ENERGY SYSTEMS RESEARCH GROUP
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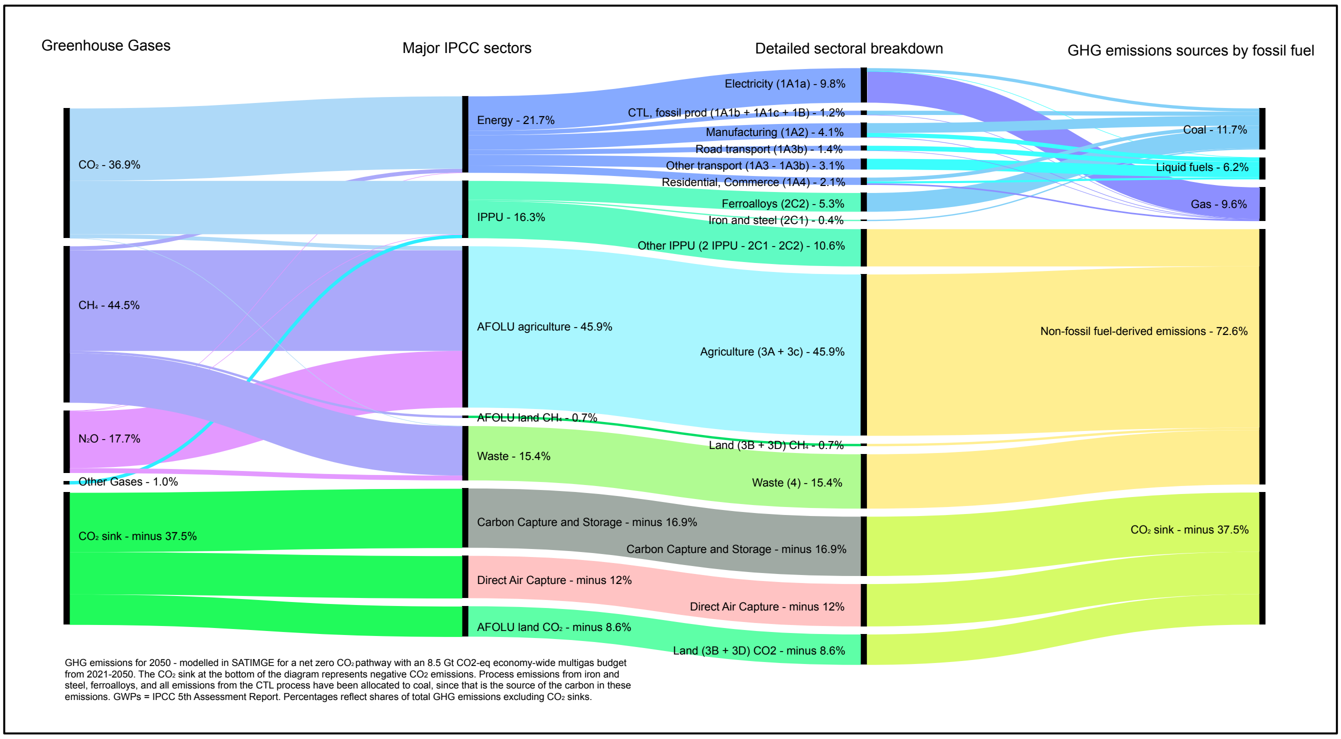
Exploring net zero pathways for South Africa

An initial study



GHG emissions for 2050 - modelled in SATIMGE for a net zero CO_2 pathway with an 8.5 Gt CO2-eq economy-wide multigas budget from 2021-2050. The CO_2 sink at the bottom of the diagram represents negative CO_2 emissions. Process emissions from iron and steel, ferroalloys, and all emissions from the CTL process have been allocated to coal, since that is the source of the carbon in these emissions. GWPs = IPCC 5th Assessment Report. Percentages reflect shares of total GHG emissions excluding CO_2 sinks.

