathways capable of limiting global warming to 1.5 degrees, to a national level in paragraph 32 and adds a qualification to national-level long-term low GHG emission development strategies referred to in Article 4.19 – that countries reach net zero emissions "by or around mid century" via a just transition, which is reaffirmed in paragraph 24 of 1/CMA.4. The reference to global pathways in 1/CMA.5, the outcome of the GST, anchors the goal of limiting global warming to 1.5 degrees to the updated analyses contained in the IPCC's 6th Assessment Report (IPCC, 2021) and in paragraph 42, stronger language "urges" countries to either communicate (for those which have not) or update (for those which have) their long-term strategies "towards just transitions to net zero emissions by or around mid-century". Thus since the ratification of the PA, subsequent decisions, including the outcome of the first GST, long-term strategies have been directly linked to the goal of limiting global warming to 1.5 degrees and subsequently linked to the achievement of net zero emissions around mid-century. The language on net zero emissions remains agnostic as to whether this is a net-zero GHG or CO_2 target.

The specific connection between national net zero strategies, their communication to the UNFCCC, and the attainment of net zero CO_2 emissions globally is provided by the GHG accounting and reporting process and the defining of GHG emissions or other targets in the multilateral regime. This consists of the reporting process for national GHG inventories developed under the UNFCCC and subsequently its Kyoto Protocol and Paris Agreement. These reporting

[7] Some small island states are vulnerable to complete disappearance at global warming of more than 1.5 degrees.

processes require annual (developed countries) or biennial reporting by each country of a national GHG inventory based on a common methodology and common and transparent accounting practices, and subject to review by an international technical expert review team. The Paris Agreement and subsequent decisions require countries to report using the 2006 IPCC guidelines and global warming potentials from the IPCC's 5th Assessment Report. This process ensures transparency, accuracy, completeness, comparability and consistency[8] and makes it possible to aggregate national GHG emissions into a global total (with reservations)[9].

Paragraph 38 in 1/CMA.5 explicitly accelerates the process whereby developing countries will move "over time" to economy-wide emissions reduction targets "covering all greenhouse gases, sectors and categories and aligned with limiting global warming to 1.5 °C, as informed by the latest science, in the light of different national circumstances", and encourages countries to move to these targets for their next NDC. A net zero CO_2 target for 2050 or 2055 is effectively the end of a series of 5-year NDC commitments. While countries are free to define their NDC targets and the indicators used to track progress, it is a reasonable assumption (based on CMA decisions) that countries will move towards economy-wide targets over time, expressed in GHG levels.

The net zero CO_2 target in itself could then be defined either in terms of the national GHG inventory, in which total CO_2 sources recorded in the national GHG inventory (excluding emissions from international aviation and shipping) equalled or were exceeded by total CO_2 sinks, or could also include accounting for internationally transferred mitigation outcomes (ITMOs)[10]. For simplicity, we have assumed here that net zero targets in ALL countries are accounted for within the current reporting process for GHG inventories and without the transfer to or from respective countries of ITMOs[11]. GHG inventory accounting is clear and precise with some caveats, and is based on estimating annual GHG emissions – in other words, the total of sources and sinks within one year. This would include accounting for direct air capture and carbon capture and storage. A national net zero CO_2 target in this context therefore implies that the sum of all the CO_2 sources and sinks emitted within the target year that are estimated in the national GHG

[8] These are the "TACCC" principles which underpin the accounting rules.

[9] However the second principle is that GHG emissions which result from international aviation and international shipping (aircraft and vessels which leave one country and arrive in another) fall under the jurisdiction of ICAO and the IMO, and are not accounted for in national GHG inventory totals[9]. All other anthropogenic GHG emissions are accounted for nationally, with the exception of some GHG emissions from "unmanaged lands"[9]. Both these gaps are entrenched in the current accounting conventions of the multilateral regime. This implies that when considering a global net zero target,

[10] The use of Article 6 mechanisms (international market mechanisms) – i.e. countries buying or selling GHG emissions reductions.

[11] Current guidance for "corresponding adjustments" in terms of Article 6 does not provide sufficient guarantees that physical aggregation of sources and sinks across countries will equate with the associated accounting. Some countries have explicitly included the use of Article 6 mechanisms in their statement of their net zero targets.

inventory (including accounting for CCS, CCUS and DAC, and excluding GHG emissions from international aviation and shipping)[12] is equal to zero or less.

Accounting for GHG emissions pathways requires an additional conventional element – the use of global warming potential[13] values to aggregate CO_2 and non-CO_2 GHG emissions. Decision 18/CMA.1 establishes clearly WHICH GWP values countries should use and also a process for updating these. The properties of global GHG pathways are well-defined by the IPCC's Assessment Reports by both a CO_2 budget and specific absolute values for 2030, 2040 and 2050.

In this study, a GHG budget has been used (the sum of annual GHG emissions from 2021 to 2050) to represent a long-term "fair and ambitious" GHG emissions pathway for South Africa. Using a GHG emissions constraint in a modelling framework such as SATIMGE is a proxy for long-term national mitigation policy at different levels of ambition. Different budgets correspond to varying contributions by South Africa to the global long-term mitigation goal in the Paris Agreement. The way in which the budget is used during the modelled period is determined by the modelling framework based on discounted total system cost; the model thus takes into account existing infrastructure and short-term constraints, and the budget, the endpoint (net zero) and these constraints thus define the long-term GHG emissions pathway. This thus provides for temporal flexibility for mitigation, as well as being an effective tool for identifying trade-offs between mitigation in different sectors in the short, medium and long terms.

Contextualising national GHG emission pathways to net zero CO_2 for South Africa

The challenge of setting both medium and long-term GHG mitigation targets cannot be addressed by simply quantifying the key policy provisos laid out in the UNFCCC, its Paris Agreement and subsequent decisions – in fact the architecture of the Paris Agreement is specifically designed to leave this task to national governments. Thus, characterising a long-term emissions pathway, or pathways, for South Africa is a challenging task that requires finding a delicate and complex balance between, on the one hand, maximising development potential to work towards overcoming the fundamental socio-economic challenges the country faces in terms of poverty, inequality and unemployment, and ensuring the long-term transition is just and equitable for everyone – especially historically marginalised communities – and on the other hand ensuring that South Africa's response is consistent with the country's international obligations and the interests of South Africa and the region in maintaining and implementing a rule-based multilateral

[12] CCS is assumed to be permanent. DAC removes CO_2 from the atmosphere, which can then either be stored (CCS) or used for manufacturing other products, as can captured CO_2. If these products are combusted, then the resulting CO_2 is accounted for only if the combustion takes place within national boundaries and not, e.g. by an aircraft leaving South Africa and landing somewhere else.

[13] Global warming potential values are calculated for non-CO_2 gases as the amount of CO_2 which would have the same global warming impact as one unit of that gas, over a specified time period.

approach to the challenge of climate change. In addition, the country faces both risks and opportunities from global shifts in technology, innovation and trade.

There are risks associated with attempting a highly ambitious low-carbon transition that could result in significant disruption to the economy, whilst there are also political and economic risks to delaying mitigation, both in political terms (a risk that South Africa will experience much stronger political pressure in the future to mitigate, requiring very rapid and disruptive mitigation), and economically (the South African economy becoming both less competitive on account of a continued reliance on high-carbon exports (for which global markets may disappear), the imposition of border taxes on high-carbon products, and a significantly more costly energy system based on existing fossil fuel technology rather than cheaper zero carbon technologies. Broadly all of these challenges can be distilled into two considerations:

- What pressure will South Africa experience to mitigate over the medium and long term?
- What are the national opportunities, constraints and risks associated with a trajectory towards net zero?

There is a complex interplay between these considerations. South Africa has up to now had two strong priorities in the multilateral climate change process. First, there is overwhelming evidence that climate change will have devastating consequences for South Africa and the region (IPCC 6th Assessment Report, 2023) and therefore for South Africa, it is critical that the multilateral effort to address climate change and achieve the long-term goals of the Paris Agreement succeeds. Second, South Africa and other middle-income developing countries of similar size or smaller have a very strong interest in a strong multilateral climate regime, since a weak regime would remove the protection which developing countries enjoy within the UNFCCC and its Paris Agreement, resulting in more pressure on countries such as South Africa to accelerate their mitigation efforts, and the availability of less or no international support to do so – there would also be little or no climate finance and a much higher risk of unilateral trade barriers.

Both the imperative of the climate crisis and the urgent need to reduce GHG emissions create strong pressure to mitigate, within a multilateral regime which is either strong or weak. Individual countries, other than a few large geopolitically dominant countries/blocs (China, USA, EU and others), do not have a determinate impact on global mitigation outcomes, but they do, especially in conjunction with other countries, have some impact. For South Africa, which has played a leadership role in the multilateral climate negotiations, this also implies committing to a significant national mitigation effort.

In order to explore both the uncertainties in the future of the multilateral regime (which South Africa has a limited ability to influence), and a range of different technically feasible national GHG emissions pathways to net zero (which fall squarely within the ambit of national policy), a two level scenario structure has been used, which is described in detail in the Appendix below. Briefly, two international scenarios (World A and World B) are the background for the analysis of national pathways. World A features a strong rules-based multilateral regime, and World B features a far weaker regime, with less climate action. On a national level, two net zero CO_2 points were modelled (2050 and 2055), and a range of cumulative GHG emissions budgets, based on (Marquard et al, 2022) focused on 9 Gt scenarios. Previous work indicates a range of 6-9 Gt as South Africa's "fair share" from 2021-50, but quantitative methods applied to the determination of "fair shares" per country are subject to high degrees of uncertainty over longer periods. Moreover, with conservative assumptions on the size of South Africa's land sink, more ambitious GHG budgets are very challenging.

Modelling approach

The methodology applied is summarised as follows:

- **Scenario development**: A series of scenario parameters were defined, following extensive discussion and consultation with subject experts. The scenarios were designed to account both for domestic policies, measures and uncertainties, as well as to allow contextualisation based on potential and uncertain international developments, in light of the uncertainties raised above. To this end, two global futures – **World A** (a collectively climate ambitious world, with phase down of fossil fuels and increasing costs of carbon reflected in trade policy) and **World B** (a more fragmented world, where fossil fuels remain in demand globally for a longer timeframe) – were developed to identify and quantify some of the key differences that may arise in different futures of the international climate regime.
- **National emission pathways**: Within the different worlds, a set of national scenarios were developed to account for different net zero target years and GHG constraints, using both a net zero target and a cumulative GHG budget to simulate South Africa's mitigation contribution (or the pressure exerted on South Africa, and other developing countries, to decarbonise).
- **Policies and Measures**: National emission pathways were further explored with a set of policies, measures and uncertainties, including carbon taxation, localisation of renewable energy component manufacture and energy efficiency.
- **Modelling and analysis**: Scenarios were analysed using the SATIMGE modelling framework (described further in the Appendix)

Further detail on the scenario development process can be found in the Appendix of this report. However, some key limitations to note about this approach are highlighted below:

- The key economic impact of pursuing ambitious mitigation pathways is the "crowding out" of investment, since the investment in new low-carbon technologies is funded through the reduction in investment in other productive sectors; Preliminary analysis indicates that this effect can be offset by internationally-sourced concessional finance[14].
- The impact of air pollution on the economy has not been included in the scenario analysis. This work was done in a separate study by the CSIR.
- Potential physical impacts and resulting costs of climate change over the modelled period have NOT been considered here.
- Global worlds (A and B) feature projections of future fuel prices from the IEA (2023b).

[14] Preliminary analysis in this regard has been undertaken in the World Bank's Country Climate and Development Report for South Africa (World Bank Group. 2022. South Africa Country Climate and Development Report. CCDR Series;. World Bank Group. http://hdl.handle.net/10986/38216)

Results

Modelled economy-wide emissions

This and all subsequent analysis is drawn from a modelled least-cost optimisation of a full range of scenarios using the SATIMGE linked model framework. The full list of scenarios, as well as a description of SATIMGE, is provided in the Appendix.

Figure 3 below shows the GHG and net CO_2 pathways to 2055 for scenario runs in World A and B, with varying cumulative GHG limits (in $MtCO_2$-eq[15]) for the period 2021 – 2050 and reaching net zero CO_2 in 2050, 2055 or not at all.

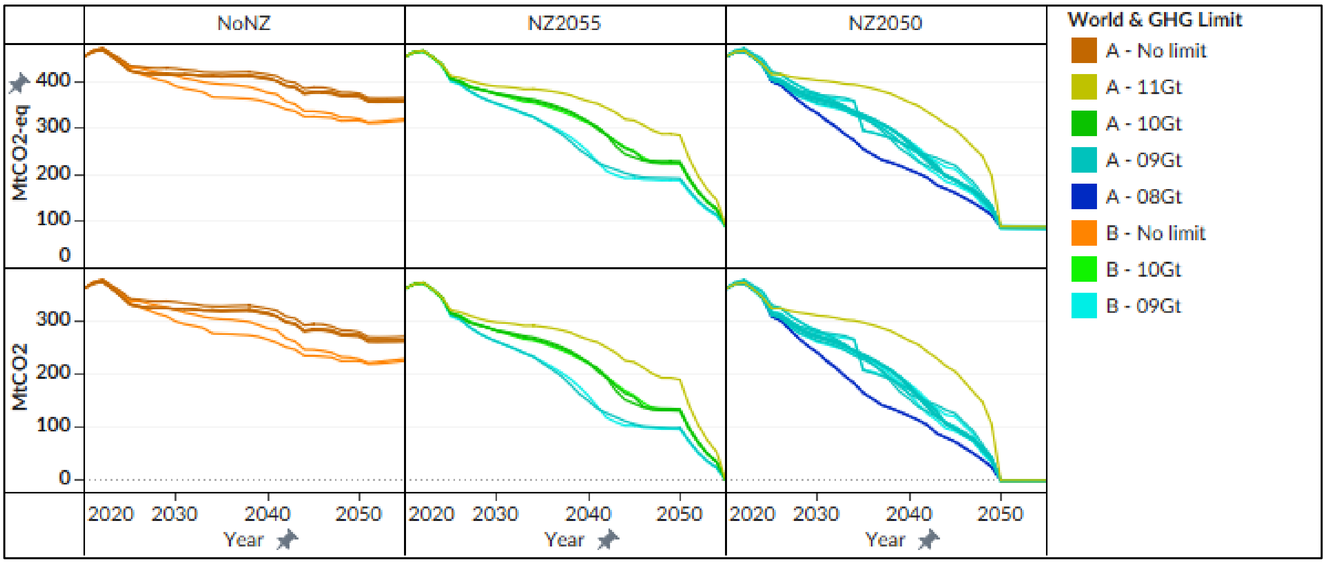

Figure 3: Net GHG (top) and CO_2 (bottom) emission pathways by World, GHG limit and net zero year.

All cases show an initial decline of emissions, due to the closure of older coal power plant units in line with the Eskom JET Strategy retirement schedule through 2025 and 2026. Thereafter emissions continue to decline at varying rates per scenario.

The lighter and darker orange lines in the left-hand panel show emission profiles for scenarios in World A and World B (respectively) that do not have a GHG constraint and do not reach net zero. These scenarios are useful to indicate the mitigation challenge, but pose several risks as feasible pathways. These include:

1. Uncertainty about global markets for fossil fuels, and whether coal export markets would remain and grow, as well as the price trajectories for future oil and gas prices.
2. Technology developments, innovations and resulting market transformations that may leave South Africa with no export markets for high-carbon technologies, and with an increasingly expensive energy system;

[15] All GHG numbers shown in this report are provided in the $MtCO_2$-eq using 100-year GWP emission metrics from IPCC AR5.

3. International developments which may necessitate later in the considered period that South Africa has to take very rapid mitigation action.

The last risk can be seen in the net zero curves to 2055 and 2050 in the middle and right hand panels of Figure 3. Scenarios with the higher GHG limits of 11 and 10 Gt CO_2-eq reaching net zero in 2055 show a gradual decline of emissions over the period from 2026 to 2050 to around 200 and 140 Mt CO_2 respectively, before declining rapidly to zero by 2055. This radical shift in the last 5 years would be extremely difficult and costly to manage and is a significant risk of delayed decarbonisation action in the event that such ambitious action became necessary around or in the years prior to mid-century.

The 9 Gt scenarios show a smaller emissions 'cliff' when reaching net zero in 2055, and show a more consistent rate of decline of emissions over the modelling period when reaching net zero in 2050. This suggests that decarbonisation action, which is taken in the short-term, and continued with consistent effort over time, would potentially allow for a smoother transition, relative to delaying action now and decarbonising at a very rapid pace in later years.

Emission pathways by sector

Figure 4 shows emission pathways by sector, and cumulatively over 2021-55, for an unconstrained scenario, as well as 10Gt scenario reaching net zero in 2055, and 9Gt reaching net zero in 2050, all in World A.

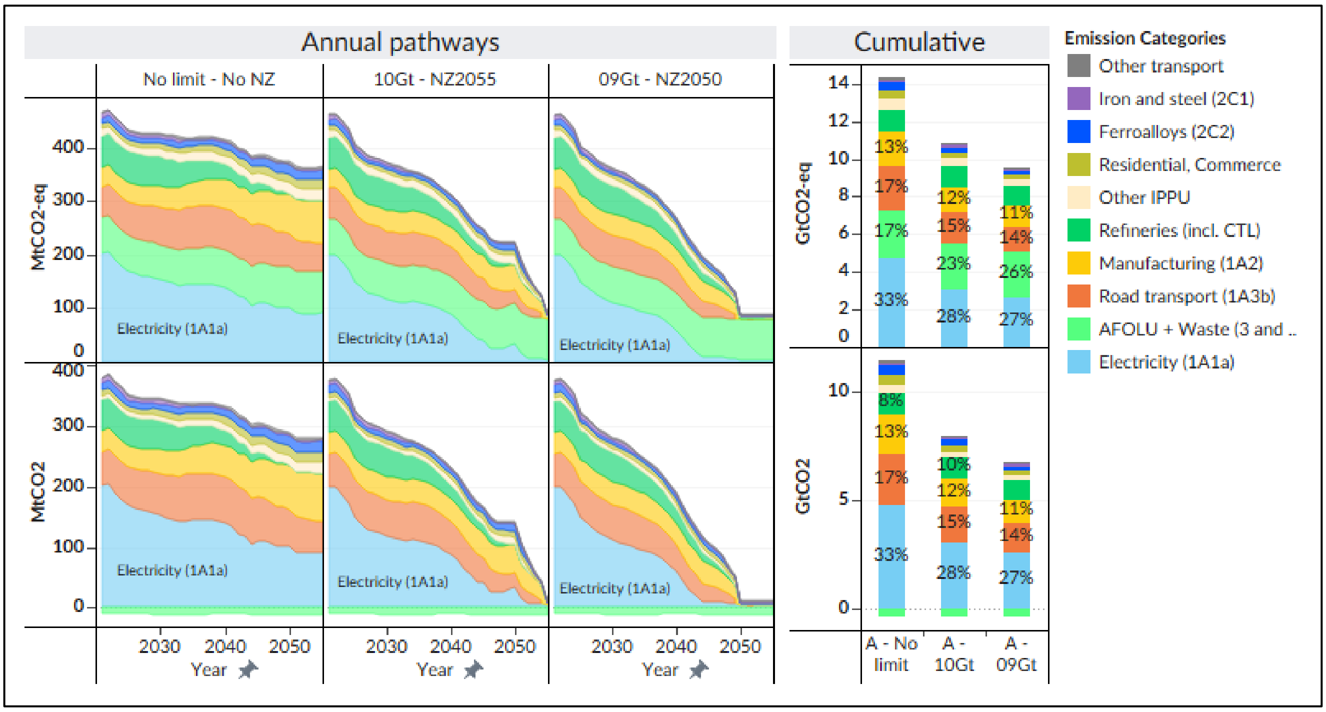

Figure 4: Annual and cumulative GHGs and CO_2 by sector for an unconstrained, 10Gt (NZ2055) and 9Gt (NZ2050) scenario.

The figure shows that the main contributors to GHG emissions are the electricity, road transport and manufacturing sectors, as well as AFOLU and Waste. The GHG constraints cause the electricity sector to decarbonise most rapidly, followed by the road transport and manufacturing sectors which only fully decarbonise in the year net zero is reached.

The electricity sector begins to decarbonise below the unconstrained cases in the mid-2020s, and accelerates in the mid-2030s in both the 10 and 9 Gt cases. Cumulatively, electricity sector CO_2 emissions are 34% lower in the 10Gt case and 43% lower in the 9Gt case compared to the unconstrained case. Decarbonisation of the electricity sector is key to all net zero emission pathways.