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Executive summary

The following study was undertaken as an extension of the analytical work that informed the update of South Africa's NDC in 2021, with the goal of undertaking some initial analysis on the options for, and implications of, a greenhouse gas emissions pathways to net zero CO_2 emissions in 2050, to inform further, more detailed work on net zero CO_2 pathways. This is primarily a techno-economic study, as a basis for more detailed scenario analysis. The study does not assess in any detail the required policies and measures, or the many other factors relevant to a low emissions development strategy. The results are focused on the techno-economic changes which will be required in the economy to meet such a goal.

Recent IPCC assessments (the Special Report on 1.5 Degree C, and the Sixth Assessment Report) highlight the very significant additional impacts to people and ecosystems, and especially to vulnerable developing countries (including African countries), of global warming beyond 1.5 degrees, proving strong scientific support for global climate action to prevent warming beyond 1.5 degrees.

The global net zero CO_2 goal, by 2050 or beyond, is derived from this scientific assessment (in the IPCC's Special Report on 1.5°C, and its 6th Assessment Report)**, of what will be necessary globally to stay within 1.5°C of global warming to 2100**. This further qualifies the provisions of the Paris Agreement concerning long-term low GHG emissions development strategies, and this was recognised at COP 26 in Glasgow. Thus both South Africa's successive NDC targets, and its long term low-emissions development strategy, will be assessed in this context in terms of a fair contribution to the global mitigation effort, taking into account common but differentiated responsibility and respective capabilities of developed and developing countries, in the light of national circumstances.

Modelled global mitigation pathways which will meet this goal halve CO_2 emissions by 2030, and reach net zero CO_2 emissions around 2050, and in all cases feature negative CO_2 emissions after this (meaning absorption by natural carbon sinks, or CO_2 removal in other ways). While the Paris Agreement is very clear in its Article 2.2 that it will be implemented "to reflect equity and the principle of common but differentiated responsibilities and respective capabilities, in the light of different national circumstances" and Article 4.5 which stipulates that developing countries will be provided with support to implement mitigation targets, within this context all countries, as appropriate, will be required to undertake very ambitious GHG emissions reductions to 2050. Global pathways to net zero all feature very steep CO_2 emissions reductions over the next three decades, and deep reductions in non-CO_2 greenhouse gases.

Cutting global CO_2 emissions rapidly and dramatically in the next decade is required to remain within 1.5 degrees C, as well as reaching net zero CO_2 emissions around 2050. Countries have been urged by both the COP decisions from Glasgow and from Sharm El-Sheikh to consider this. This also has very significant equity implications.

Like other developing countries, South Africa's low emissions pathway must contribute to this global outcome, taking into account the country's status as a developing country, the country's specific development challenges, and other relevant national circumstances. A range of cumulative GHG emissions over the modelled period were derived for this study on the basis of a survey of existing literature on burden-sharing in the context of a 1.5°C global emissions pathway.

The GHG emissions pathways to net zero modelled here therefore have two characteristics:

> **1. CO_2 emissions will reach net zero in 2050. It is assumed here that land sector emissions will be between minus 10 and minus 45 Mt CO_2-eq in 2050 – in other words a CO_2 sink – and the remaining CO_2 emissions in the economy will be equal or less than the CO_2 absorbed in the land sector.**
>
> **2. total GHG emissions from 2021-2050 will be within a rage from 6-9 Mt CO_2-eq, which represents a "fair share range" for South Africa derived from different studies.**

In addition, cases were modelled with and without currently planned climate mitigation policies and measures, with and without new green export industries (iron and steel, ammonia), with two economic growth rates, and two variations on the land sink (currently estimated to be around 10 Mt/annum) – -20 Mt by 2050, and 45 Mt by 2050. No use of Article 6 (international emissions trading) was modelled; i.e. it was assumed that this target will be met nationally only. In all 64 cases were modelled. Cases which are consistent with the 2030 NDC target range were NOT explicitly modelled, and electricity supply policy in the form of the IRP 2019 was also not explicitly modelled.

CO_2 comprised 82% of South Africa's GHG emissions in 2021 (Figure 7). **80% of these CO_2 emissions derive from coal**, and 17% from liquid fuels combustion (including some liquid fuels manufactured from coal). **The electricity sector accounts for 54% of CO_2 emitted annually** (Figure 8)**, followed by road transport (14%), liquid fuels manufacture (13%), and the industrial sector (8% combustion only, 15% with industrial process emissions)**. **Any net zero CO_2 pathway will need to be focused primarily on these sectors, and on the transition away from coal.**

In the baseline scenario (without any additional policies and measures, and without any GHG or CO_2 constraint), **GHG emissions decline by about 130 Mt CO_2-eq by 2050** – mainly as a result of a slow transition from coal power to renewable energy in the electricity sector, and a partial shift away from internal combustion engines in the transport sector, leading to reduced output in national liquid fuels supply and its associated GHG emissions. **With a net zero CO_2 target by 2050, CO_2 emissions diverge from the baseline scenario from 2035**, and electricity demand increases rapidly relative to the baseline by the need for hydrogen to decarbonize other sectors, and additional electric mobility. This results in a massive investment spike in the electricity sector after 2045 – between 30 and 45 GW of new capacity is added each year by 2050 (Figure 18). This has the result of reducing cumulative GHG emissions (2021-50) from 11.6 Gt in the baseline, to 10.2 Gt and 9.5 Gt for the 20 Mt land sink and 45 Mt land sink cases. However, **a CO_2 target for 2050 ONLY results in the implausible acceleration of investment in the electricity and other sectors in a very short interval** (Figure 33); investment requirements are more than 400% higher in the last five years to 2050. Staggering these investments, i.e. **a faster, earlier transition will be required to reach net zero CO_2 in 2050**. Moreover only one of these pathways reaches the NDC 2030 target range. In addition there is some GDP loss by 2050 on account of the crowding-out effect caused by the dramatic investment spike in the last five years.

Adding a GHG emissions budget (6-9 Gt CO2-eq from 2021-50) for the whole period results in a far earlier transition (Figure 36), with the majority of the additional mitigation still coming from the electricity sector, in both relative and absolute terms (Figure 61), with important but smaller contributions from the IPPU sector. **The "last mile" decarbonization depends for some remaining CO_2 emissions on carbon capture and storage, which may not be available at this scale**, which stores around 30 Mt per year in cement, ferroalloys and the power sector (gas). Crowding-out effects result in a smaller economy in 2050 in the most ambitious cases (6 Gt), and less in the others; this is partially or wholly offset by (a) implementing demand-side policies, and (b) developing export industries. This could be further offset if South Africa has access to concessional international climate finance at scale over the next 30 years. **An addition of demand-side measures, coupled with green exports, results in a larger economy in 2050 than the in the reference case**, **even with a GHG emissions constraint of 7 Gt.**

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1. Introduction

In the wake of recent scientific, policy and legal developments in the international climate change regime, the concept of "net zero" as a climate change mitigation goal for countries, sub-national entities, sectors, firms and other non-state actors has become ubiquitous, and has been given additional impetus by the outcomes of COP 26 in Glasgow. The goal of reaching net zero emissions is increasingly associated with mitigation pathways "compatible" with the Paris Agreement (UNFCCC, 2015), specified in the long term global goal for mitigation in Article 4.1, and consistent with pursuing efforts to keep global warming within 1.5 degrees C (Article 2.1 a).

Almost all major economies (Meinshausen et al., 2022), and many others (van Soest et al., 2021), as well as many businesses, cities and other entities and organisations (Net Zero Tracker, 2022), have announced net zero emission pledges or targets. These have reflected a wide variance of what a net zero emissions target actually means, as well as when this target should be reached and how firmly the target is contained in policy and/or legislation.