The model does not optimise for AFOLU and Waste emissions. Net GHGs from these sectors are mostly in the form of CH_4 and N_2O, while CO_2 emissions are balanced by CO_2 absorption by the land sink (hence the net-negative CO_2 for AFOLU and Waste in the bottom graphs). This illustrates two key points that require further exploration:

1. **The importance of the land sink in reaching net zero CO_2** – greater sink capacity would allow more ‘positive’ emission space for electricity, manufacturing and road transport, while smaller sink capacity would reduce this space. Accurately estimating and forecasting the land sink is therefore critical for net zero policymaking, and further work should be done to extend the initial analysis of this performed by Stevens et al. (2016)
2. **In the absence of GHG mitigation options for AFOLU and Waste, greater decarbonisation is required in other sectors** – especially electricity, road transport and manufacturing – to remain within the same cumulative GHG limits. Further work is needed to explore mitigation potential and measures for AFOLU and Waste, and to incorporate optimisation of mitigation measures for these sectors in modelling.

The following section and sub-sections elaborate on the energy and emission transitions for each key sector, under GHG constraints and meeting net zero CO_2.

Sectoral and technology pathways

This section and sub-sections elaborate on the energy and emission transitions for each key sector, under GHG constraints and meeting net zero CO_2. The section addresses each of the key emitting supply-side (electricity and liquid fuels) and demand-side (transport, industry and commerce and residential) sectors, as well as the land sink and use of CCS technology which crosscuts multiple sectors. The report begins with arguably the most important sector for decarbonisation, namely the power sector.

Electricity

South Africa's electricity generation is currently dominated by the Eskom coal power fleet of roughly 40 GW in total. According to current plans[16], by 2050 this will reduce to roughly 10 GW, as most units (with the exception of Medupi, Kusile and 3 units at Majuba) will have been retired by then. Least-cost projections from SATIMGE show that, in all cases, coal power will be replaced predominantly by a mixture of gas, PV, wind and some storage technology. However, variations with the mix of technologies occur depending on GHG constraint and net zero ambition.

Generation and technology mix

Figure 5 shows domestic electricity production for four World A scenarios: an unconstrained non net zero[17] case, a 10 Gt constrained case reaching net zero in 2055, and 9 and 8 Gt constrained cases reaching net zero in 2050. The figure shows that, as mitigation ambition increases, both the total amount of electricity supplied, and the proportion of low or zero carbon technologies in the mix, grows considerably, especially in years approaching and after net zero is reached.

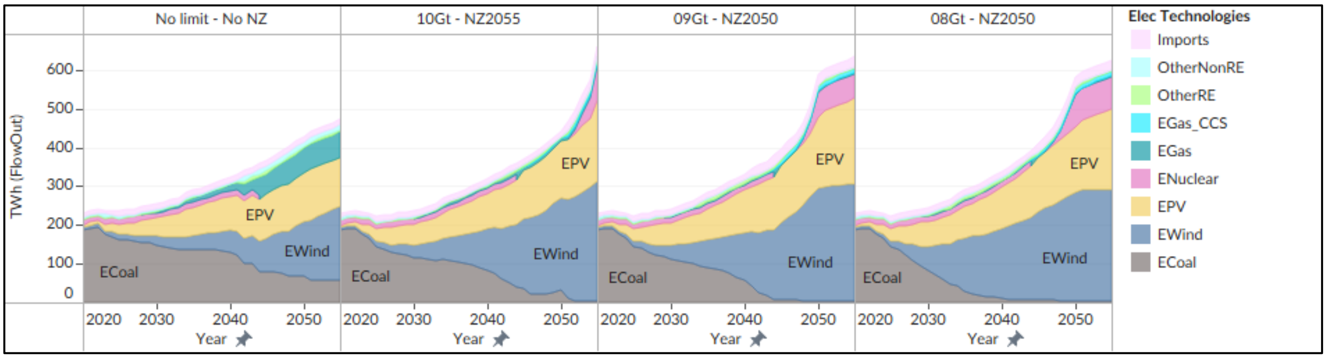

Figure 5: Electricity production for scenarios with different GHG constraints

Total generation increases in GHG constrained cases as demand sectors switch from coal and liquid fuels to electricity to meet their energy needs in order to decarbonise. Coal generation decreases and reaches minimal levels in the years approaching net zero, with the rate of phase-down increasing under more stringent GHG constraints. Wind and PV generation grow in all cases

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[16] Eskom's original intention to shut down each plant after 50 years of operation would result in around 10 GW remaining by 2050; recent proposals to extend the life of the fleet to 60 years would increase this remaining capacity considerably.

[17] In a world with a strong multilateral climate regime, it may not be plausible to avoid having a net zero target and more stringent GHG emissions constraints.

(including the unconstrained case), and this occurs more rapidly with greater emissions constraints.

There is minimal gas generation without CCS in all constrained cases, while gas with CCS is used moderately in cases with more stringent climate ambition. There is also a significant ramp up of nuclear generation in years approaching net zero (and after net zero in 2050 cases), as a result of constraints within the model on the growth of renewable energy and battery storage[18].

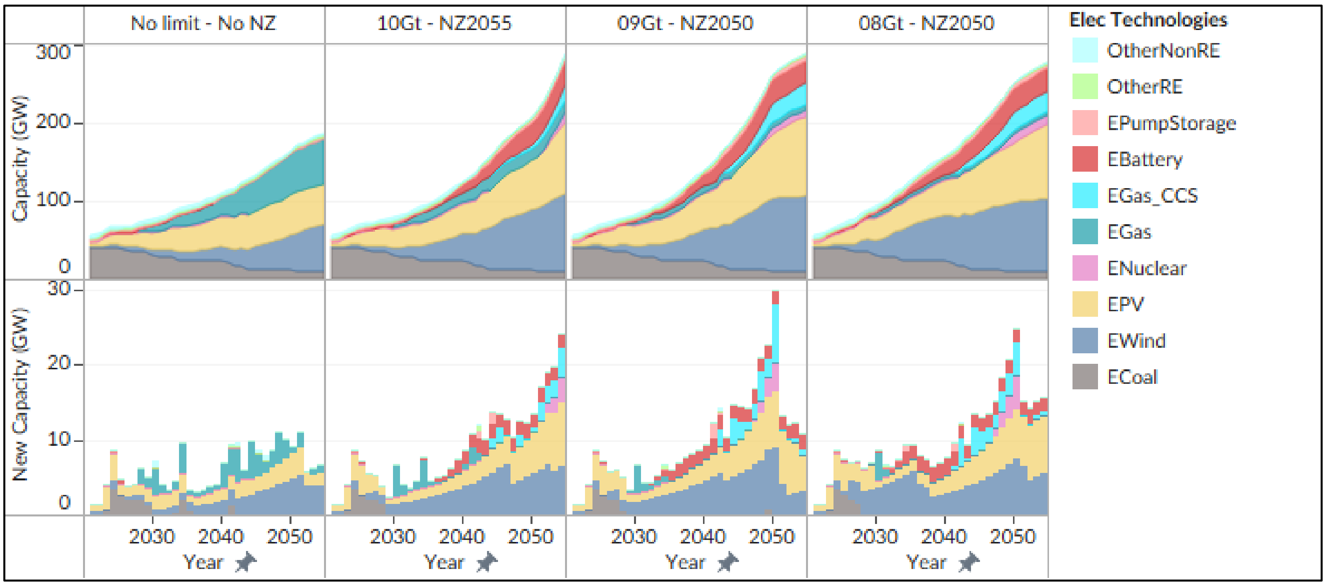

Figure 6: Annual Total (top) and New Build (bottom) capacity projections for World A scenarios

The capacity projections in Figure 6 show ramped up build of wind and PV technologies in all cases, especially GHG constrained cases. Note that, whereas in the unconstrained case several GW of gas without CCS are built, minimal unabated gas is built in emissions-constrained scenarios, whereas increasing amounts of abated (with CCS) gas are built especially in the more ambitious scenarios. In the 8 Gt 2050 net zero scenario, a total of 30 GW of battery storage and 26 GW abated gas are deployed by 2055, in addition to 95 GW of PV (including embedded generation, not shown or discussed here) and 93 GW of wind. The 9 Gt scenario also sees around 8.4 GW of new nuclear come online between 2048 and 2050, while in the 8 Gt scenario this increases to 11 GW.

The high deployment of gas with CCS, battery storage and nuclear generation in the late 2040s and 2050s is a reflection of the effort required to completely decarbonise the electricity sector, which is essential to achieving net zero CO_2 economy wide. Note that if one compares Figure 6 and Figure 5, a large amount of gas (CCS) capacity is built, but relatively little contributes to

[18] It is important to note that as currently the cost of new nuclear power is estimated to be much higher than other low-or zero-carbon electricity sources, selection of nuclear capacity by the model is the result of a lack of other low- or zero-carbon options. The constraints on battery storage and renewable energy in this version of SATIMGE are more aggressive than previous or future versions, and other studies. With more relaxed constraints on these technologies, the model does not select nuclear power.

generation – reflecting the marginal costs of this technology that suggest it would be limited to producing peaking power.

It should be noted that the annual increase of newbuild of wind and PV in each year was limited to 10% of new build of the previous year. This is an artificial constraint that was added to the model to prevent an unfeasible amount of variable generation being installed in the final years leading up to net zero (see Section 0 for more on '*last mile effects*'). However, this constraint does not necessarily reflect the existing or potential future grid constraints or bottlenecks that may occur in regions with high renewable resource potential on the one hand (which may not be significant constraints in the medium to long term), and is considerably lower than some historical cases on the other. Since this limit has a very significant impact on technology choice in the model in the last decade before net zero, further research is needed.

Figure 7 shows the cumulative investment for new build in the power sector under different scenarios as shown above, with the addition of an 11 Gt scenario reaching net zero in 2055. The figure shows that even the least ambitious net zero pathway would still require a doubling of investment in power capacity and infrastructure by 2055 relative to an unconstrained scenario.

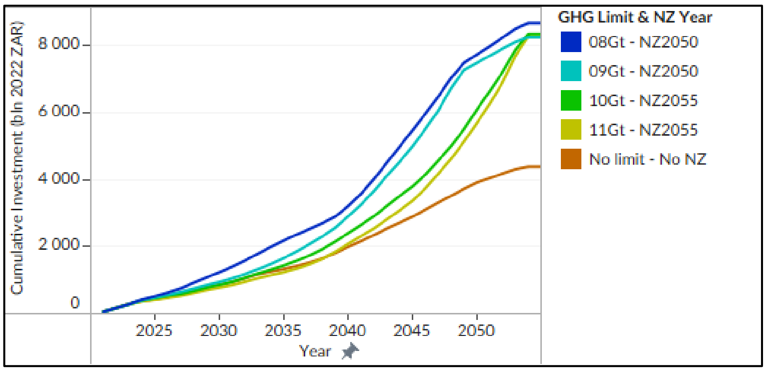

Figure 7: Cumulative power sector investment costs

Investment ramps up notably from the mid-2030s across all constrained cases, reflecting the increased build of low or zero carbon electricity technologies, and ramps up more steeply in the years approaching net zero, with increased deployment of battery storage, gas with CCS and nuclear technology, as well as renewables. Notably, by 2055, cumulative investment reaches similar levels regardless of which mitigation pathway is followed.

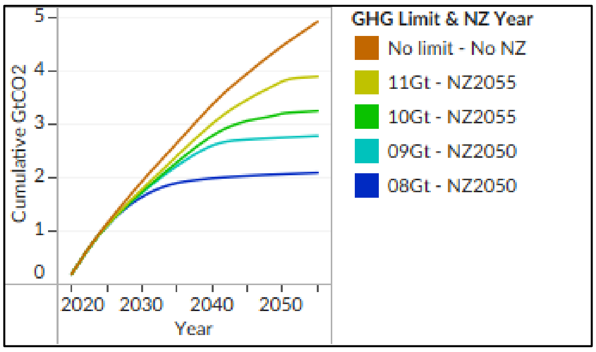

Figure 8: Cumulative CO_2 emissions from the power sector for progressively ambitious scenarios

Figure 8 shows cumulative CO_2 emissions for each of the scenarios, showing the difference in power sector GHG budgets for progressively ambitious net zero scenarios. The more stringent the target, the earlier annual emissions from the power sector are reduced to net or 'near' zero CO_2. The 8 Gt scenario has 3 Gt CO_2 fewer than the unconstrained scenario cumulatively by 2050. This reiterates the key role of the power sector in achieving decarbonisation for the entire economy.

Coal power

This section briefly considers the effects of GHG emissions constraints on coal capacity and generation, in light of recent uncertainty about the current performance of the coal fleet as seen for example in Eskom's 2023 Medium Term System Adequacy Outlook 2024-2028 or DMRE's 2024 Draft Integrated Resource Plan for Electricity (at the time of writing still open for public comment)[19].

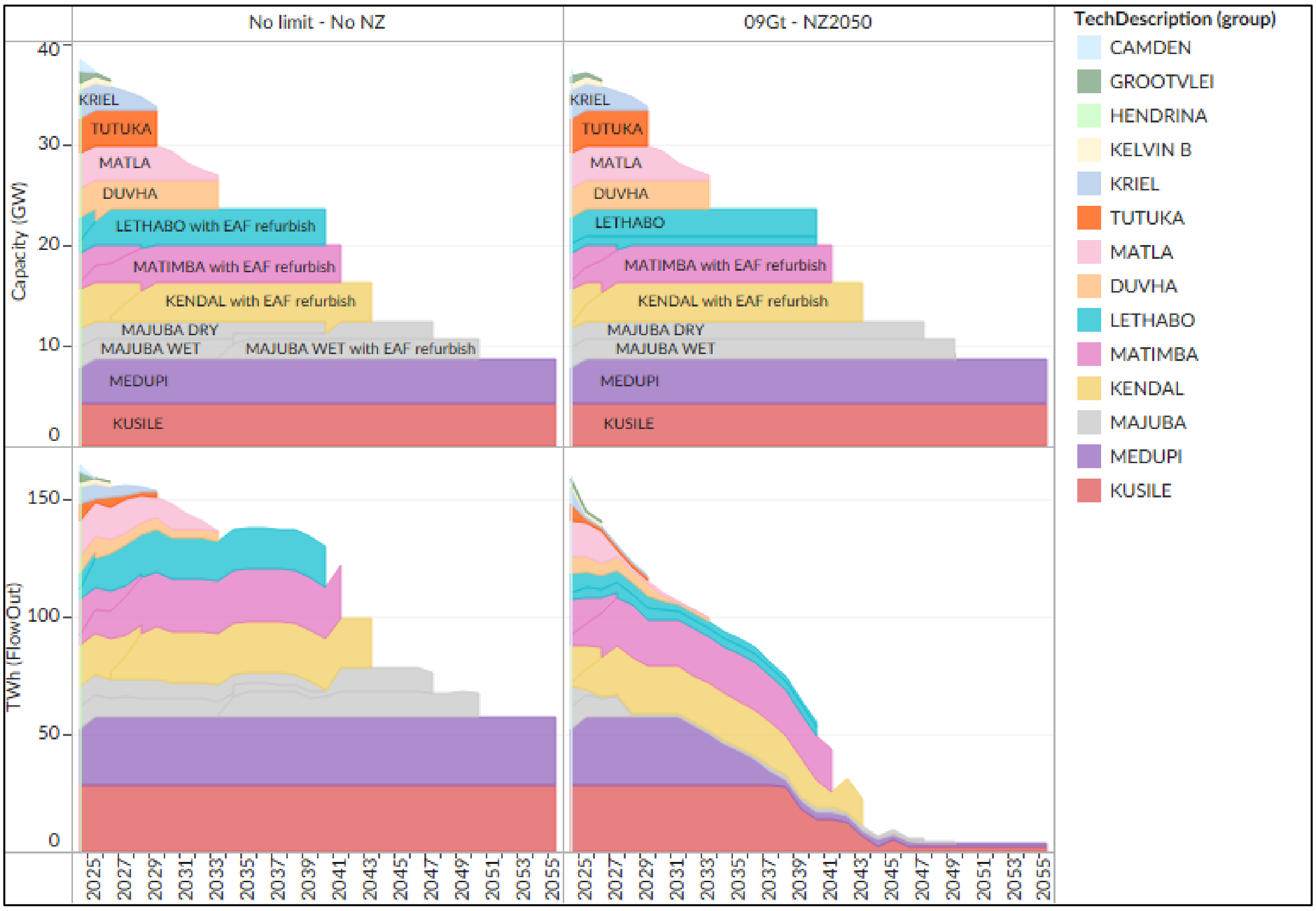

Figure 9: Coal plant capacity (GW) and electricity sent out (TWh) for an unconstrained and 9Gt scenario.

The analysis takes the existing plant performance, based on energy availability factor (EAF) data available at the time, as the baseline for coal power plant capacity factors. The model then has the option to endogenously choose on a least-cost basis whether (1) to 'refurbish' low performing

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[19] This report was written prior to the publication of the report on the investigation commissioned by the National Treasury into Eskom's coal plant performance, and does not make reference to any findings, conclusions or recommendations made therein.

plant, measured by proxy with an increased annual fixed operations and maintenance (O&M) cost, (2) to allow the plant to continue at the lower capacity factor until its scheduled retirement date, or (3) to retire the plant in an earlier year. Figure 9 shows two examples of coal fleet projections based on the model analysis using this approach, for an unconstrained and 9 Gt case respectively.

The top half of the graph shows some difference in capacity, whereby the fully refurbishes Kendal, Lethabo, Matimba and Majuba units, and allows them to continue operating, under the unconstrained scenario, whereas under the 9 Gt scenario, Lethabo is only partially retrofit and Majuba not at all. The model generally opts not to retire any capacity earlier than the Eskom planned shut-down years. The coal fleet is utilised considerably less in the 9 Gt scenario, with further work needed to determine whether coal plants could in fact feasibly run at such low capacity factors; i.e. the model may be significantly overestimating the case to keep these plants on the grid.

Transport

The second largest energy sector from an emissions perspective is the transport sector, and more specifically road transport. This section highlights some key findings from scenario analysis of domestic land transport, focusing mainly on road transport.

Shifting from liquid fuels to electricity

The main shift in the transport sector, under net zero scenarios, is a shift from liquid fuels – specifically diesel and petrol (gasoline) – to electricity. Figure 10 highlights this shift, comparing final energy supply for the transport sector in a 9 Gt net zero 2050 case relative to an unconstrained, no net zero case (both in World A).

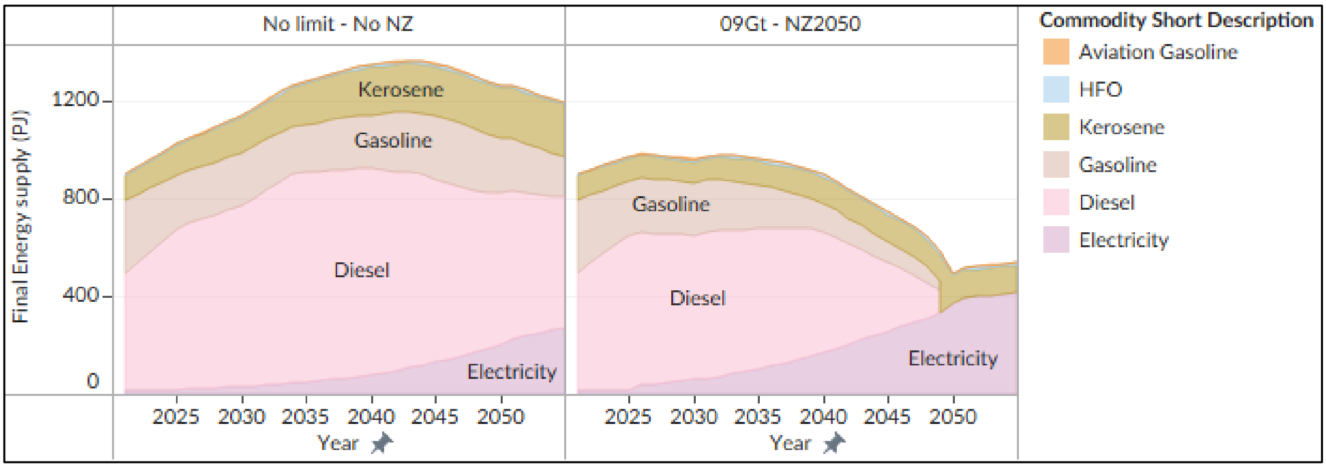

Figure 10: Transport fuel projections for a scenario without either a GHG emissions constraint or a net zero target (left) and a scenario with a 9 Gt GHG emissions constraint and a 2050 net zero target.

The figure shows that there is a greater shift at more accelerated pace in the 9 Gt scenario, relative to the unconstrained run. Overall transport energy consumption is also lower in the GHG constrained world, as the greater portion of electric vehicles improves the overall energy efficiency of the sector, due to EVs being significantly more efficient than conventional internal combustion vehicle (ICE) vehicles.

Passenger transport

The shift from ICE to EV for passenger transport demand is shown in Figure 11, with the 9Gt scenario further split into two cases where energy efficiency (EE) improvements are and are not achieved respectively. When GHG emissions are constrained, there is a greater and more rapid shift to EVs for passenger cars, SUVs and minibus taxis, whereas this shift is moderate to non-existent in the unconstrained case. The difference between the non-EE and EE case is reflected in the greater demand for passenger rail in the EE scenario (due to less mode switching).

The model runs analysed in this study showed that vehicle type choice and usage are highly sensitive to vehicle price projections, and assumptions about learning rates for electric vehicles (and whether/when they reach cost parity with ICE vehicles). In earlier runs, with more optimistic EV pricing, the transition appeared far more rapidly. This highlights a key sensitivity for the sector, which needs further work to explore more extensively. Further work must also be undertaken to determine the key factors that influence EV price projections in the South African market, including the extent to which domestic manufacturing capacity grows and becomes cost competitive, and the extent to which this is supported by international trade (i.e. export markets both overseas and within Africa).

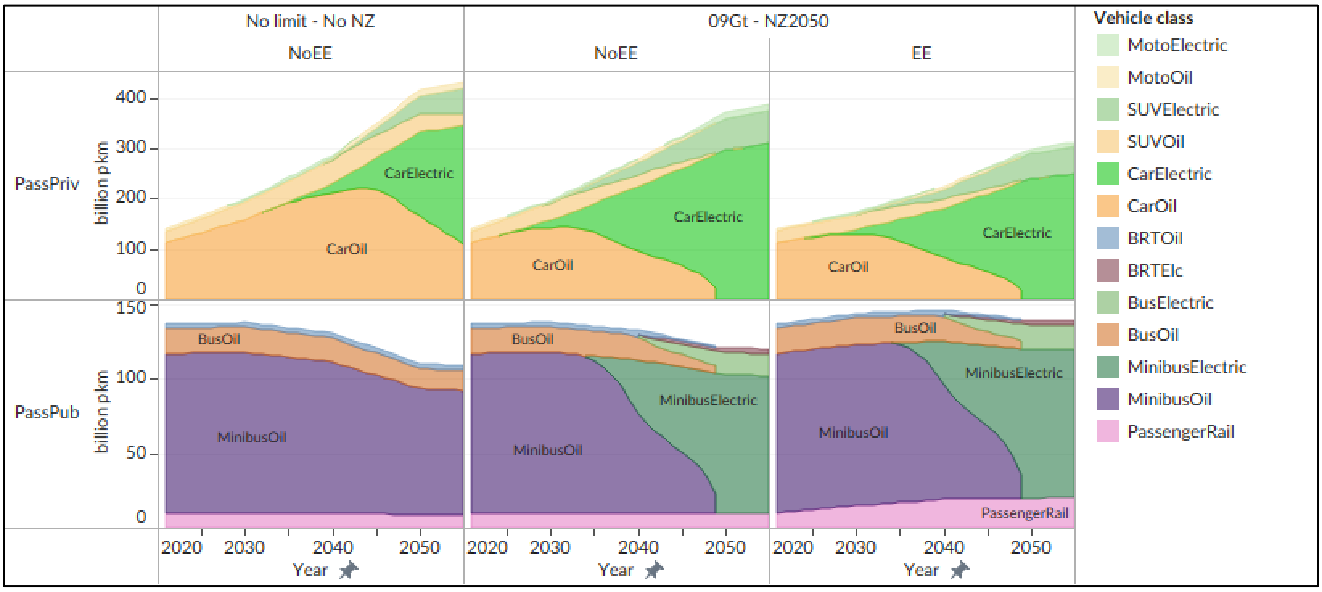

Figure 11: Projected passenger transport demand (in pkm) by vehicle type for unconstrained and 9Gt scenarios, the latter without and with energy efficiency mesures respectively.

There are notable risks that need further analytical unpacking including:

- Whether South Africa risks becoming laggard in the EV transition, and whether this may hinder long-term domestic and export markets, or whether this may prove prudent if ICE vehicles are phased out more slowly around the world than is currently being signalled in Europe

- The 'just' element of this transition needs further analysis, and particularly effects on employment that major shifts in the structure vehicle manufacturing and roll out

The DTIC's Electric Vehicle White Paper provides a starting point for further work to inform this sector (DMRE, 2023).

Freight road transport

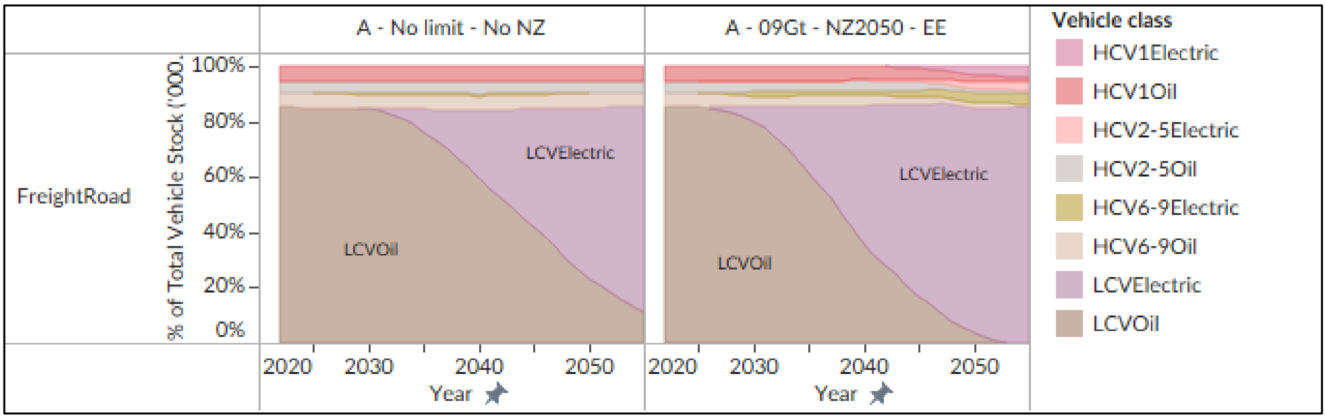

Figure 12: Share of total freight vehicle stock in unconstrained and 9 Gt EE scenarios

Figure 12 shows that liquid fuels remain the predominant fuel for freight transport even under GHG constrained scenarios, with transition to EVs more accelerated in the 9Gt case. Once again, results are highly sensitive to assumptions about cost projections for electric commercial vehicles, with considerable uncertainty remaining particularly for large HCVs.

Liquid fuels supply

In addition to electricity, liquid fuels supply is the main source of energy for the South African economy. In recent years, much of South Africa's crude oil refining capacity has been shut at one time or another, such that Sasol's coal-to-liquids assets in Secunda have remained the predominant domestic producer of liquid fuels for the South African market, with the balance of demand supplied through imports of refined product.

With the current set of assumptions on crude vs imported refined products, and refinery costs, it is expected that existing crude refining capacity at Natref and Cape Town will cease to operate in the mid 2030s, and this is the baseline with which all scenarios are modelled in this analysis. Additionally, the Sasol Climate Change Report of 2023 indicates Sasol's long-term plan to reach net zero by 2050, and to achieve this by ramping down the use of coal for liquid fuel product supply between 2030 and the 2050 end point.

In this work, it is assumed this ramp-down would take place linearly, and the majority of scenarios were modelled on this basis (see the left-hand panel of Figure 13). Two additional sensitivity runs were modelled, also shown in Figure 13:

1. Allowing the model to endogenously retire CTL capacity for liquid fuels on a least cost basis in 2035

2. Maintaining full CTL liquid fuels capacity up to 2045, followed by a ramp down to 2050

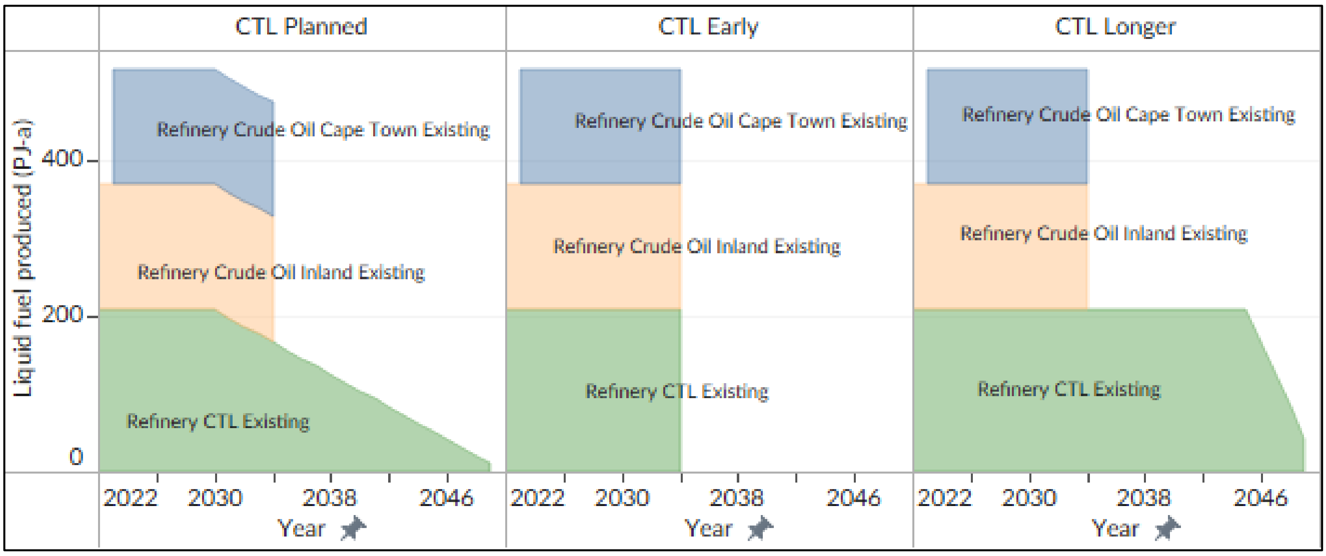

Figure 13: Comparison in modelling of domestic refining capacity and liquid fuels production

The balance of liquid fuels supply to the domestic market is made up of imports of refined product, as shown in Figure 14 (all three scenarios shown for a 9 Gt scenario reaching net zero in 2050 in World A).

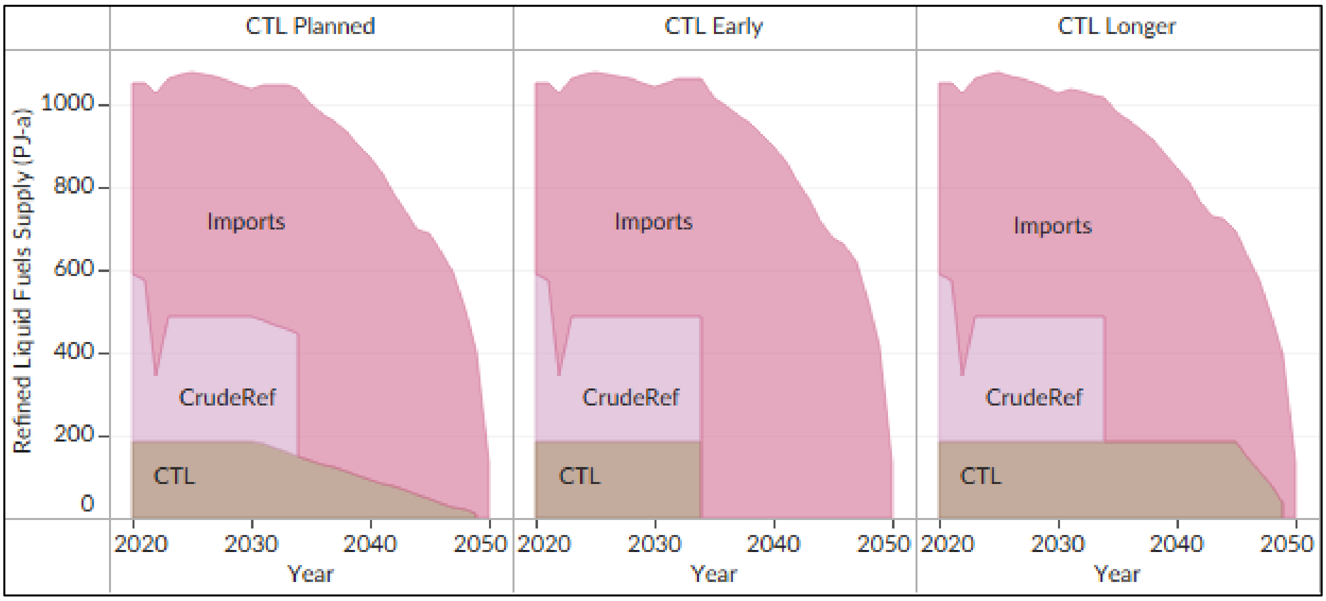

Figure 14: Balance of liquid fuel supply, showing that CTL production balances imported refined product, under 9Gt 2050 Net Zero scenarios

The effect of the different CTL approaches in terms of GHG emissions is shown in Figure 15, which shows that the trade-off in emissions in this context lies between CTL production and electricity; i.e., if CTL capacity is utilised for longer, this reduces the emissions space available for coal power generation, and *vice versa*.

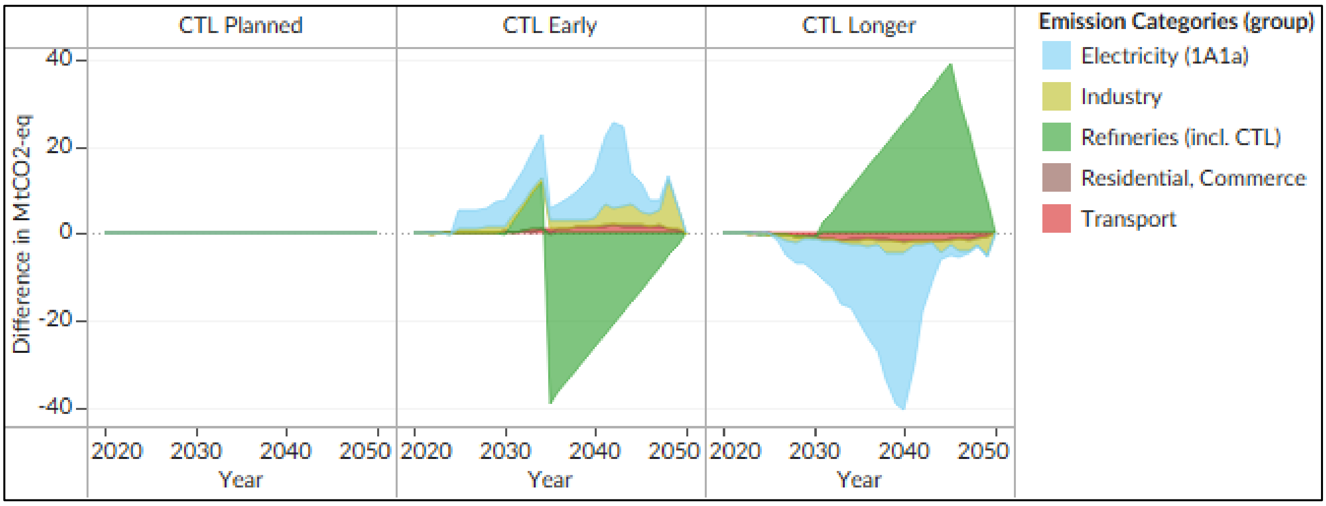

Figure 15: Difference in annual emissions by sector relative to scenarios with CTL ramp down as planned

It must be noted that this is preliminary initial work on the liquid fuels sector and does not account fully for the extent and complexity to which coal-to-liquids is also central to the South African chemicals and petrochemicals sector. Further work is needed to explore this in more detail.

Industry

The industry sector in South Africa in the SATIMGE framework is represented by two different approaches; one for heavy or energy-intensive industries with large facilities such as steel furnaces, and cement kilns. The second approach is used in the more spatially dispersed and less energy-intensive industries such as food and beverages manufacture. Synfuels manufacture is represented separately with other liquid fuels manufactures, but with linkages to the industry sector as required.

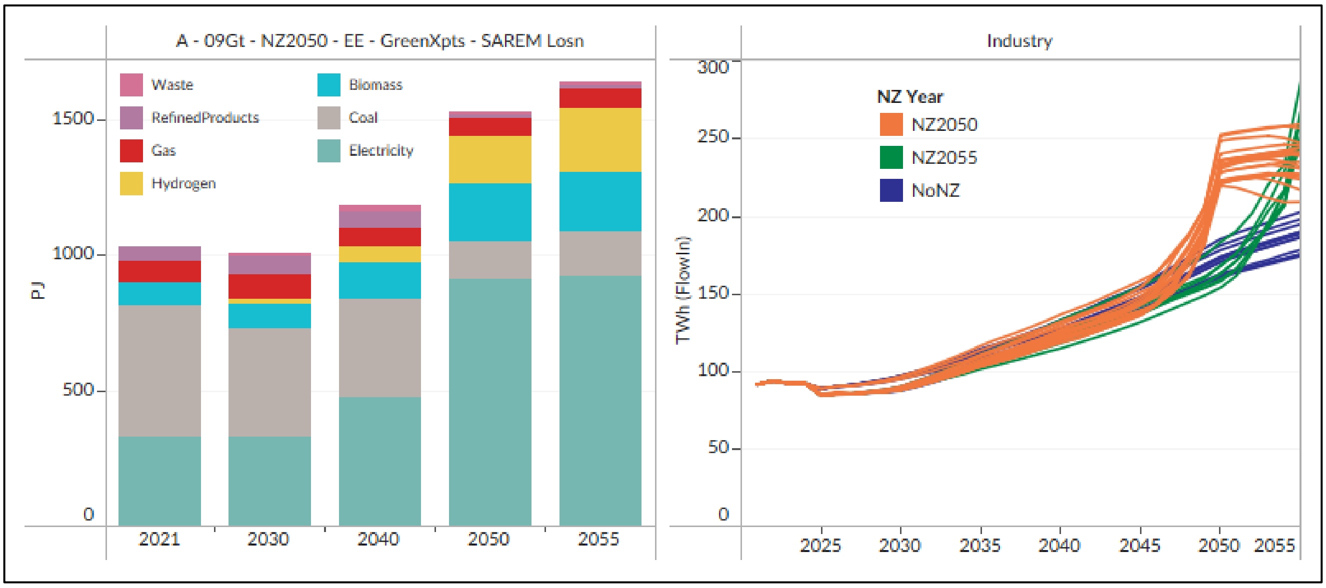

Figure 16: Illustrative fuel transition for industry for a 9Gt net zero transition (left) and electricity consumption pathways for industry for different net zero scenarios (right).

Heavy industry

Iron and Steel

South Africa produced approximately 5 Mt of crude steel in 2021, down from a historical high of about 9.6Mt in 2006. The industry at its peak in the late 2010s had a maximum capacity of about 12Mt of steel production but has historically never reached maximum utilisation owing in large part to stagnant economic growth, and competition from cheap Chinese imports.

The majority of virgin steel production in South Africa today is through the Blast Furnace – Basic oxygen furnace (BF-BOF) route, wholly owned by ArcleroMittal South Africa (AMSA) at two production sites: Vanderbijlpark Park, and Newcastle, located in Gauteng, and Kwazulu Natal provinces respectively. The Saldanha Steel facility, also owned and operated by AMSA, is a world-unique combination of Midrex and Corex furnaces for primary iron production into a CONARC furnace. This facility is located near the export terminal of Saldanha harbour in the Western Cape Province. The harbour is used mainly for the export of iron ore from Sishen in the Northern Cape. The Saldanha Steel facility was an export market-facing facility, and due to pressure on the international markets, and economics of running the facility, it was shut down in 2020 with a loss of about 1500 jobs. It is now "moth-balled".

Iron and Steel, along with only a couple other industries, have been described as 'hard-to-abate' sectors globally, largely owing to their need for carbon to reduce iron ore to metal iron, with no feasible alternative routes/technologies that could replace the blast-furnace technology, and only CCS a potential low carbon emissions option.

In the last few years however, the potential role of hydrogen in replacing carbon in the industry has attracted growing interest and investments, with the Hydrogen Direct Reduction of Iron (DRI) technology, not new, but now potentially more feasible.