South Africa made an aspirational commitment of "ultimately moving towards a goal of net zero carbon emissions by 2050" in its inaugural 2050 Low-Emission Development Strategy under Article 4.19 of the Paris Agreement (LEDS, South Africa, 2020), repeated this pledge in its updated NDC (South Africa, 2021), and clearly specified a long-term net zero goal in the Just Transition Framework: "A just transition aims to achieve a quality life for all South Africans, in the context of increasing the ability to adapt to the adverse impacts of climate, fostering climate resilience, and reaching net-zero greenhouse gas emissions[1] by 2050, in line with best available science" (PCC, 2022a)[2].The national utility, Eskom, has committed to net zero CO_2 by 2050 (Ramaphosa 2021).

So far, formally, South Africa has not gone beyond the aspirational goal specified in the LEDS, and the long-term "peak, plateau and decline" (PPD) trajectory, specified in the country's 2011 National Climate Change Response Policy (DEA, 2011) and included under Schedule 3 of the draft Climate Change Bill (described as the "Interim National Greenhouse Gas Emissions Trajectory", DFFE, 2022b), remains the country's long-term benchmark emissions trajectory and official policy. The PPD does not reach net zero CO_2 or GHG emissions at any point, and is not consistent with the updated NDC[3]. The DFFE have indicated their intention to update this benchmark range when the Climate Change Bill, currently before parliament, becomes law (DFFE, 2022a). It is therefore very likely that South Africa will more formally adopt a long-term net zero goal in the near future, and the details and implications of this need to be more clearly understood.

This study provides an initial exploratory modelling analysis, through comparison and evaluation of multiple modelled scenarios, of what a net-zero economy could look like in South Africa in 2050, and what potential pathways there may be towards such an economy, characterised in a range of dimensions including:

- What the GHG, CO_2 emissions profile and energy production and use profile is now and what it would look like in 2050;
- What transitions this will involve and when these would occur, in emissions-related sectors of the economy;
- What the socio-economic impacts of these transitions would be.

The goal of the study is to conduct an initial mapping exercise as a prelude to more detailed work on net zero emissions pathways that will be undertaken after this, by the ESRG team and others. The study is NOT intended as a detailed or exhaustive study of net zero pathways for South Africa and, as well as reporting on its results, it highlights a long list of areas for further work. The study also does not assess in any detail what policies and measures will be required to achieve a net zero outcome in 2050. The precise characteristics of the net zero target which is assessed here are described more below, but in summary, it has the following characteristics:

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[1] The current draft on the PCC's website contains the more ambitious net zero GHG emissions target, whereas the version approved by Cabinet contains a net zero target for CO_2 only.

[2] The Just Transition Framework was completed by the Presidential Climate Commission and communicated to the President for approval by the Cabinet on 23 June 2022 (PCC, 2022b).

[3] The updated NDC contains a target range for 2030, with the lower end pf the target range below the lower point of the PPD trajectory in 2030.

- Achieving net zero CO_2 emissions in 2050, i.e. annual CO_2 emissions as accounted for in South Africa's GHG inventory will be net zero.
- "net zero" in this context means a balance between CO_2 sources and sinks in the target year (2050), and it is assumed here that CO_2 emissions will be accounted for as in the national GHG inventory – this therefore excludes CO_2 emissions from international aviation and shipping.
- This also excludes any offsetting of CO_2 emissions by purchasing internationally transferred mitigation outcomes in terms of Article 6 of the Paris Agreement – i.e. it is assumed here that the target would be reached by domestic reductions alone.
- This net zero CO_2 target would be accompanied by NDC targets every five years, including the current targets for 2025 and 2030. It is assumed in this study that these would be formulated on the same basis as the current NDC targets, i.e. cover all sectors and all gases, and would constitute South Africa's fair contribution to the global mitigation effort. The impact of medium term targets constituting South Africa's fair share has been quantified here by a cumulative GHG emissions budget over the period 2021-2050.