The relevant technology options for the sector in SATIMGE in a net-zero pathway are:

- CCS for steel, either on existing furnaces, or on new blast furnaces (refer to the CCS section below)
- Hydrogen – DRI to electric arc furnace (DRI - EAF)

All net-zero and mitigation pathways in this work result in Hydrogen based DRI-EAF production routes as being the most economically interesting options compared to BF-BOF + CCS routes. An example of these is presented in Figure 17. Existing blast furnaces at Vanderbijl park, and Newcastle[20] were estimated by the authors based on AMSA annual reports to be retired in the early 2030s. As these blast furnaces reach end of life and need reinvestment, the hydrogen-based route becomes feasible and begins to be deployed as the demand for steel outstrips the existing production route capacity. This transition relies on technology transfer, and, should hydrogen

[20] Newcastle works were scheduled to be shut-down by AMSA in 2024 owing to low demand for Steel

electrolyser technology learning[21] not be sufficient by the 2030s, financial support for the local industries.

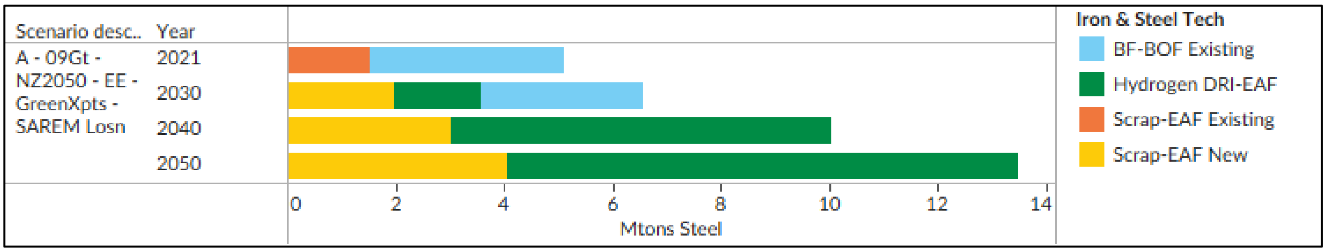

Figure 17: Steel production technologies for a 9Gt net zero transition

Ferroalloys

Owing to South Africa's vast mineral deposits, including chrome and manganese ores, and the history of coal based cheap electricity capacity from the 1980s and 1990s, South Africa has an established ferro-chrome, and ferro-manganese metals smelting industry, located in the Northern, and North-Eastern parts of the country, the smelters are large consumers of power. Ferrochrome, and ferro-manganese are used in alloying speciality steels, notably stainless steel. Most of this product has been exported, with a small share for local stainless-steel production.

Of all the industries globally, which face difficulties with low carbon transitions, Ferroalloys are arguably on the short list of 'hard-to-abate' sectors. Different to most other hard-to-abate sectors, however, is that FerroAlloy production is not a large industry in most other countries, apart from China, and Indonesia. Thus, the attention on this industry, globally from a decarbonisation perspective, is limited. Further to this, is that unlike the steel industry where Hydrogen can reduce iron ore into metal iron, only carbon can reduce chromite ore into chrome metals.

The options for this industry in a decarbonising pathway are realistically limited, but include:

- Newer efficient processes coupling the furnace to pre-reduction steps, like Premus technology[22];
- Biomass and biochar to replace the fossil-based carbon from coal and coke (up to limits)'
- CCS.

The biomass options are limited due to the furnace technologies and the chemistry of the carbon-bearing substances. Coal and coke have chemical, and structural properties within the bed of materials in the furnace that allow for the efficient reduction of chromite ore into chrome metals, and replacing with biomass-based carbons affects the operations of typical furnaces.

[21] Learning costs on hydrogen-based electrolysers are based on the IEA 2019 Future of Hydrogen report.

[22] The recent Lion project commissioned by Merafe in South Africa uses the Premus process: https://www.engineeringnews.co.za/print-version/lion-ferrochrome-smelter-eastern-chrome-mines-restart-merafe-2020-05-08

Owing to the electrical-energy intensive nature of chrome smelting, switching to newer processes like the Premus technology which uses less electricity would contribute to mitigating CO2 emissions from coal power plants in the short and medium term. Coupled with biomass-based charcoal or 'biochar' replacing a portion of the coke inputs, these types of production processes would be required in the industry, and is prevalent in all net-zero scenarios, and is coupled with CCS to capture the remaining fossil origin-carbon reductants.

It should be noted that with biomass carbon input to this process, in conjunction with CCS, there is potential for this industry to be carbon-negative.

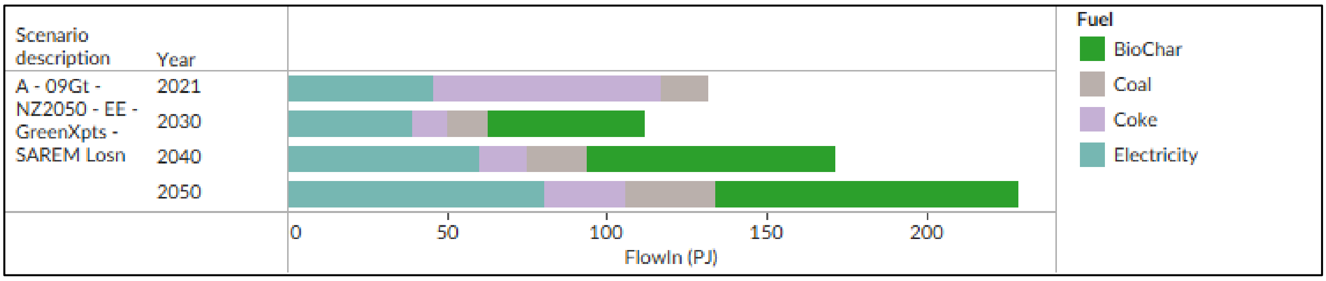

Figure 18: Ferroalloy sector fuel consumption for a 9Gt net zero transition

Pulp and paper

The pulp and paper (P&P) industry relies heavily on thermal fuels for steam production for the various production routes of pulping and paper manufacture. Today, in the industry in South Africa heat is produced primarily with coal, biomass, and natural gas fuels.

Even with cheap RE electricity generation, the cheapest source of heat is from combustion of thermal fuels. In this sector, and in NZ scenarios, thermal switching options are included for heat to electricity boilers, but this is observed to occur only late in the horizon and just before the NZ target year is reached. This is due to the cost advantage of thermal fuels like coal over electricity-based boilers. Biomass usage for boilers is deployed to the constraints imposed. Further work is needed to understand the potential limits of biomass for fuel, linking to the land sector (plantations), and other demand sectors like cement, and ferroalloys.

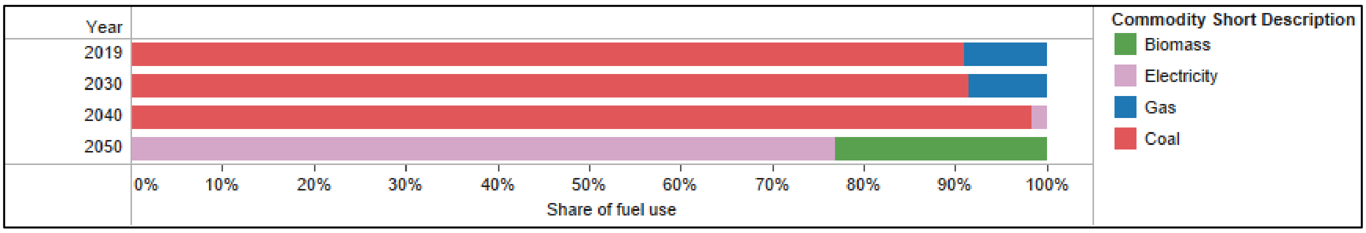

Figure 19: Pulp and paper sector fuel consumption for a 9Gt net zero transition

Cement

Cement is essential for construction and for the economy. Cement is made from clinker, which itself is made from calcining (heating) of limestone. CO_2 emissions from the cement sector are partly from fossil fuel combustion for the heating process, and partly from the calcination of limestone into clinker – releasing CO_2 molecules from the limestone. South Africa produced about 14Mt of cement in 2017 from about 10Mt of clinker and 4Mt of clinker substitutes.

Clinker substitution is a key lever to reducing the CO_2 emissions from the calcination process, and the ratio of clinker substitutions are regulated for safety reasons. Coal power station fly-ash, calcined clays, gypsum, and ground granulated blast furnace slag (BFS) are used today by the cement industry as substitutes for clinker. Of these, only BFS can replace a large portion (around 90%) of clinker, with the other substitutes in lower regulated portions of the overall clinker mix. Data on BFS stockpiles in South Africa is limited, and new product is dependent on future blast furnace output. In this work, maximum clinker substitution is limited to 50% of cement, up from approximately 32% today.

Coal is the main source of thermal fuel for the industry, with natural gas, HFO, and waste tyres making up the rest of fuel requirements. Biomass is also an option – utilising crop residues, or alien invasive species, but is limited due to the transportation limits.

Generally, the results of the Net-Zero pathways for this sector include fuel switching to biomass for thermal fuel (to the allowed limits), but then a switching back to coal, as other industries compete for the biomass resource in reaching the NZ target. CCS is essential for this sector, and is deployed in all net-zero pathways to capture both the clinker IPPU emissions, and the coal combustion emissions. More of this is covered in the CCS section for industry below.

Clinker substitution represents the easiest form of CO_2 mitigation in this sector, and in this analysis is utilised to its maximum allowed potential in all net-zero pathways.

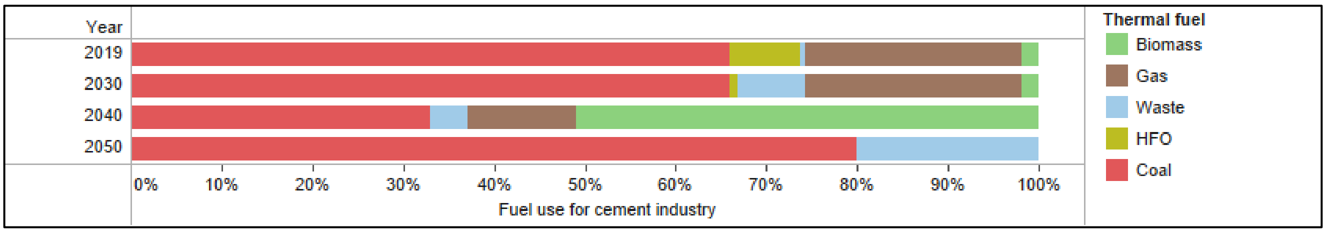

Figure 20: Fuel use in the cement industry in a 9Gt, 2050 Net-Zero pathway

Aluminium

South Africa has a primary aluminium production capacity of about 720kt per year at South32's Hillside facility in Richard's Bay, Kwazulu Natal. The smelter, at ~1200MW, is the largest aluminium smelter in the Southern Hemisphere, and although South Africa has no Baxuite, the smelter imports alumina (partially reduced bauxite) for aluminium production. The smelter uses roughly 5% of the annual electricity output from Eskom, and owing to their operations and high volume of energy usage and demand, has a pricing arrangement with Eskom. "The Hillside smelter provides flexible interruptibility (size and is instantaneous) which is utilised by the National System Operator (NSO), within predetermined contractual limits, to maintain grid stability and meet peak demand requirements. It further plays a key role in Eskom's response plan to a national blackout disaster and provides large base load demand at low demand times that satisfies a large portion of the minimum generation issue at critical off-peak periods and reduces the risk of the curtailment of independent power producers (IPPs)." – Eskom submission to NERSA (Eskom, 2021).

During the reduction process, perfluorocarbon compounds (PFCs), in particular CF_4 and C_2F_2, are emitted during anode effects in the aluminium producing cells. PFC gases such as CF_4 and C_2F_6, are 6,630-11,100 times more potent greenhouse gases than CO_2.

While electricity consumption, from coal-based power plants, accounts for the largest share of CO2 emissions resulting from the aluminium production process, the PFC gases are the largest GHG source from direct operations.

Aluminium production traditionally uses carbon anodes in the Hall-Héroult process which are consumed during the electrolysis process, leading to CO_2 emissions. Inert anode technology using metal oxides or ceramics being developed by the industry, are non-consumable and can significantly reduce CO_2 emissions from the aluminium production process.

The general result is that a technology like inert anodes would be needed in the industry to meet the Net-Zero targets, and this type of technology would need to be deployed earlier with higher levels of mitigation effort (8Gt scenario in the figure below).

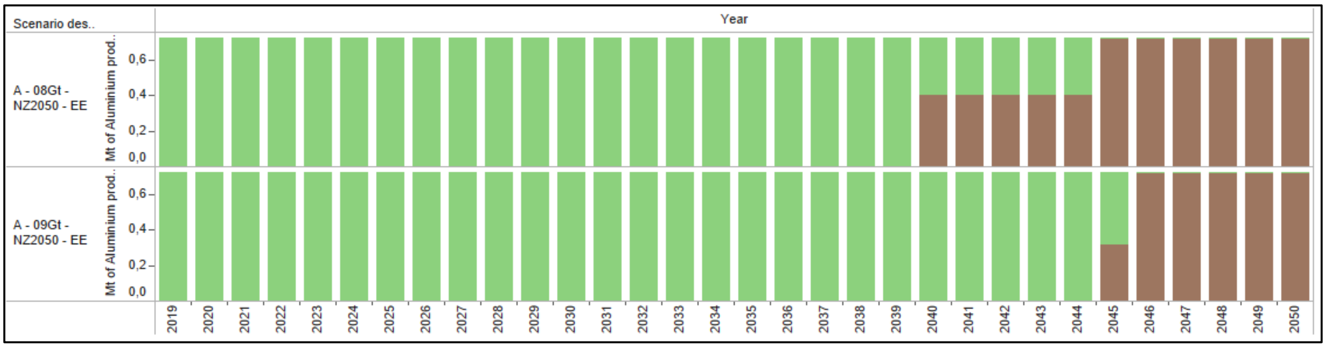

Figure 21: Aluminium production by technologies for 3 different pathways

CCS use in industry

CCS technology is deployed in heavy industry, mostly for cement and ferrochrome industries, as these industries do not have at this time, other technology options for significant CO_2 mitigation. CCS deployment occurs in all scenarios with net-zero targets. The timing and scale of the deployment depends on the mitigation effort (carbon budget) and carbon tax levels, and reaches around 15Mt of sequestration in the Net-Zero year.

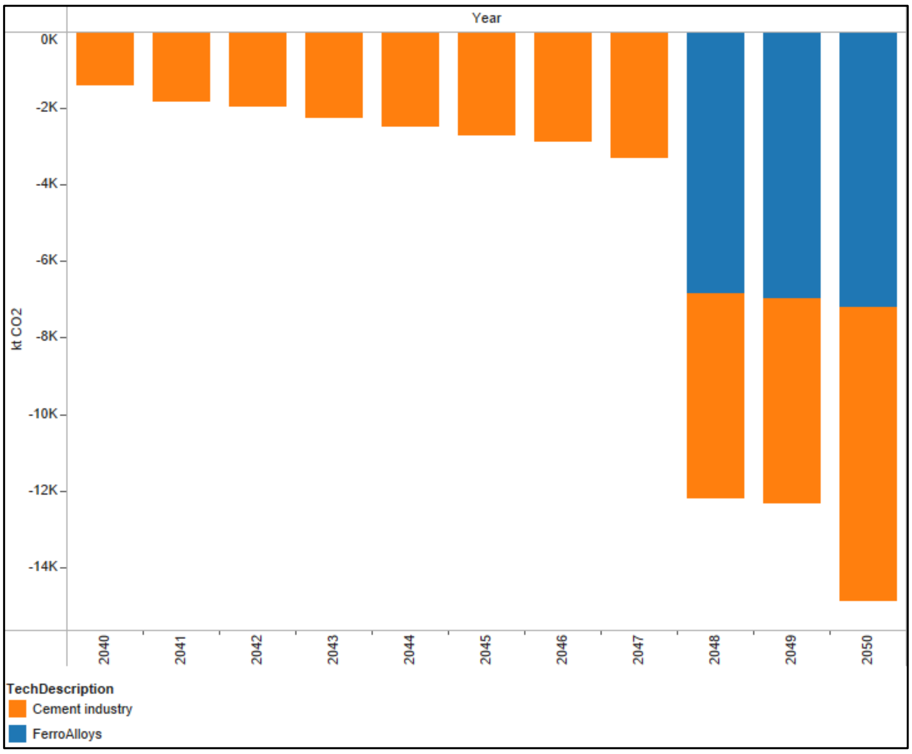

Figure 22: CCS use in industry in a Net-Zero pathway; common among all net-zero pathways in this analysis

Other industries

For the rest of industries in South Africa, process heat is the main challenge for the transition to low carbon pathways. Despite low cost of energy of RE electricity generation, thermal fuels (in particular coal) are still the most cost-effective method for providing process heat. Apart from electricity, the only other low-carbon option is biomass, but this is limited in supply and also has considerable transportation and preparation costs for most industries. For higher temperature requirements such as in kilns, hydrogen may be required for decarbonization, but this too is relatively expensive compared to fossil-derived thermal fuels.

As a result, in the rest of industry, fossil fuel use continues until the 2040s, where fuel switching occurs rather rapidly to electricity to meet the NZ target. Biomass is used to its maximum potential in industries such as in food and beverages, and hydrogen is deployed in some cases such as for heating brick kilns. All these however, occur late in the model horizon.

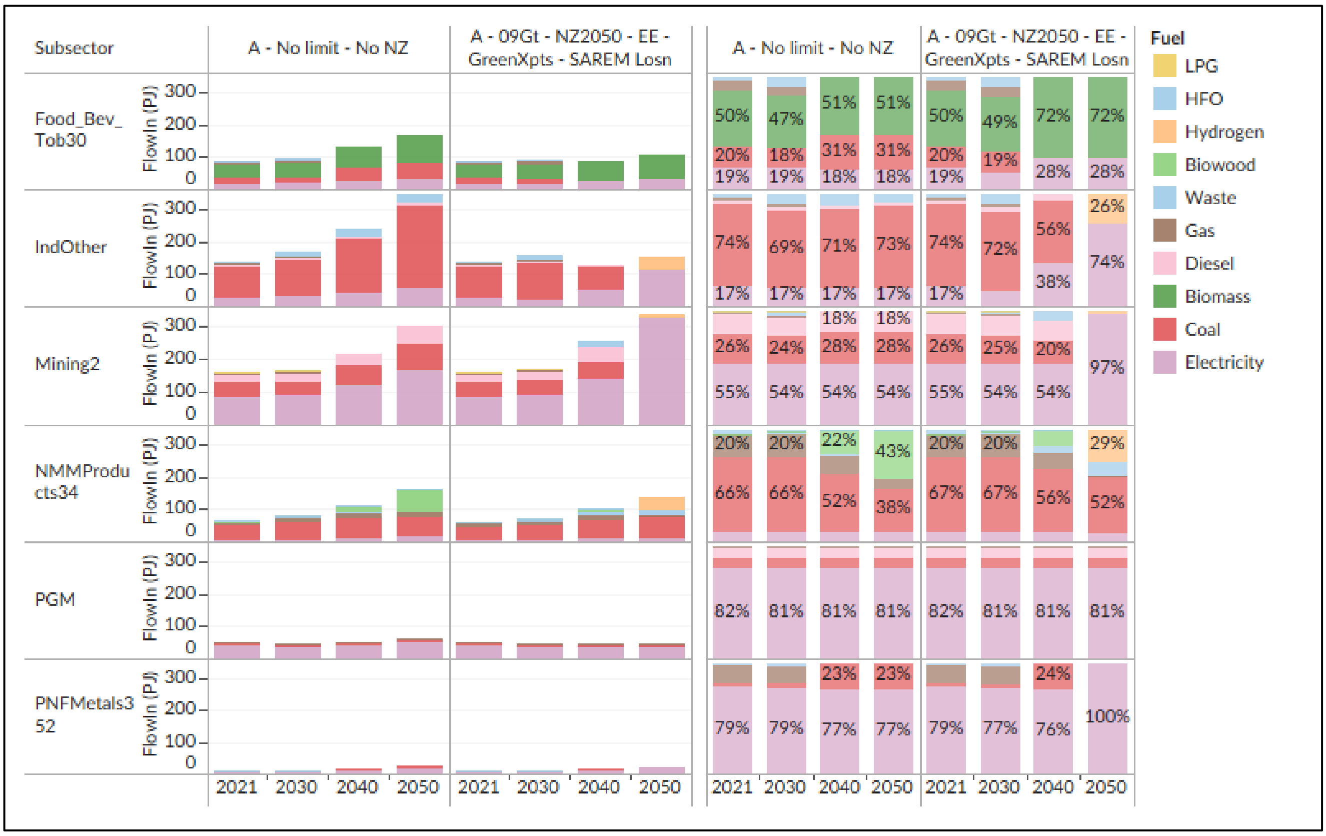

Figure 23: Energy transitions in other industry subsectors, comparing an unconstrained and a 9Gt NZ2050 case

Other sectors

Two other energy demand sectors – Commerce and Residential – are briefly described here. Buildings make up the majority of energy use in these sectors and are their main contributions to emissions. Commerce includes commercial buildings such as offices, retail spaces, hospitals, schools and government buildings, while residential buildings comprise households disaggregated at high, medium and low-income levels.

Commerce

Figure 24 shows the effects of the GHG emissions constraint on commercial building energy usage, and further shows the effects of achieving improved energy efficiency for buildings.

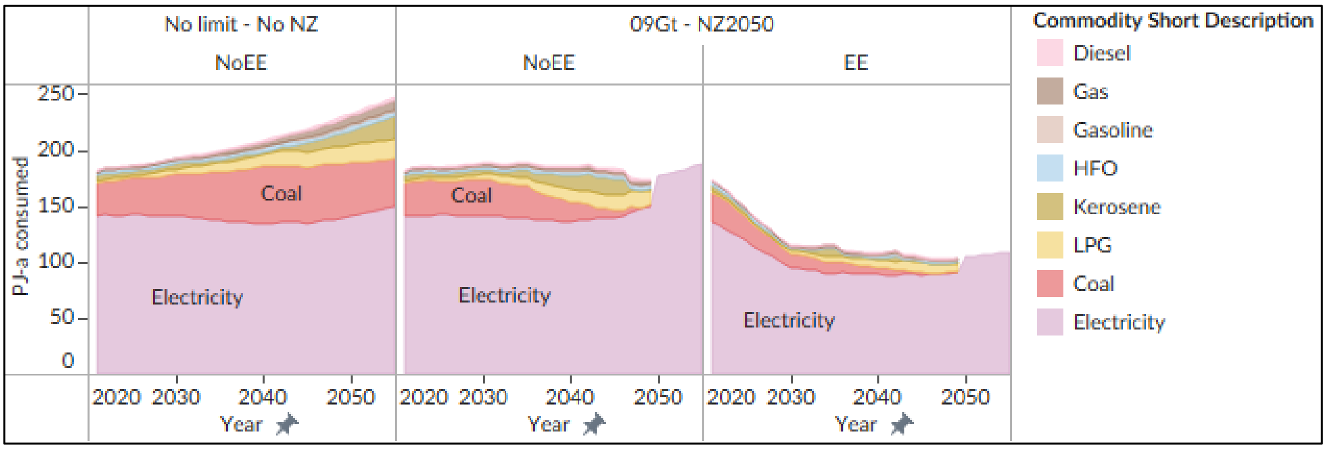

Figure 24: Commercial fuel use for unconstrained and 9 Gt net zero 2050 scenarios, the latter showing scenarios without and with energy efficiency respectively

The GHG constraint causes a phase down of liquid and solid fuels in favour of electricity, particularly in the years immediately preceding net zero in 2050. The energy efficiency scenario shows the impact of EE measures, based on the following parameterisation in the model:

- New commercial buildings constructed post-2018 are projected to achieve energy intensity improvements of 27% per m^2 by 2030, 54% per m^2 by 2040, and 70% per m^2 by 2070, relative to a 2015 baseline, in line with adjusted targets set in the 2015 draft NEES
- Similarly retrofits of existing buildings are assumed to result in an average improvement in energy intensity of 20% per m^2 by 2040.

As such, energy efficiency measures are shown to result in a significant reduction in overall energy use for the commercial sector, due to interventions such as more efficient lighting and cooling of workspaces. However, further work is needed to address sensitivities around costs and performance of energy efficiency measures available to the commercial sector, and uncertainties around feasibility of the adjusted NEES targets.

Residential

Figure 25 shows summary analysis of fuel transitions across income levels for households under net zero pathways with and without energy efficiency, relative to an unconstrained (no net zero) case.

The model shows that total energy use for high income households increases significantly (drawn mainly from electricity), while low-income household total energy use shrinks. This highlights that through the modelling period there is a shift upwards shift in income and standard of living, with the proportion of low-income households to total households shrinking in future years relative to today's ratio. This effect is consistent across all scenarios modelled. Further work is needed here to examine the impact of increasing mitigation ambition and reaching NetZero on household energy expenditure.

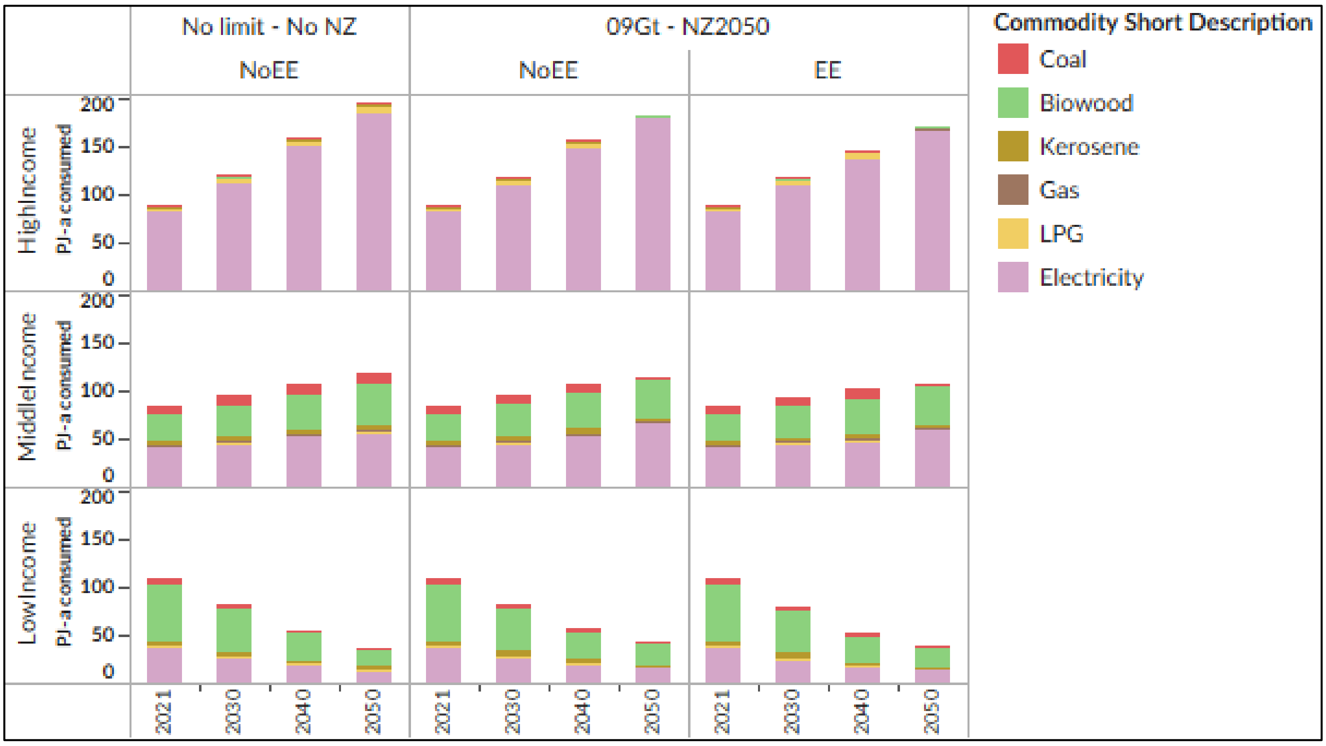

Figure 25: Residential fuel use for scenarios without constraint and two 9Gt NZ2050 scenarios without and with energy efficiency measures respectively

Land sink and CCS

The achievement of net zero CO_2 emissions requires that there be some way to absorb residual CO_2 emissions after all feasible mitigation has been achieved. This is critical for 'hard to abate' sectors, such as cement and ferroalloys as described in heavy industry above – there are no zero-carbon options for these sectors currently available in the modelling framework.

The modelling framework includes two mechanisms by which CO_2 emissions can be sequestered:

- The land sink
- Carbon capture and storage technologies

Land sink

For all scenarios in this study, the land sink was modelled conservatively with a net sink of around 10 Mt CO_2 per annum. The combination of sinks and sources contributing to this balance is shown in Figure 26, showing that land use (including crop land) accounts for the majority of emissions from the land sector, while afforestation and grassland development account for the majority of the land sink. Further work is needed to ascertain the extent to which this land sink can be maintained, or enhanced, and how this may affect other factors such as food and water security, and biodiversity.

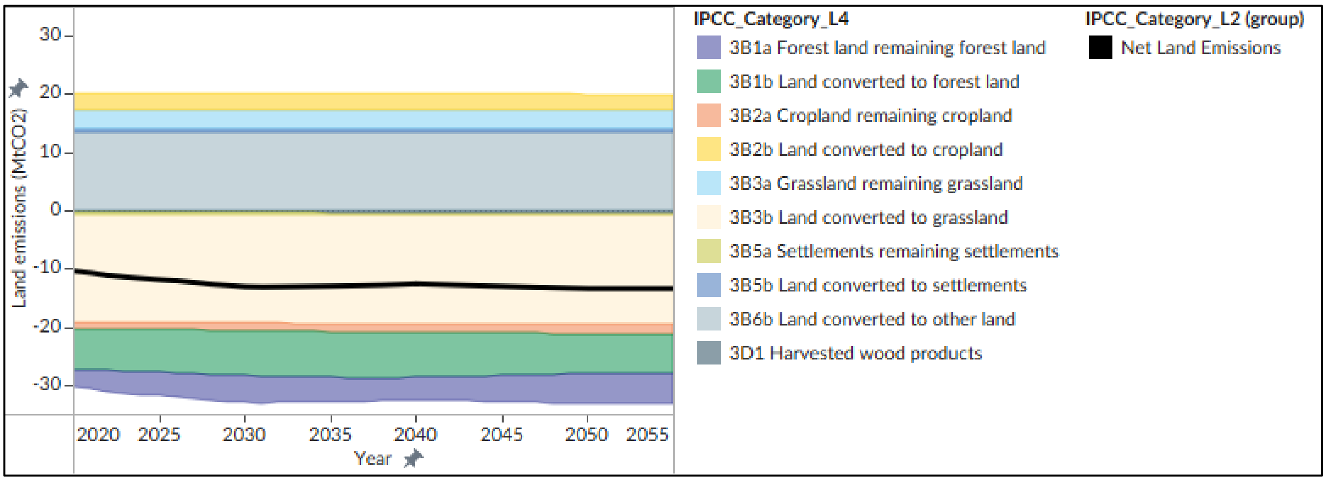

Figure 26: Assumed land emissions projections for all scenarios, with a net sink of 10 - 14 $MtCO_2$

CCS across power and industry

As discussed in the power and industry sections above, CCS is required in both these sectors to enable the economy to reach net zero CO_2.

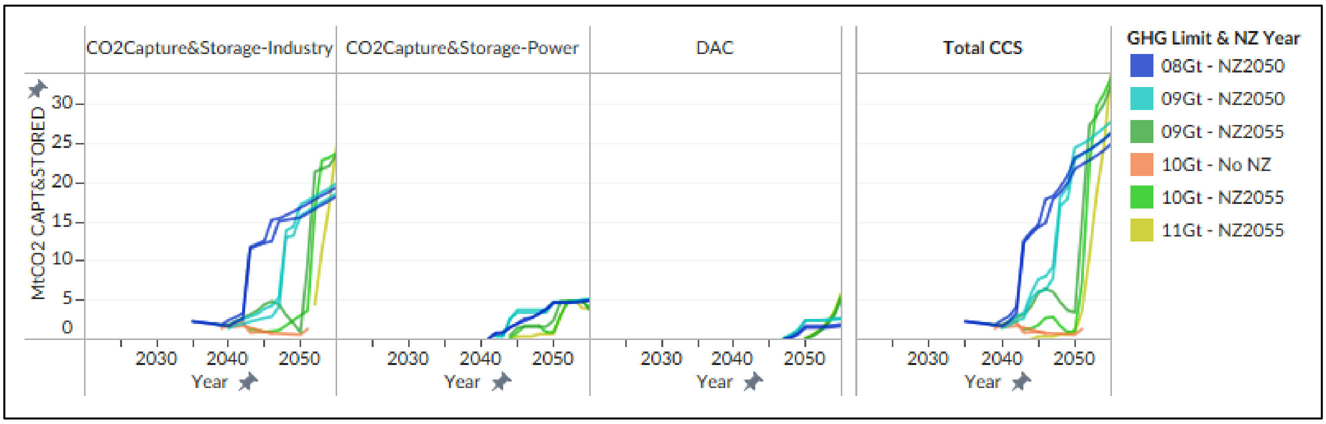

Figure 27: CCS by technology and overall for scenarios with varying GHG and net zero constraints

Figure 27 presents CO_2 captured through CCS technology for various scenarios with increasing net zero and GHG ambition, as applied either in the industry or power sectors, or in the form of 'direct air capture' (DAC) technology. Total CO_2 captured by these methods reaches around 30 Mt CO_2 per annum across net zero scenarios. Carbon capture and storage technology is as yet unproven at commercial scale anywhere in the world, and there is a risk that it may not be available as modelled. More work is needed to explore the consequences of the unavailability of this technology.

The "last mile" challenge

The analysis above highlights one of the foremost risks and uncertainties in achieving a net zero target, in that as yet the technology does not currently feasibly exist to achieve net zero CO_2 emissions (let alone net zero GHGs) without substantial and costly investment in as yet unproven technologies such as CCS and DAC. Without these technologies, it would be even costlier and likely impossible to fully decarbonise the economy without curtailing production in specific sectors. Even with these technologies, the uncertainties, and the high prices associated, cause a significant ramp up of cost and investment in the years leading up to net zero – known as the "last mile" effect.

Figure 28 shows a quantification of last mile effects in terms of annual GDP, in real terms, relative to the unconstrained case where net zero is not achieved (dark orange line), wherein no CCS technology is required.

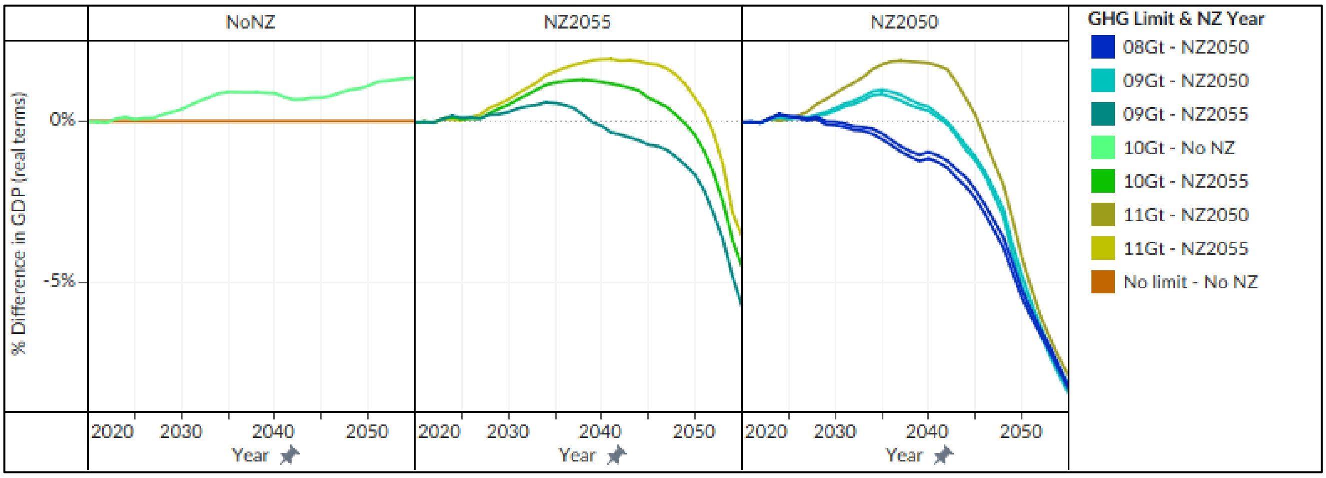

Figure 28: Projections in GDP relative to the unconstrained case for different GHG budgets and net zero years

The figure shows that, in some cases with higher GHG cumulative emissions limits (9 and 10 Gt), economic performance is better than the unconstrained case in the next two decades, up to and in some cases beyond 2040. However, in the 2040s, as net zero approaches and the model begins investing heavily in expensive zero (or negative) carbon technology, the impact on GDP becomes stark, particularly when net zero is reached in 2050. These losses could be offset via more access to affordable capital and other industrial policy initiatives aimed at localising low-carbon technology value chains.

Socio-economic analysis

Comparative analysis of cumulative GHG emissions and GDP growth/capita

In this section, the concept of Pareto optimality has been adapted to identify scenarios which achieve the most economic output for a given total GHG budget (2021-55) – in other words, to identify the point at which none of the selected measures would result in further mitigation. These points comprise a "pareto frontier". Figure 29 plots the percentage increase in GDP per capita from 2021 to 2055 (y-axis) against cumulative GHG emissions from 2021-55 (x-axis), to identify a "Pareto frontier), in other words, the best economic outcome for each cumulative GHG emissions value. The yellow points are scenarios which both remain within a cumulative GHG budget of 10 Gt or less from 2021-2050 and feature a net zero target, the red points are scenarios which do not meet these criteria, and the blue points are scenarios without a GHG constraint or a net zero target, but with a high carbon tax level. The dashed yellow line represents a "frontier" above which there are no higher GDP outcomes for that specific cumulative GHG point. Scenarios with the same GHG constraint have significantly different economic outcomes, depending on what measures accompany the mitigation process.

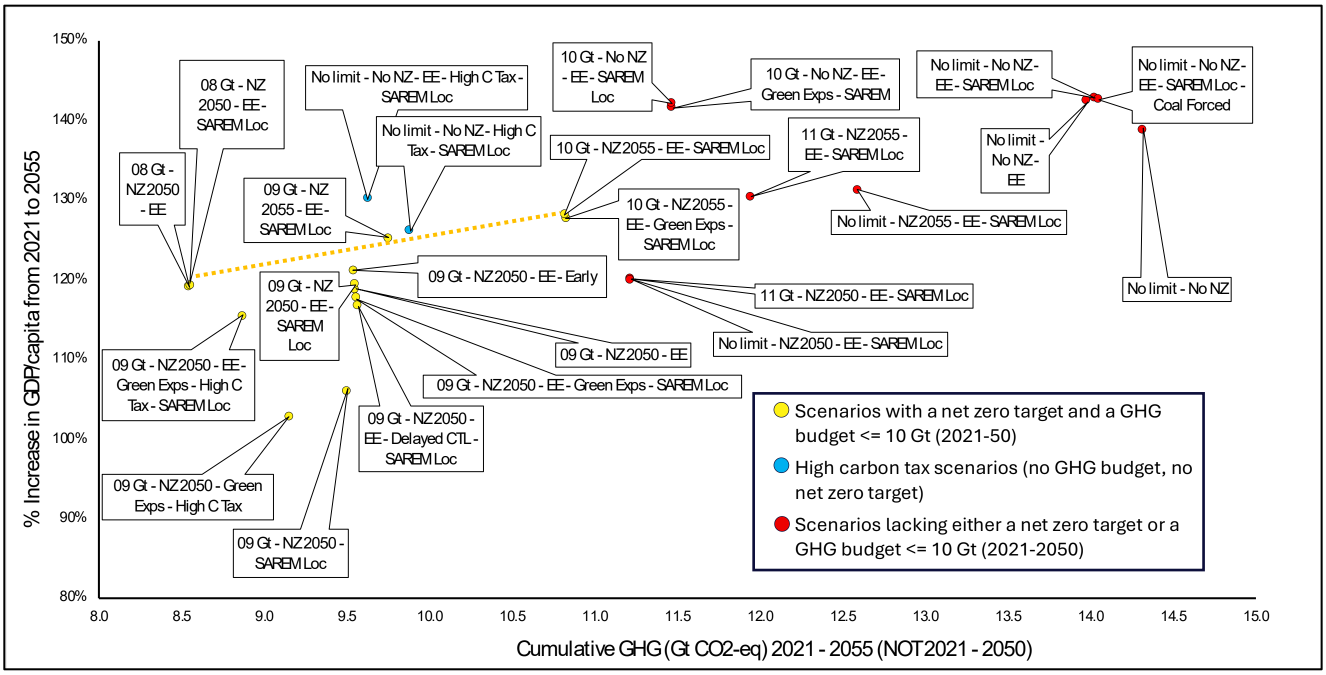

Figure 29: correlation of the % GDP/capita change from2021 to 2055, and cumulative GHG emissions from 2021 to 2055[23]

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[23] It should be noted that the GHG emissions budgets for individual scenarios apply to GHG emissions from 2021-2050. This figure uses cumulative GHG emissions per scenario from 2021 to 2055 (i.e. the total INCLUDES the years 2051-5). Thus, a scenario which is labelled as a 10 Gt scenario will have higher cumulative emissions in this figure because of the inclusion of the additional years. The extended range is necessary to facilitate a meaningful comparison between scenarios which reach net zero CO_2 in different years.