The study has been undertaken using the SATIMGE modelling framework, which is an economy-wide energy/emissions/economy modelling framework comprising an energy model (SATIM), an economic model (ESAGE), and linked AFOLU and waste models, which were also used for the technical analysis supporting South Africa's NDC update (ESRG, 2021; Marquard et al., 2021). An initial discussion of the international scientific, legal and policy context (including South Africa's legal obligations in terms of the UNFCCC and its Paris Agreement) is followed by a methodological outline, a focus on the specific challenge of a net zero CO_2 target, and a detailed description and analysis of the results of the modelling. Finally, key areas for further work are outlined in the conclusion. The Annex contains a detailed account of modelled cases.

2. International scientific, legal and policy context

Net zero pathways have their source in the confluence of several different developments in the international climate change regime. The "net" in net zero is derived from the fact that it is possible to remove CO_2 from the atmosphere, either via natural processes (absorption by land or ocean sinks) or artificially (by direct air capture of CO_2 and its permanent storage). It is not technically feasible to remove other (non-CO_2) GHGs from the atmosphere at present[4]; in addition, most other anthropogenic GHGs which are emitted in significant quantities have relatively short residence times in the atmosphere compared to CO_2. The concept of net zero emissions of CO_2 measured over a specific short time interval (in almost all instances, one year) is clear from a physical science perspective – anthropogenic sources of CO_2 must balance absorption of CO_2 by sinks during the applicable time interval, using a specific accounting approach.

The specification of a net zero GHG emissions target (which covers more GHGs than just CO_2) requires an extra step. Different GHGs have significantly different global warming impacts both because these react differently to infrared radiation, and because these have different residence times in the atmosphere. For policy purposes, the impact of different gases is equated using a "common metric". Common metrics are coefficients which equate the impact of the emissions of one unit of a non-CO_2 GHG with one unit of CO_2. These metrics can vary considerably, depending on the time horizon considered and on other factors. The current metric which Parties to the UNFCCC and its Paris Agreement are required to use is the Global Warming Potential over a 100-year period of other gases compared to CO_2 by mass[5]. GWP values for other gases are estimated by the IPCC in every new cycle of IPCC assessment reports – see e.g. Working Group I's contribution to the 6th Assessment Report (Forster et al., 2021) – and, in terms of reporting under the Paris Agreement (including NDCs), it was agreed that GWP_{100} values from the 5th Assessment Report , (IPCC, 2014) (UNFCCC 2018 , decision 18/CMA.1) must be used by all Parties in estimating their GHG emissions in their national inventory reports[6].

The concept of "net zero GHGs" entails balancing the total CO_2-eq quantity of GHGs emitted in a specific time period with the removal of an equivalent (in CO_2-eq terms) amount of CO_2. Some countries have put forward net zero GHG targets, which are far more ambitious than net zero CO_2 targets due to the need to balance all GHG emissions with CO_2 removal, which is currently very challenging for hard-to-abate non-CO_2 GHG emissions such as those from agriculture and cement.

There are three contexts, as referred to above, which are centrally important in assessing the implications of net zero pathways.

The first is the scientific context, which is provided most succinctly, and with the most policy relevance, by the IPCC's Special Report on 1.5 Degrees C, and the IPCC's 6th Assessment Report (working groups 1 and 3). The second and the third contexts are the international legal and policy contexts. The legal context is provided by the UNFCCC and specifically its Paris Agreement and associated decisions[7], which provide the normative and institutional framework for the evolution of international climate policy, which occurs formally via decisions of the CMA[8], and informally via a number of other climate-related multilateral and minilateral engagements[9]. The

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[4] There is initial technical work on the possibility of artificially removing methane from the atmosphere using zeolites (https://news.mit.edu/2022/dirt-cheap-solution-common-clay-materials-may-help-curb-methane-emissions).

[5] The 100-year GWP of a non-CO_2 gas is defined as the mass of CO_2 which would be result in the same warming as one unit of that gas over a 100-year period. Since e.g. methane is comparatively short-lived in the atmosphere, the GWP over a shorter period is much higher.

[6] The decision requires all countries to use GWP100 values, or subsequent common metrics decided by the CMA. Countries may in addition report using other metrics.