Caveats in considering these correlations are that i) GDP gains resulting from lower air pollution levels (as a result of a faster rate of decarbonization) are not factored in[24]; ii) the "crowding out" effect of accelerated investment in the electricity sector and elsewhere in cases with lower GHG budgets may be offset via access to more international capital / climate finance iii) scenarios with cumulative GHG emissions greater than 10 Gt, and/or without a net zero target, pose risks which are not factored in to this analysis. In addition, conclusions here are limited to the specific scenarios in this study.

With these caveats, there are several important conclusions that can be reached. The first is that moving from a cumulative GHG outcome of 14 Gt to 10 Gt has very little impact on GDP per capita, and a 10 Gt pathway (without a net zero target) is a no regrets option. The second is that it is possible, given the assumptions in this study, to reach net zero by 2050 with a cumulative GHG budget of 8-11 Gt, with only a 4-6% GDP loss compared to the unconstrained case in 2050 (see Figure 28). Further work will be necessary to explore this further, and specifically the potential impact of concessional finance and/or access to higher levels of foreign direct investment, the economic impact of air quality differences between scenarios, and the impact of individual measures.

Hereafter, this study considers various policy measures that were implemented into the SATIMGE framework to test their impact on South Africa's least cost energy investment, emissions pathways and socio-economic outcomes. These policy measures include carbon pricing, energy efficiency and the localization of renewable energy manufacturing.

Carbon pricing

South Africa's official carbon tax sits at R144 per tonne. However, after accounting for allowances the effective tax rate sits at approximately R30 per tonne. In the 2022 budget the government proposed to strengthen the carbon tax policy the government plans to raise the carbon tax rate to at least US$20/t CO_2 by 2026, to US$30/t CO_2 by 2030, and accelerating to higher levels up to US$120/t CO_2 beyond 2050. To evaluate the potential impact on the proposed carbon tax put forward we compare this ramp up in the tax rate to a scenario where current levels are help constant with the effective tax rate equal to R30 beyond 2050.

Impact of carbon tax

Figure 30 presents the impact of the carbon tax on shifting South Africa's cumulative emissions to 2055. In the ramp up scenario without any other policy measures the proposed carbon tax drastically shifts South Africa's emission pathway to reach a 2055 cumulative GHG budget similar to the 2050 9GT carbon budget and net zero scenario. Placing a price on carbon equal to that of the proposed carbon tax changes the optimal energy investment pathway with investment in low-carbon technologies becoming significantly cheaper relative to carbon intensive technologies.

[24] Externalities for air pollutants are included in the SATIMGE model, sourced from IRP 2019. But these exclude the damage estimates from the CSIR's work in this project on air pollution.

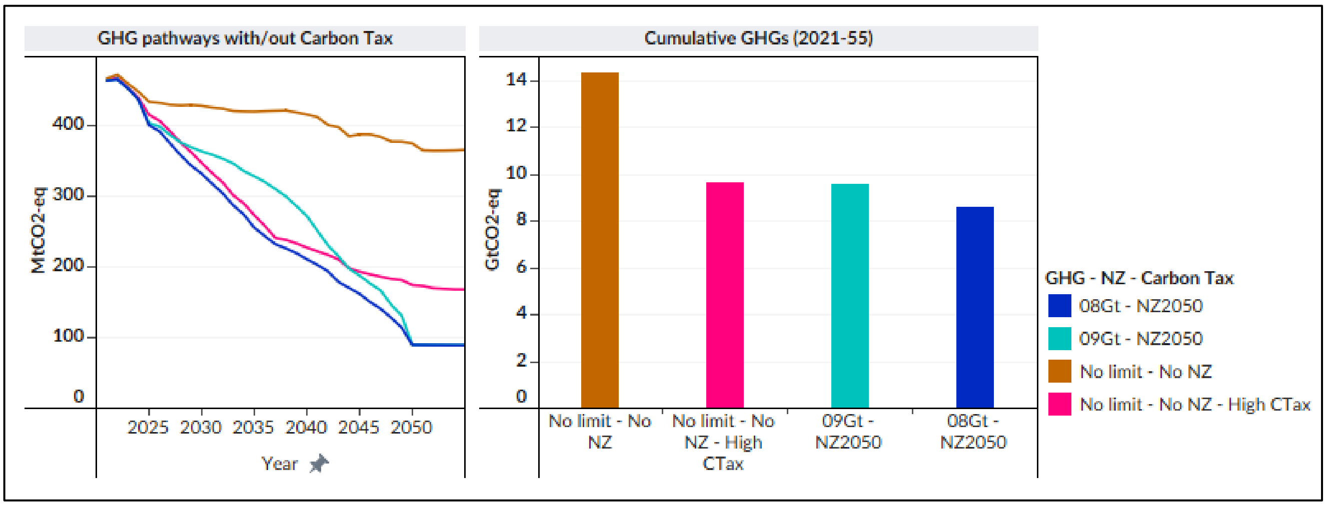

Figure 30: Comparing pathways with a GHG budget to an unconstrained pathway with the higher carbon tax.

The resulting expedited low-carbon transition because of the carbon tax would increase power sector investment and the cost of energy in the South African economy. The model is structured in such a way that a significant increase in investment in the power sector is funded through a reduction in investment in other sectors leading to the 'crowding-out' of investment and negative economic impacts. In reality this need not be the case if concessional finance and foreign investment reaches a certain scale (Pollitt & Marcure, 2018). The model also does not capture the governments planned revenue recycling of carbon tax income into the green economy, which should reduce the burden on energy prices. Figure 31 shows that while the carbon tax is a powerful policy lever to significantly reduce carbon emissions, when foreign investment, green finance and tax revenue recycling is not considered, this policy could have negative impacts on the South African economy through a reduction in GDP and employment growth. When the carbon tax ramp up proposed in the 2022 budget is applied to an unconstrained scenario, we see a reduction of approximately 4Gt-CO2-eq emissions, this sets the economy back by just over one year of economic growth with the average annual growth rate up to 2050 reducing from 3,38% to 3,21%.

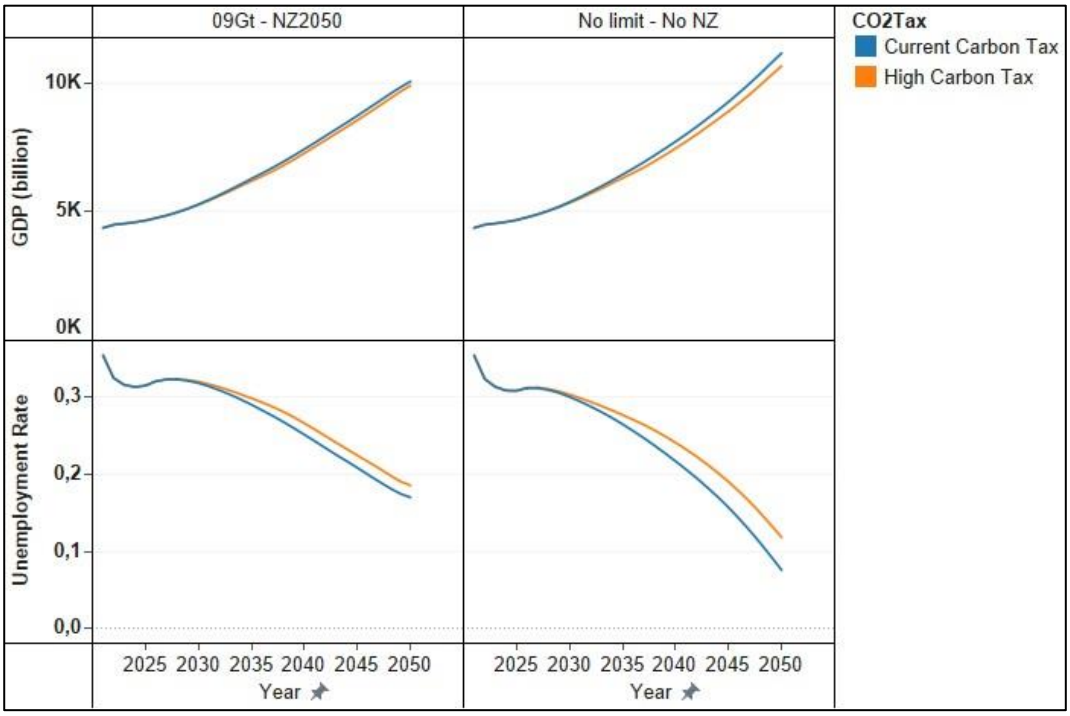

Figure 31: Economic impact of a high carbon tax.

One interesting finding is that despite the carbon tax resulting in a decrease in economic growth and employment, it also leads to a decrease in the Palma ratio. The Palma ratio has been implemented in SATIMGE as the share of all income received by the 20% of households with the highest income divided by the share of all income received by the bottom 20% of households. A higher Palma ratio represents a higher level of inequality therefore a reduction in the Palma ratio as seen in Figure 32 shows that the carbon tax leads to a reduction in inequality. The before tax Palma ratio was calculated to be 11.94 in the unconstrained scenario in 2050, this decreased to 11.85 when the carbon tax was applied. While the decrease in inequality is small, these results point to the inefficiency of GDP growth as a measure of universal welfare. The outcome suggests that while the economy grows faster without the implementation of a carbon tax, this grows seems to benefit wealthier households relatively more. Higher economic growth provides little insight into whether we are achieving a just transition and should not be considered in isolation as the main indicator for improved welfare. Further work is needed to unpack how the model allocates income between households in order to draw meaningful conclusions on the impact of low-carbon policy measures on inequality.

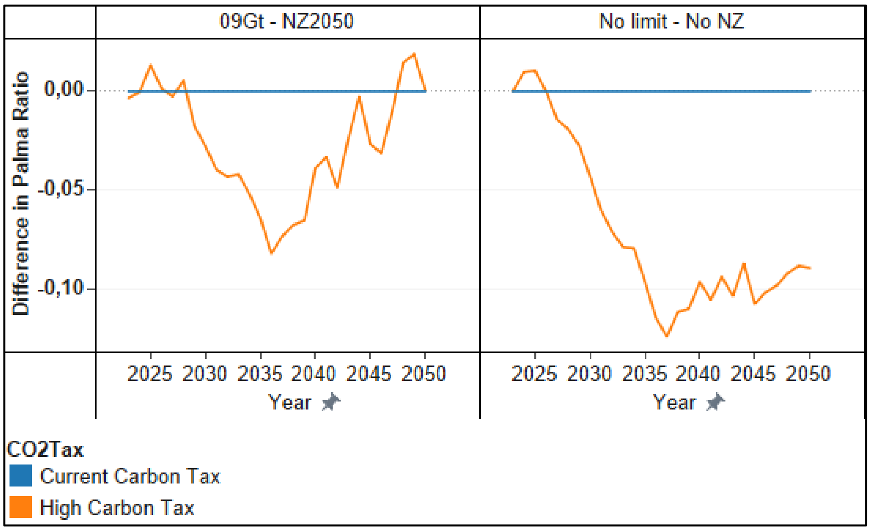

Figure 32: The Palma Ratio showing changes in income inequality, where a decrease in the Ratio is a decrease in inequality.

Energy efficiency

There are three main avenues through which energy efficiency has been implemented into the SATIMGE modelling framework. Firstly, it is assumed that there is partial achievement of the draft 2015 National Energy Efficiency Strategy targets in industry and commerce (RSA, 2016). Improvements in residential energy efficiency are based on findings from a study on residential load management undertaken by DMRE, SANEDI and ESRG (2024 report under review). Energy efficiency in transport is incorporated through the partial mode switching (private to public and road to rail) in land transport (Ahjum et al, 2020).

Impact of energy efficiency

In the economy, energy efficiency measures reduce the energy required to produce the same output. This reduces the level of investment in new capacity to meet demand and as a result there are more funds available to invest in the growth of other sectors. Figure 33 presents how energy efficiency measures reduce the new electricity generating capacity required in the economy and in turn the cumulative power sector investment requirement. The results show that there is significant economic benefit in the implementation of energy efficiency strategies as can be seen in Figure 34.

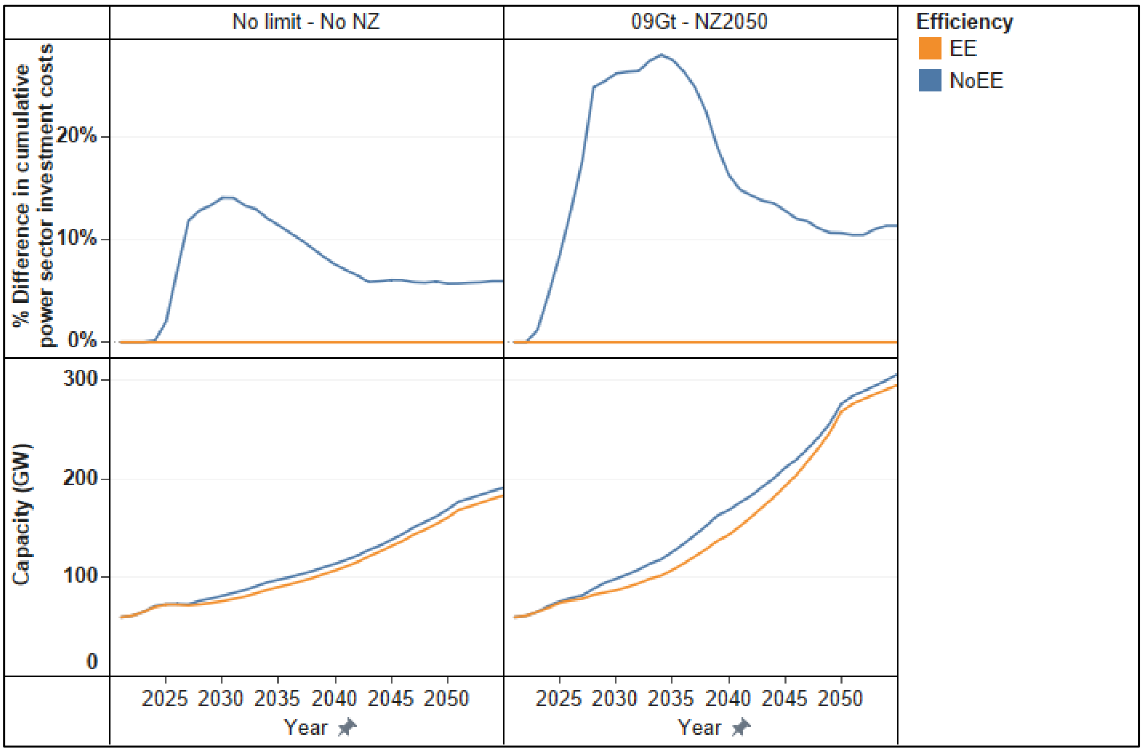

Figure 33: Difference in power capacity build and investment with and without energy efficiency.

The magnitude of these economic benefits is highly sensitive to the amount of power sector investment required. Energy efficiency measures that are implemented in an unconstrained scenario contribute to a 1.4% increase in GDP by 2055. These energy efficiency measures result in an increase in GDP of 6.4% in a 2050 Net Zero scenario with a 9GT carbon budget, compared to such a scenario with no additional energy efficiency measures. The results suggest that energy efficiency is critical strategy in offsetting the 'crowding-out' effect of increased power sector investment seen when transitioning to a net zero carbon economy.

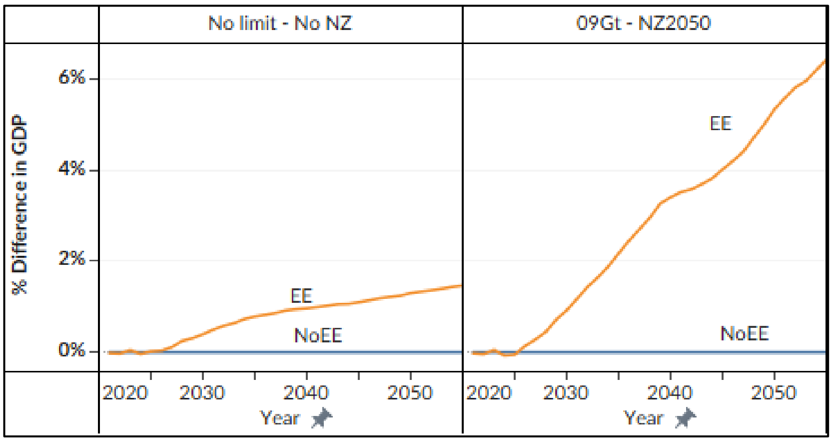

Figure 34: Economic impact of energy efficiency measures, in terms of increased real GDP growth.

Figure 35 shows that along with significant economic growth as a result of energy efficiency we also see a decrease in the unemployment rate. The magnitude of the impact on unemployment is much greater in the net zero scenario, where the unemployment rate decreases by approximately 5 percentage points (from 18% to 13% unemployment by 2050).

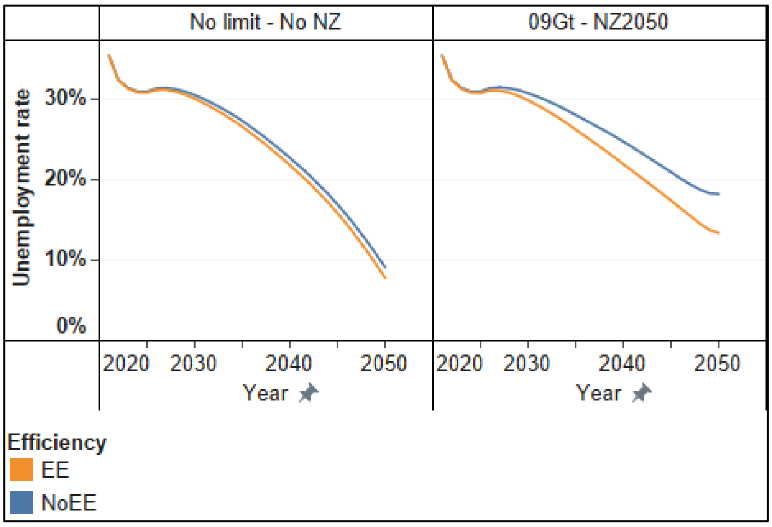

Figure 35: Difference in unemployment rate in economy with and without energy efficiency measures.

Localisation

Localisation of value-chains for renewable energy generation technologies is an important element of a transition to a sustainable economy in South Africa. Thus, a dedicated effort to create the representation and characterisation of localising the value-chains of renewables in SATIMGE was required, and was supported by the European Commission funded project 'IMAGINE', organised by IDDRI within the DDP network[25].

Modelling approach to localisation

Localization of renewable energy was implemented through four renewable energy technologies, namely wind, utility scale solar, rooftop PV, and utility scale battery storage. In SATIMGE there are five major sectors that feed into the development of these renewable energy technologies (construction, construction business services, machinery, electrical machinery, and metal products). Figure 36 presents the different components that go into the development of the four renewable energy technologies and how these components are classified into different sectors in the model. The proportion of local content differs for each of these activities. In the base year (2019) in SATIMGE we see that 47,1% of machinery produced for the South African power sector comes from local sources while the rest is imported. This compares to 94% local content for construction and business services, 76% local content for metal products, and 47,5% local content for electrical machinery. In Figure 36, the proportion of local content for each activity that exists in the base year is represented in green. The red colour represents the proportion of production that South Africa will not be able to produce locally, and the orange represents the proportion of industry that could potentially be produced locally in the future. We can see that the sectors where there is high growth potential for localization are machinery and electrical machinery. Both these activities are classified as manufacturing activities.