[7] Both the Paris Agreement and associated decisions made by the Parties to the agreement have legal force in international law, but some provisions impose legally-binding obligations on Parties (for instance, the obligation to submit an NDC every five years), whereas other provisions do not impose legally-binding obligations on countries, but have strong normative characteristics (for instance, the provision in Article 4.19 in which Parties "should strive to formulate and communicate long-term low greenhouse gas emission development strategies".

[8] CMA is UNFCCC shorthand for "Conference of the Parties serving as the Meeting of the Parties to the Paris Agreement", which is the decision-making body of the Paris Agreement.

[9] A particularly important example of these was the United Nations' Climate Action Summit in 2019 which was organized under the auspices of the UN Secretary General rather than the UNFCCC, and was seminal in establishing the goal of reaching net zero CO_2 emissions

Paris Agreement specifies a number of goals, which include the global temperature goal in Article 2.1.a and the mitigation goal in Article 4.1, but what these imply for collective action, and for individual Parties, is further elaborated over time, including in CMA decisions. The recognition of the latest science in a CMA decision at COP 26 in Glasgow is to a large extent a *qualification* of the temperature and mitigation goals, and provides more specificity for collective and national climate mitigation. These will be discussed below in more detail as a basis for the net zero analysis which follows.

2.1. International scientific context

The long-term goal of "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system" contained in the UNFCCC's Article 2 as THE objective of the Convention (United Nations, 1992) does not specify what this means in terms of global GHG emissions quantitatively, and has been the subject of climate science and the IPCC's assessment of it since. Two specific characteristics are important: first, what IS the temperature level at which "dangerous anthropogenic interference with the climate system" will have significantly negative consequences, and secondly, what does this imply for global GHG emissions? The question of the threshold has primarily been addressed via the concept of global average temperature, and defining a global temperature threshold beyond which the impacts of climate change are assessed as being "dangerous". This was defined from at least Copenhagen (COP 15 in 2009) as being 2 degrees C above pre-industrial levels. Before this, and particularly up to the conclusion of the Paris Agreement at COP 21 in 2015, many countries, especially small island states and vulnerable developing countries argued that 2 degrees was too high, and would result for many countries in catastrophic damage to themselves and to ecosystems.

In 2015, there were relatively few global GHG emissions scenarios which had been analysed to establish what would be required to stay within a 1.5 degree limit, compared to the number of scenarios analysed on the basis of a 2 degree limit. During the same period, a more specific global policy goal was advocated for and incorporated in the Paris Agreement of achieving "..a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century" in its Article 4.1 (UNFCCC, 2015), thus establishing the goal of "net zero" GHG emissions as a key global goal of the Agreement. The long-term goal for mitigation contains not only net zero GHG emissions as a collective goal, but also other elements that comprise an important context (though often ignored) – Article 4.1 explicitly refers back to the temperature goal (as does 7.1), aims to reach global peaking as soon as possible, but recognises this will take longer in developing countries, calls for rapid reductions thereafter (implicitly by all), then refers to the 'net zero' GHG emission balance by the second half of the century (of which 2050 is the earliest possible year), all on the basis of equity, and in the context of sustainable development and efforts to eradicate poverty. There is no obligation in the Paris Agreement for individual countries to reach net zero GHG or CO_2 emissions, since the net zero goal in Article 4.1 is a global goal. Article 4 also specifies than developed countries' emissions will peak earlier than developing countries.

The Paris Agreement defined a global temperature goal (a degree of global warming which we should aim not to go beyond) with two parts: limiting temperature rise "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". The COP also decided, in the accompanying decision, to invite the IPCC to "to provide a special report in 2018 on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways" (para 21, 1/CP.21, UNFCCC, 2015).