[25] https://www.iddri.org/en/reseau/deep-decarbonization-pathways

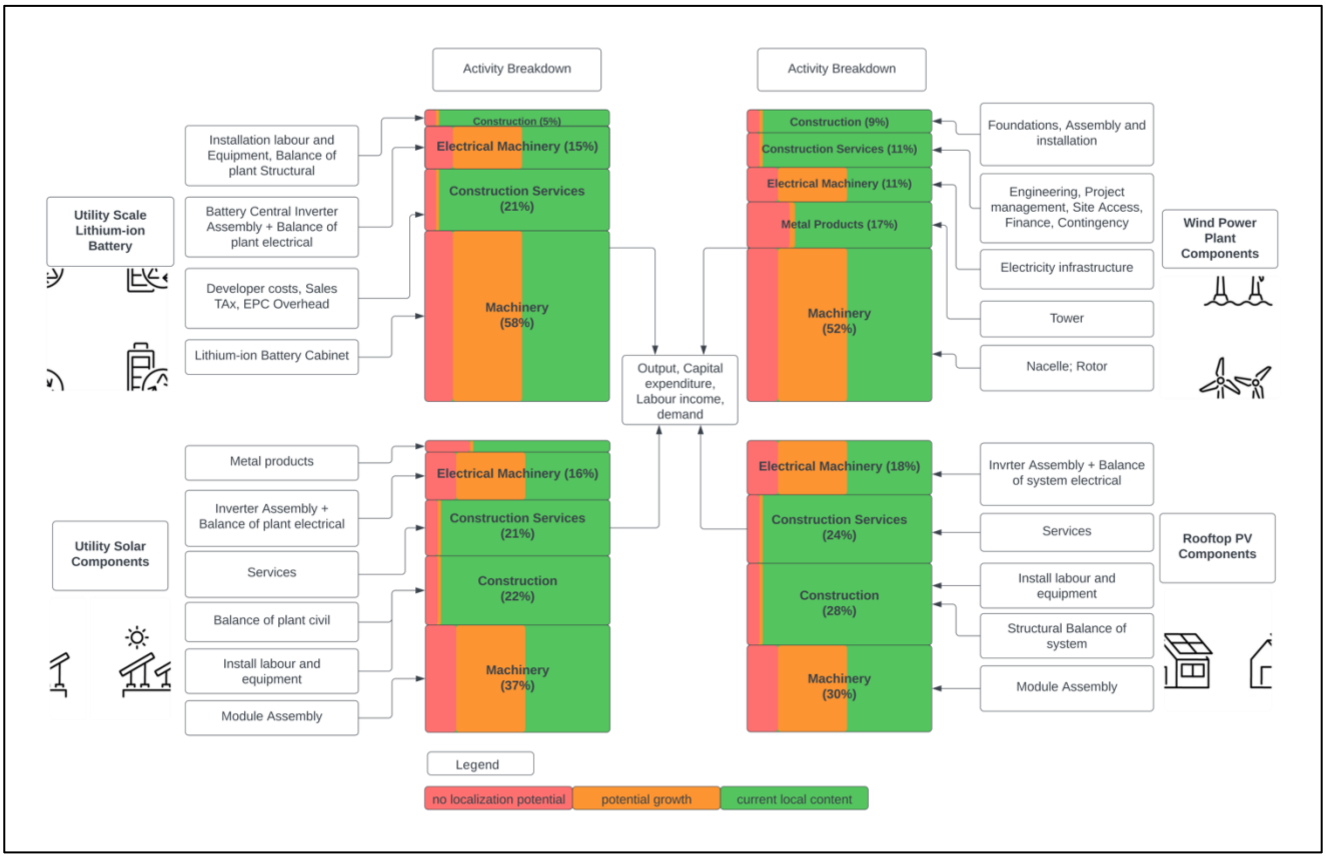

Figure 36: Breakdown by technology and value chain components of current levels of localisation, potential localisation and the percentage of the value chain for which there is no localisation potential.

Two scenarios were modelled to test the impact of the ambitious manufacturing localization estimates put forward in the 2022 draft South African Renewable Energy Masterplan (SAREM) (DMRE, 2022). Current levels assumed that the level of local content present in the renewable energy value chain in the base year (2019) would be held constant to 2050. In line with the SAREM 2022 estimates, the manufacturing of renewable energy components reaches 70% local content by 2030 and increases to 85% by 2050. A 5% premium on the cost of generation from new renewable capacity was applied in the 'SAREM consistent' scenario to account for the assumed premium resulting from local manufacturing on energy system costs and the economy.

Impact of localisation

Figure 37 presents the percentage difference in GDP per capita and the difference in the unemployment rate of SAREM consistent localization scenarios compared to current levels of localization. The results show positive economic outcomes in all scenarios. The positive impact associated with localization is more pronounced in the Net Zero scenarios despite the application of a 5% price premium on renewable energy technology. While the benefits of economic growth and increased employment from this policy are significant, the impact is not enough to offset the 'crowding out' of power sector investment experienced in the 'last mile' of the net zero transition.

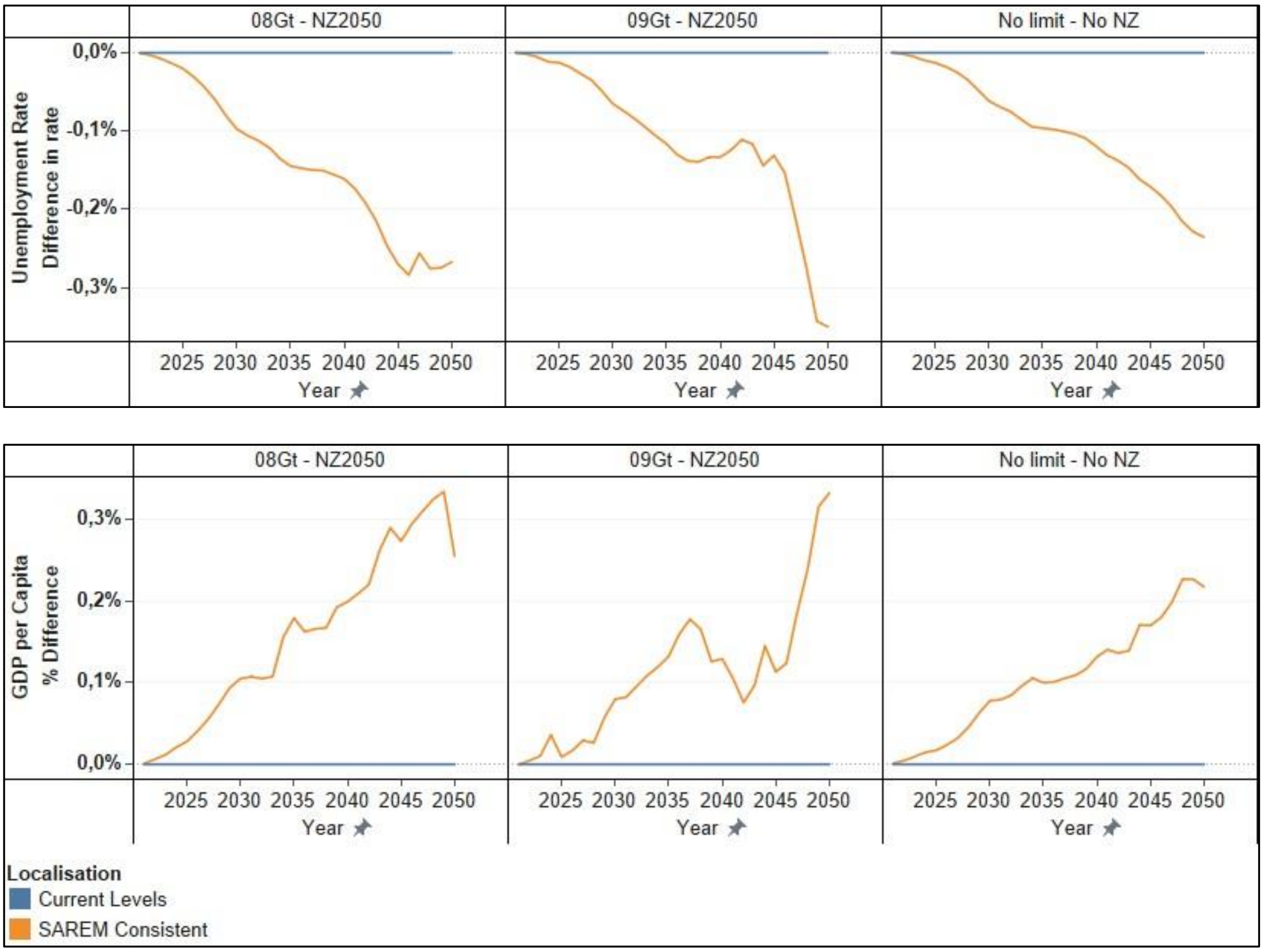

Figure 37: Difference in unemployment and GDP per capita from SAREM consistent localization strategy.

Conclusions

The analysis above of pathways to net zero CO_2 emissions for South Africa reaches some key conclusions and highlights some critical areas for further analysis. In a context in which South Africa is required to develop a long-term mitigation response consistent with the Paris Agreement and its subsequent decisions, and with the complex and urgent development challenges that the country faces, these findings comprise an essential initial evidence base, and provide some key assessments of the socioeconomic implications of different pathways, as well as key findings on sectoral pathways. Areas for further work are outlined below.

A key finding is that a pathway with a cumulative GHG budget of 10 Gt from 2021-2050 which does not reach net zero, results in the same level of GDP growth per capita as a pathway without any further climate policy, and to 2055 avoids 3 Gt of GHG emissions. In other words, while duly noting the massive challenges in implementing the measures necessary to achieve such a pathway, this is a no-regrets option. Further, as the CSIR's companion study to this indicates, there are significant co-benefits to mitigation, which are not included in this economic analysis. More critically, with the right combination of accompanying measures, the analysis indicates that it is possible to increase the GDP/capita by 120%, reach net zero in 2050 and impose a long-term GHG budget of 8 Gt on the economy.

There are also risks associated with delaying mitigation action if net zero CO_2 is to be reached in 2050 or 2055, as reflected in the GHG and CO_2 pathways shown in Figure 3. Pathways with higher GHG limits reaching net zero show very rapid transitions and concomitantly massive investment/infrastructure requirements, especially in the electricity sector, in the years immediately preceding net zero, which may be impossible to achieve. The 9 Gt scenarios show an initially accelerated reduction in emissions which then follow a consistent decline throughout the modelling period, suggesting that initial decarbonisation action with continued consistent effort over time would potentially allow for a smoother transition relative to delayed action now, and very rapid decarbonisation in later years.

Decarbonisation of the electricity sector is key to all net zero pathways: all modelled scenarios that reach net zero CO_2 in 2050 or 2055, with varying GHG constraints, show extensive decarbonisation of the power sector until it reaches net zero CO_2 emissions itself in the years of or immediately prior to the point of reaching net zero economy-wide. Nevertheless a doubling of cumulative investment in the power sector would be required for it to reach net zero CO_2, with investment ramping up significantly in the 'last mile' years. Moreover, decarbonization in other sectors (for instance transport) is dependent on decarbonization in the electricity sector (discussed below). As with previous studies, decarbonization in the electricity sector is driven by diversifying away from coal power at a pace determined either by the carbon tax or the magnitude of the relevant GHG emissions constraint. Net zero budgets for the power sector range from 2Gt to a maximum of 4Gt. There is no coal power generation past any of the net zero years in the net zero scenarios, which would mean the retirement of the whole coal fleet, including Medupi and Kusile, by 2050 (or 2055), in line with Eskom's extant NZ commitment.

The pace of transition in road transport from ICEs to EVs depends largely on the cost and learning rates of electric vehicles and fuel prices. The model results show that, on a least-cost basis, road vehicle stocks shift from ICEs to EVs for both passenger and freight transport irrespective of GHG constraint or net zero target. The modelling analyses showed however that the rate at which this transition takes place is largely determined by how optimistic cost assumptions are for EVs reaching price parity with ICEs. This is a key sensitivity which needs to be explored further, in order to inform further policymaking on measures to support the rollout of EVs in South Africa and manage the just transition in this sector.

Increased electricity use is at the core of the industry transition in net-zero scenarios. Where electricity cannot replace fossil-based carbon fuels and feedstocks, biomass is used to its physical limits, and CCS is deployed to capture much of the remaining CO_2 emissions. Heavy industry will need to rely on new processes and technologies, such as hydrogen for steel production, more efficient chrome smelters utilising biochar, and cement kilns with CCS. These are industries with long investment cycles and long technological lifespans, and thus bear more risk than most other sectors in terms of investment and timing for net zero pathways, globally, and also in South Africa. The rest of industry will shift to technologies using electricity instead of thermal fuels. Owing to the costly nature of using electricity for heat, most of these transitions occur late in the horizon, toward the 2050 or 2055 net zero target, with steeply increasing investment requirements. Energy efficiency thus has a major role, while electricity is still largely coal based, but also in the future where much of industry needs to be electrified.

Pathways reaching net zero CO_2 emissions in this study require up to 40 Mt CO_2 per annum to be absorbed by the land sink or captured and stored by CCS technology. Throughout the study a consistent and conservative estimate of 10 Mt CO_2 is used for the annual land sink. The balance of residual CO_2 after the land sink has been taken into account, up to 30 Mt CO_2 per annum, is accounted for by CCS technology which, as yet, has not been demonstrated at large commercial scale, and for which the feasibility in South Africa at scale has yet to be sufficiently established. Should neither of these options be available in the 2040s and 2050 at the required scale, then reaching net zero CO_2 would require other measures including technologies that are as yet unavailable to mitigate emissions in the relevant sectors, and/or the substitution of goods and services associated with these residual CO_2 emissions.

The "last mile" to net zero CO_2 requires a dramatic ramp-up in investment in the electricity sector and other key sectors, as well as, under the current modelling framework, considerable reliance on emergent technologies such as CCS. As it stands, it would be very difficult for South Africa to fund such measures without considerable international support. This analysis is based on an assumption that there are limits to the availability of foreign capital for infrastructure development in South Africa, and does not consider the potential for climate finance (on concessional terms) to expand the capital supply dramatically, as required. Thus, the results effectively demonstrate the impact of NOT having access to climate finance at scale. Availability of climate finance at the necessary scale could offset the crowding-out effect by the investments requirements of the electricity sector in these scenarios.

Specific policies and measures have a significant impact on economic outcomes, and finding the optimal package is important to a just transition. The carbon tax proposed in the 2022 budget is enough to shift the least cost energy investment to meet a cumulative GHG emissions of the 2050 9Gt net zero scenario without any other policy intervention. This, however, comes at a cost of just over one years' worth of economic growth when foreign aid, green finance and tax revenue recycling are not considered. Localisation has a discernibly positive impact in all scenarios despite the assumption of a 5% premium on the cost of renewable energy technology. The benefits of localization alone; however, are not able to offset negative impacts of the "last mile" of the net zero transition and must be considered with other policy measures. Energy efficiency on the other hand is a critical policy tool that can reduce electricity sector investment requirements, and offset a significant proportion of the 'crowding out' of investment that occurs in most scenarios.

Further work

As highlighted throughout this study, there are a number of areas that would benefit from further research and analysis, given their importance in developing a deeper understanding of the potential characteristics, risks and opportunities of a transition towards a net zero CO_2 economy. Key areas of further work are highlighted below, namely:

- **Financing the transition:** the occurrence of the crowding-out effect in modelling long-term mitigation-focused transitions is a key problem which arises in similar modelling frameworks in different context. More work is required on both long-term economic modelling of such transitions, and also on the impacts of the availability at a much greater scale of climate finance from outside South Africa. In addition, another layer of analysis is necessary to better understand the domestic constraints in financing the massive infrastructure programmes which would be required to implement an ambitious mitigation pathway.
- **Understanding the spatial impacts of policy choices in key sectors**: currently, the modelling framework used in this study does not include spatial disaggregation of South Africa's energy and industrial sectors. However, as the renewable energy sector grows, the location of renewable energy resources and the grid infrastructure to transport renewable electricity to load centres will become a key factor in electricity planning. Similarly, the transition away from fossil-derived liquid fuels has important spatial elements. Additionally, analysing the socioeconomic effects of transitions at regional level would allow deeper insights into risks and opportunities that transitions will pose at provincial or local level, and would inform appropriate policymaking at subnational government level particularly in areas such as Mpumalanga where the effects of the transition will be most apparent.
- **Understanding the mitigation potential and risks of the AFOLU sector:** The land sector will play an important role in any net zero target. There are both risks that the land sector becomes a net CO_2 source, and opportunities for expanding the land sink. Both will have significant impacts on the available CO_2 space in net zero pathways. Similarly, there are few measures currently being contemplated to mitigation GHG emissions from the agriculture sector.
- **Key sector and technology-specific themes to be explored further** include:
  - Price projections and sensitivities for electric vehicles, the effects these have on a transition to EVs from ICEs, and how this transition can effectively be managed in terms of infrastructure roll-out and ensuring a just transition in this sector;
  - Policy complexities related to the coal-to-liquids process in South Africa (currently a large CO_2 emitter), what the options are for decarbonization, and how these would be managed in relation to the supply of basic chemicals, the trade balance, air quality and a declining demand for liquid fuels as the transport sector shifts away from liquid fuels;

    - Availability, feasibility and trade-offs of increased usage of biomass in industry, especially in ferroalloys and pulp and paper production, in terms of understanding limits of and impacts on land use, and how this affects sectoral and national GHG emissions budgets;
    - Feasibility, costs and performance of energy efficiency measures available to all demand sectors, especially the commerce and residential sectors, and on the demand for industrial process heat;
    - Further work on the potential and trade-offs of shifting freight transport from road to rail, and the associated infrastructure requirements;
    - Further work on all the elements of the electricity sector relevant to decarbonization;
    - Further work on adaptation linkages, including increased cooling demand;
- **Integration of energy/economic modelling with findings on the costs of air pollution**: there are technical and conceptual challenges in integrating the findings of the CSIR team on the costs of air pollution into SATIMGE, and an integrated analysis would provide far better insights into the economic impacts of air pollution and avoided costs of ambitious mitigation pathways;
- A more detailed analysis of **the impact of the Treasury's proposed increases in the carbon tax,** including the relationship between these increases and climate-motivated trade measures including the EU's CBAM.
- Further work on **"last mile" technology options and alternatives** (reducing / avoiding goods and services) is necessary, and technology options and costs will develop over time. Furthermore, the potential (scale) and cost of **CCS and CDR (which relies on CCS)** need to be more thoroughly assessed for South Africa.
- Finally **additional work should be undertaken to explore other net zero CO_2 target years**, such as 2060, and potentially to explore whether net zero GHGs may be achievable in future years later this century.

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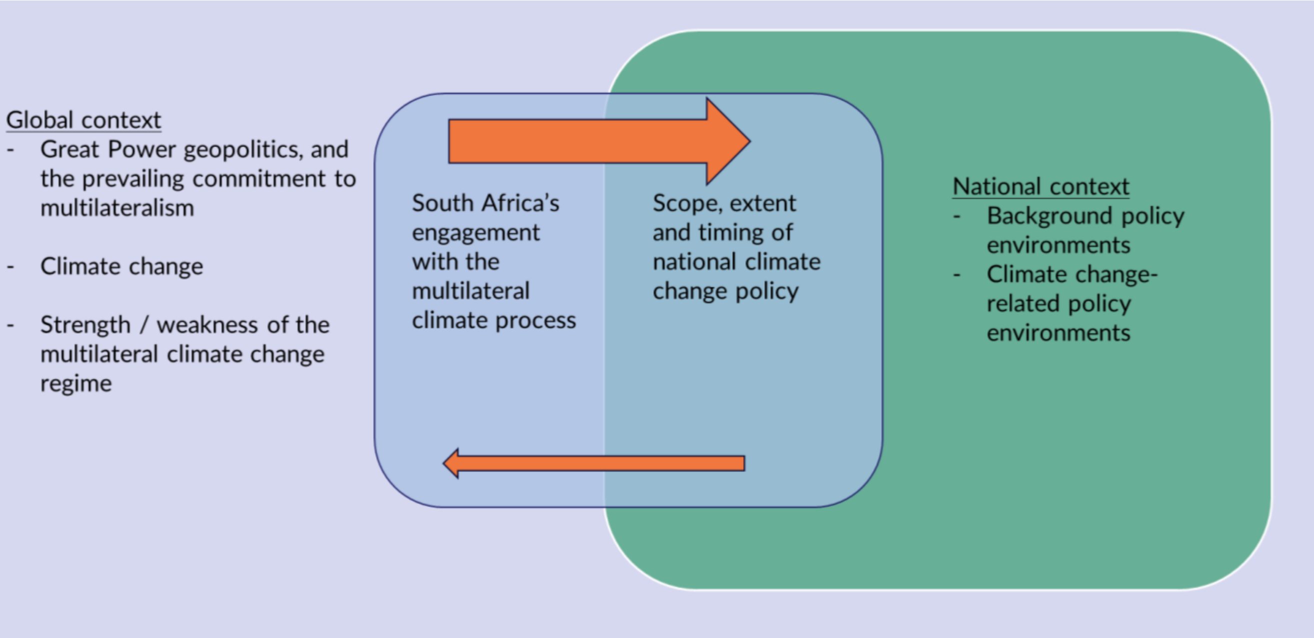
Appendix: Detailed methodology

Scenario descriptions and elements

In analysing long-term potential decarbonisation pathways for South Africa, this study adopts a two-tier approach, in order to unpack the complexities and uncertainties that exist at multiple levels:

1. Global context – developing a framework for navigating different possible pathways for the multilateral climate regime and the consequences
2. National context – assessing how different national policy choices and market developments would position SA within the different global futures, and identifying opportunities and risks.