The IPCC did so, and their Special Report provided two key insights: the first was that there is indeed a very significant difference in terms of climate change impacts between average global temperature rise of 1.5 degrees above pre-industrial levels, and a rise of 2 degrees.; and the second insight concerned findings on the global GHG emissions pathways necessary to remain within 1.5 degrees. These latter findings are presented in Figure SPM.3a of the Special Report's Summary for Policymakers, reproduced here in Figure 1. This figure presents the basis for the key finding regarding the characteristics of global emissions pathways which will limit temperature increase to 1.5 degrees during this century, which is contained in paragraph C.1.2 of the Summary for Policymakers:

> "In model pathways with no or limited overshoot of 1.5°C, global net anthropogenic CO_2 emissions decline by about 45% from 2010 levels by 2030 (40–60% interquartile range), reaching net zero

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by 2050, globally and nationally. In addition to this, there are a large number of so-called "climate clubs" which have no status in the multilateral process and are often focused on specific goals such as the phaseout of coal or methane.

around 2050 (2045–2055 interquartile range). For limiting global warming to below 2°C CO_2 emissions are projected to decline by about 25% by 2030 in most pathways (10–30% interquartile range) and reach net zero around 2070 (2065-2080 interquartile range). Non-CO_2 emissions in pathways that limit global warming to 1.5°C show deep reductions that are similar to those in pathways limiting warming to 2°C. (high confidence)" (IPCC, 2018).