International Context – Worlds A and B

Two future 'worlds' were conceived to unpack the complexities of potential different international futures, and to contextualise South Africa's emission pathways and policy decisions within two different global mitigation pathways:

- **World A**: a more ambitious climate world with a strong multilateral rules-based regime, with stricter policies on carbon-intensive trade, a more rapid transition to EVs, reduced demand for fossil fuels and a greater market for 'green' export trade, and greater climate support for developing countries
- **World B**: a more divergent climate world, with a slower transition to clean fuels, products and technologies, and more limited or no support to developing countries. This world comes with high risks that SA and other developing countries will be subject to greater pressure to mitigate than in World A.

Distinctions between these two worlds were quantified as follows:

World	Fossil fuel projections	EV price projections	CBAM	Green exports
A	Lower demand – IEA NZE price	IEA NZE (faster learning)	Full price ramp-up (2021 – 2055)	Available (applied as a sensitivity in some cases)
B	Higher demand – IEA APS prices	IEA APS (slower learning)	Partial price ramp-up (2021 – 2034)	Not available

IEA NZE and IEA APS prices for fossil fuels refers to projections found in the latest (2023) version of the International Energy Agency's World Energy Outlook publication (IEA, 2023).

The Carbon Border Adjustment Mechanism is applied as follows, informed by analysis on its implementation and effects on South African trade:

- A penalty cost is applied to all CBAM commodities in the CGE model. These commodities include chemicals such as hydrogen and ammonia, plastics, cement, aluminium and iron and steel.
- The penalty cost is then ramped differently into future years according to two projections
- In World A, the cost is ramped up in line with the full CBAM projection of up to EUR 240 per tCO_2 by 2050 (see below).
- In World B, the cost is ramped up to 2034, and then capped at a constant rate, in line with the projected CBAM cost of EUR 100 per tCO_2 (see below).

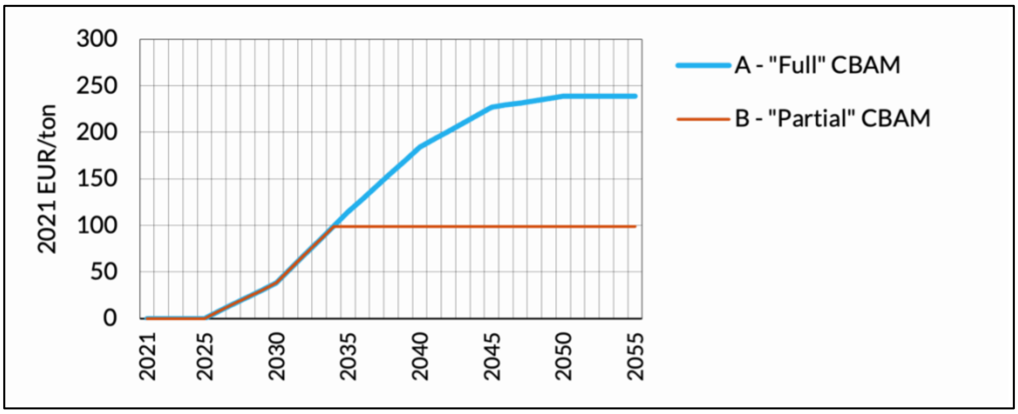


Figure 38: CBAM implementation in the model.

National scenario elements

The key uncertainty in the context of South Africa's transition to net zero CO_2 arising from an uncertain global future is the extent of 'pressure' that would be applied, economically and politically, to decarbonise, and this translates nationally into the 'pace' at which transitions take place, especially in energy, transport and industry sectors, the availability of finance to support these transitions, and the extent to which they can support and drive socio-economic development (or, alternatively, the opportunity costs of the transition and/or crowding out of investment elsewhere in the economy and society). In this light, this study considers three groups of scenarios that frame net zero pathway analysis, with key variables for which sensitivity analysis would be conducted across scenarios. These include:

- Year in which net zero CO_2 is reached –this study examines net zero years of 2050, 2055 and not being reached; in further work, 2060 may also be considered as a potential net zero target year
- Cumulative GHG budget, which in this study is applied as a proxy for international pressure as outlined above. In this study, cumulative GHG constraints (in $GtCO_2$-eq) are applied for the period 2021 – 2050, of 8, 9, 10 and 11 Gt CO_2-eq, and these are contrasted with unconstrained (unlimited) runs
- Energy efficiency: cases are modelled with or without the achievement of improvement of energy efficiency in demand sectors (transport, industry, commerce and residential). Cases with energy efficiency are based on partial achievement of draft 2015 NEES targets in industry and commerce, improvements in residential energy efficiency based on ESRG/SANEDI data (report under review), and partial mode switching (private-to-public and road-to-rail) in land transport (Ahjum et al, 2020).
- Liquid fuels supply: all cases assume that existing domestic crude refining capacity will close in 2034 and not be replace. For coal-to-liquids (CTL) refining, most cases assume default projection of CTL production in line with the plan outlined in Sasol Climate Change Report 2023 (Sasol, 2023). A couple of sensitivity cases are also run, by (1) allowing the model to endogenously retire CTL units on a least-cost basis from 2035 ("early") and (2) forcing CTL units and activity to remain online until 2045, followed by a linear ramp down to 2050 ("late")
- South Africa's domestic carbon tax is modelled at the current levels, equivalent to R120 per tonne with existing allowances, and at higher levels ramped up to ~$120 per tonne by 2050, as per the tax proposal contained in the 2022 National Budget Review (National Treasurey, 2022).
- Localisation: Cases modelled with existing local content requirements and policies ("current levels") or adjusted to meet levels as per the draft South African Renewable Energy Masterplan 2022 ("SAREM consistent"); the latter are modelled with a localisation price premium of 5%, implemented on a gradual basis from 2020 – 2050
- Green export availability is only modelled as a sensitivity in selected World A cases; it is assumed green exports would not be available in World B

Variations of national scenario parameters are summarised below:

Parameter	Values
World	A, B (see International context above)
Net zero CO2 year	2050, 2055 and not reached
GHG limit (2021-50) [GtCO2-eq]	8, 9, 10, 11 and unlimited

Energy Efficiency	Adjusted NEES (see above) and not achieved
CTL	Sasol Plan, Early and late (see above)
Green exports	Yes or No
SA carbon tax	Current or High
Localisation	Current levels or reaching draft SAREM targets

Full scenario matrix

Scenario name	World	GHG limit (2021-50)	NZ CO_2 Year	Efficiency	CTL	Exports	CO2Tax	Localisation	ECoalRefurbish	CCS
A - 08Gt - NZ2050 - EE	A	08 Gt	NZ 2050	EE	PlannedPhaseOut	NoGreenExprts	Current Carbon Tax	CurrentLevels	EndogenousRefurbish	WithCCS
A - 08Gt - NZ2050 - EE - SAREM Loc	A	08 Gt	NZ 2050	EE	PlannedPhaseOut	NoGreenExprts	Current Carbon Tax	SAREMConsistent	EndogenousRefurbish	WithCCS
A - 09Gt - NZ2050 - EE - Early CTL - SAREM Loc	A	09 Gt	NZ 2050	EE	EarlyRetirement	NoGreenExprts	Current Carbon Tax	SAREMConsistent	EndogenousRefurbish	WithCCS
A - 09Gt - NZ2050 - EE - Delay CTL - SAREM Loc	A	09 Gt	NZ 2050	EE	DelayedPhaseOut	NoGreenExprts	Current Carbon Tax	SAREMConsistent	EndogenousRefurbish	WithCCS
A - 09Gt - NZ2050 - EE - GreenXpts - High C Tax - SAREM Loc	A	09 Gt	NZ 2050	EE	PlannedPhaseOut	GreenExprts	High Carbon Tax	SAREMConsistent	EndogenousRefurbish	WithCCS
A - 09Gt - NZ2050 - EE - GreenXpts - SAREM Loc	A	09 Gt	NZ 2050	EE	PlannedPhaseOut	GreenExprts	Current Carbon Tax	SAREMConsistent	EndogenousRefurbish	WithCCS
A - 09Gt - NZ2050 - EE	A	09 Gt	NZ 2050	EE	PlannedPhaseOut	NoGreenExprts	Current Carbon Tax	CurrentLevels	EndogenousRefurbish	WithCCS
A - 09Gt - NZ2050 - EE - SAREM Loc	A	09 Gt	NZ 2050	EE	PlannedPhaseOut	NoGreenExprts	Current Carbon Tax	SAREMConsistent	EndogenousRefurbish	WithCCS
A - 09Gt - NZ2050 - EE - SAREM Loc - No CCS	A	09 Gt	NZ 2050	EE	PlannedPhaseOut	NoGreenExprts	Current Carbon Tax	SAREMConsistent	EndogenousRefurbish	NoCCS
A - 09Gt - NZ2050 - GreenXpts - High C Tax	A	09 Gt	NZ 2050	NoEE	PlannedPhaseOut	GreenExprts	High Carbon Tax	CurrentLevels	EndogenousRefurbish	WithCCS
A - 09Gt - NZ2050 - SAREM Loc	A	09 Gt	NZ 2050	NoEE	PlannedPhaseOut	NoGreenExprts	Current Carbon Tax	SAREMConsistent	EndogenousRefurbish	WithCCS
A - 11Gt - NZ2050 - EE - SAREM Loc	A	11 Gt	NZ 2050	EE	PlannedPhaseOut	NoGreenExprts	Current Carbon Tax	SAREMConsistent	EndogenousRefurbish	WithCCS
A - No limit - NZ2050 - EE - SAREM Loc	A	No limit	NZ 2050	EE	PlannedPhaseOut	NoGreenExprts	Current Carbon Tax	SAREMConsistent	EndogenousRefurbish	WithCCS
B - 09Gt - NZ2050 - EE - Early CTL - SAREM Loc	B	09 Gt	NZ 2050	EE	EarlyRetirement	NoGreenExprts	Current Carbon Tax	SAREMConsistent	EndogenousRefurbish	WithCCS
B - 09Gt - NZ2050 - EE - Delay CTL - SAREM Loc	B	09 Gt	NZ 2050	EE	DelayedPhaseOut	NoGreenExprts	Current Carbon Tax	SAREMConsistent	EndogenousRefurbish	WithCCS
B - 09Gt - NZ2050 - EE - GreenXpts - High C Tax - SAREM Loc	B	09 Gt	NZ 2050	EE	PlannedPhaseOut	GreenExprts	High Carbon Tax	SAREMConsistent	EndogenousRefurbish	WithCCS
B - 09Gt - NZ2050 - High C Tax - SAREM Loc	B	09 Gt	NZ 2050	EE	PlannedPhaseOut	NoGreenExprts	High Carbon Tax	SAREMConsistent	EndogenousRefurbish	WithCCS
B - 09Gt - NZ2050 - EE - SAREM Loc	B	09 Gt	NZ 2050	EE	PlannedPhaseOut	NoGreenExprts	Current Carbon Tax	SAREMConsistent	EndogenousRefurbish	WithCCS
B - 09Gt - NZ2050	B	09 Gt	NZ 2050	NoEE	PlannedPhaseOut	NoGreenExprts	Current Carbon Tax	CurrentLevels	EndogenousRefurbish	WithCCS
B - 11Gt - NZ2050 - EE - High C Tax - SAREM Loc	B	11 Gt	NZ 2050	EE	PlannedPhaseOut	NoGreenExprts	High Carbon Tax	SAREMConsistent	EndogenousRefurbish	WithCCS
A - 09Gt - NZ2055 - EE - SAREM Loc	A	09 Gt	NZ 2055	EE	PlannedPhaseOut	NoGreenExprts	Current Carbon Tax	SAREMConsistent	EndogenousRefurbish	WithCCS
A - 10Gt - NZ2055 - EE - GreenXpts - SAREM Loc	A	10 Gt	NZ 2055	EE	PlannedPhaseOut	GreenExprts	Current Carbon Tax	SAREMConsistent	EndogenousRefurbish	WithCCS
A - 10Gt - NZ 2055 - EE - SAREM Loc	A	10 Gt	NZ 2055	EE	PlannedPhaseOut	NoGreenExprts	Current Carbon Tax	SAREMConsistent	EndogenousRefurbish	WithCCS
A - 11Gt - NZ2055 - EE - SAREM Loc	A	11 Gt	NZ 2055	EE	PlannedPhaseOut	NoGreenExprts	Current Carbon Tax	SAREMConsistent	EndogenousRefurbish	WithCCS
A - No limit - NZ2055 - EE - SAREM Loc	A	No limit	NZ 2055	EE	PlannedPhaseOut	NoGreenExprts	Current Carbon Tax	SAREMConsistent	EndogenousRefurbish	WithCCS
B - 09Gt - NZ2055 - EE - SAREM Loc	B	09 Gt	NZ 2055	EE	PlannedPhaseOut	NoGreenExprts	Current Carbon Tax	SAREMConsistent	EndogenousRefurbish	WithCCS
B - 10Gt - NZ2055 - EE - SAREM Loc	B	10 Gt	NZ 2055	EE	PlannedPhaseOut	NoGreenExprts	Current Carbon Tax	SAREMConsistent	EndogenousRefurbish	WithCCS
B - No limit - NZ2055 - EE - SAREM Loc	B	No limit	NZ 2055	EE	PlannedPhaseOut	NoGreenExprts	Current Carbon Tax	SAREMConsistent	EndogenousRefurbish	WithCCS
A - 10Gt - No NZ - EE - GreenXpts - SAREM Loc	A	10 Gt	No NZ	EE	PlannedPhaseOut	GreenExprts	Current Carbon Tax	SAREMConsistent	EndogenousRefurbish	WithCCS
A - 10Gt - No NZ - EE - SAREM Loc	A	10 Gt	No NZ	EE	PlannedPhaseOut	NoGreenExprts	Current Carbon Tax	SAREMConsistent	EndogenousRefurbish	WithCCS
A - No limit - No NZ - EE - High C Tax - SAREM Loc	A	No limit	No NZ	EE	PlannedPhaseOut	NoGreenExprts	High Carbon Tax	SAREMConsistent	EndogenousRefurbish	WithCCS
A - No limit - No NZ - EE	A	No limit	No NZ	EE	PlannedPhaseOut	NoGreenExprts	Current Carbon Tax	CurrentLevels	EndogenousRefurbish	WithCCS
A - No limit - No NZ - EE - SAREM Loc	A	No limit	No NZ	EE	PlannedPhaseOut	NoGreenExprts	Current Carbon Tax	SAREMConsistent	EndogenousRefurbish	WithCCS
A - No limit - No NZ - EE - SAREM Loc - Force Refurb	A	No limit	No NZ	EE	PlannedPhaseOut	NoGreenExprts	Current Carbon Tax	SAREMConsistent	ForcedRefurbish	WithCCS
A - No limit - No NZ - High C Tax - SAREM Loc	A	No limit	No NZ	NoEE	PlannedPhaseOut	NoGreenExprts	High Carbon Tax	SAREMConsistent	EndogenousRefurbish	WithCCS
A - No Limit - No NZ	A	No limit	No NZ	NoEE	PlannedPhaseOut	NoGreenExprts	Current Carbon Tax	CurrentLevels	EndogenousRefurbish	WithCCS
B - 10Gt - No Nz - EE - SAREM Loc	B	10 Gt	No NZ	EE	PlannedPhaseOut	NoGreenExprts	Current Carbon Tax	SAREMConsistent	EndogenousRefurbish	WithCCS
B - No limit - No NZ - EE - High C Tax - SAREM Loc	B	No limit	No NZ	EE	PlannedPhaseOut	NoGreenExprts	High Carbon Tax	SAREMConsistent	EndogenousRefurbish	WithCCS
B - No limit - No NZ	B	No limit	No NZ	NoEE	PlannedPhaseOut	NoGreenExprts	Current Carbon Tax	CurrentLevels	EndogenousRefurbish	WithCCS
B - No limit - No NZ - No Refurb	B	No limit	No NZ	NoEE	PlannedPhaseOut	NoGreenExprts	Current Carbon Tax	CurrentLevels	NoRefurbish	WithCCS

SATIMGE Modelling

The SATIMGE modelling framework consists of an energy model – SATIM – and an economy-wide CGE model – SAGE – which are then linked and solved iteratively, to show how shifts in the annual energy balance, solved on a system least-cost basis within various GHG, technological and other constraints and assumptions, cause shifts in the annual economic balance, which in turn causes the cost-optimal annual energy balance to shift, and so the iterative cycle repeats. These models are described briefly below.

SATIM - South African TIMES Model

The South African Times Model – SATIM – is a full sector, national energy system, least cost optimisation model for the South African energy system that can be applied to the planning problem of meeting projected future energy demand given assumptions such as the retirement schedule of existing infrastructure, future fuel costs, future technology costs, learning rates, and efficiency improvements, as well as any constraints such as the availability of resources, including the setting of economy-wide GHG emissions targets. SATIM (being a full sector model) differs from sector specific models such as PLEXOS, in that all energy commodities and their full supply chains are considered, and demand for energy services (e.g., process heat, mobility) is specified rather than the demand for the commodities themselves.

SATIM is a single region, multi-sector, multi-period, bottom up (end use) TIMES model. It captures the full economy and its energy related emissions (including NO_X, SO_X, CO_2, CH_4, N_2O, PM10 and others), allowing the modelling of carbon taxes and carbon budgets in addition to energy supply, demand, resource utilisation, imports and exports.

Within SATIM there are three supply sectors (electricity, liquid fuels (including biomass and hydrogen), coal and gas supply) and five demand sectors (industry, agriculture, residential, commercial, and transport). Each sector is further disaggregated into subsectors as appropriate. By including a detailed representation of both the supply and demand sectors in SATIM it is possible to explicitly capture the impact of demand side changes, such as structural changes in the economy (i.e., different sectors growing at different rates), process changes, fuel and mode switching, technology change and efficiency gains in the supply side optimisation. It also allows energy sector emissions to be captured in full and allowing combined supply and demand side targets to be set.

Each demand sector within SATIM is governed by a number of parameters and general assumptions relating to (a) the structure of the sector and its energy service needs; (b) the base year demand for energy by fuel type; (c) technical and cost parameters of the technologies available to satisfy the demand for energy services in the base year and over the model horizon and; (d) the demand for energy services over the planning horizon.

SATIM uses intra year (temporal – i.e., seasonal/diurnal) disaggregation into time-slices to model typical energy service load profiles for electricity use and RE resource availability for winter and summer. By default, the load profiles include a morning and evening peak and late night time period with lower average demand. Due to the increased computational time needed with increased temporal resolution, SATIM has been developed to easily accommodate different temporal disaggregation's, in order to accommodate a range of research questions.

SAGE - South African General Equilibrium model

SAGE is a dynamic recursive computable general equilibrium (CGE) model built on the framework from Diao and Thurlow (2012). It is an economy-wide model calibrated in the base year to data from a social accounting matrix. Social accounting matrices are datasets which capture all transactions and transfers between different production activities, factors of production, and institutions (households, corporate sector, and government) within the economy and with respect to the rest of the world for in given year thus capturing all market linkages within a country. The model is based on microeconomic theory with the interactions of economic agents mediated via prices and markets. Closure conditions ensure that macroeconomic and resource constraints are respected.

The version of SAGE used in this analysis uses an enhanced version 2019 social accounting matrix (SAM) for South Africa, developed by Davies and van Seventer (2020), to inform the underlying structure of the economy in the base year. The SAM is enhanced by disaggregating the agriculture, mining, and energy sectors. The agriculture sector is disaggregated to reflect different crop activities and linked to food processing sub-sectors to capture respective food value chains. The underlying data used to inform the disaggregation is Phoofolo (2018). Mining and energy sectors are disaggregated to align with SATIM sub-sectors using energy and industry data. The SAM is hybridised with the same energy data underlying the SATIM model to ensure that the models are aligned. A key feature of the eSAGE model used in SATIMGE is the behaviour of household consumption over time. Most CGE models assume a Linear Expenditure System for household expenditure. eSAGE takes a Cobb-Douglas approach, changing consumption shares over time in response to changes in household incomes to account for changes in living standards. For example, if incomes in the poorest 10% of households increase to the level of the poorest 20% the consumption shares are adjusted to reflect the profile of households in the poorest 20%. Such an evolution in household consumption is better suited for long term analysis as it better captures the "welfare-enhancing feature of modern economic development" (Chai, 2018). Such an approach is also important for understanding household energy needs as fuel demands evolve with lifestyle changes. More detail on this approach can be found in Merven, Hartley and Schers (2020c).