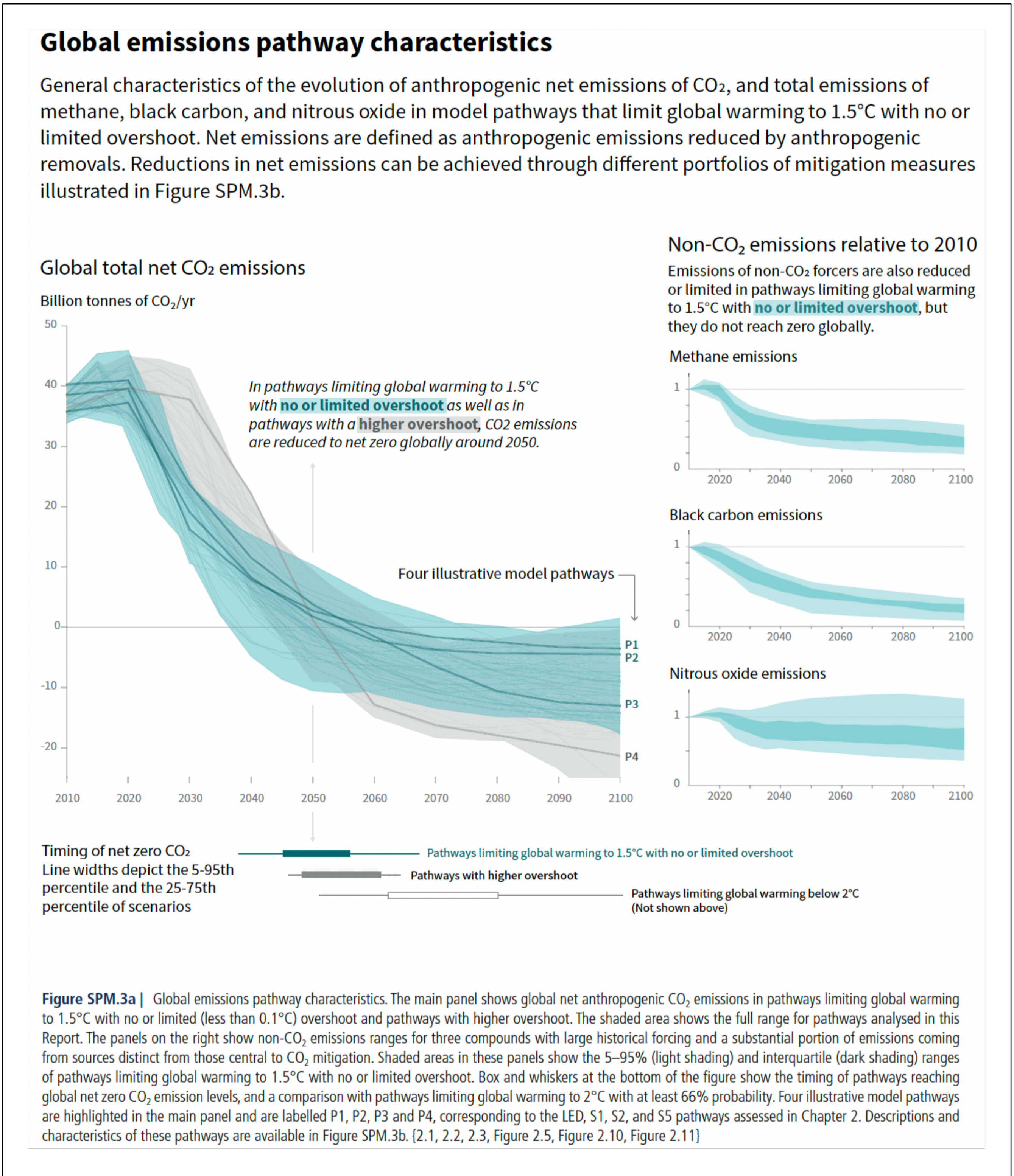

Figure 1 – Global emissions pathways to limit global temperature rise to 1.5 degrees above pre-industrial levels. Pathways for both CO_2 and non-CO_2 gases are presented. Source: IPCC (2018)

There are several key findings in this paragraph:

- Modelled global CO_2 emissions pathways which have 50% chance of limiting global temperature rise to 1.5 degrees, are characterised by i) a decline in CO_2 emissions from 2010 levels of 45% by 2030, and reach net zero CO_2 around 2050;
- Modelled global CO_2 pathways which result in limiting global temperature rise to 2 degrees are characterised by i) a decline in CO_2 emissions from 2010 levels by 25% but 2030, and reach net zero CO_2 around 2070
- Non-CO_2 gases "show deep reductions" to 2050, and reductions are similar in both pathways, and the results regarding CO_2 pathways are consistent with these "deep reductions".

It is very important to note two additional features of this analysis: i) The IPCC's findings are based on common features which 1.5 degree pathways have, as modelled. This does not preclude other pathways which were not modelled here being consistent with a 1.5 degree outcome. And (ii) almost all of these pathways require very large CO_2 absorption from the atmosphere after 2050, either through enhanced natural sinks, or artificial extraction. The remaining carbon budget available before the 1.5 degree limit is reached was estimated by the Special Report as between 420-580 Gt of CO_2, compared to annual global CO_2 emissions of 42 Gt of CO_2. This constitutes 10-12 years of CO_2 emissions at current levels (the Special Report was published in 2018), which is why all global CO_2 emissions pathways which keep within 1.5 degrees with a probability of 50% or more, feature dramatic CO_2 emission declines in the decade to 2030. The latest estimate from the Global Carbon Project is that at current CO_2 emissions levels, we will use the remaining carbon budget left within the 1.5 degree limit in around nine years[10]. Keeping 1.5 degrees alive therefore requires not only net zero CO_2 emissions around 2050, but very steep reductions in the next decade, which would need to be significantly more rapid than a linear decline from now until 2050.

Paragraph C.1.3 finds that "Limiting global warming requires limiting the total cumulative global anthropogenic emissions of CO_2 since the preindustrial period, that is, staying within a total carbon budget (high confidence)" (IPCC, 2018)[11]. Thus aside from the key points around 2030 and 2050 which the 1.5 degree-compliant pathways share, these also share the property of not exceeding the remaining carbon budget associated with keeping global warming under 1.5 degrees. The relationship between the reduction of CO_2 and non-CO_2 GHG emissions, and their impact on climate change, is more complex because of the different residence times in the atmosphere and the different global warming impact of each gas. The policy implications of this will be further discussed below.

These results were refined and updated in the IPCC's Sixth Assessment Report (Working Group 3). The Summary for Policymakers finds that scenarios which limit warming to 1.5 degrees reach net zero CO_2 "in the early 2050s", and those which limit warming to 2 degrees reach net zero CO_2 "in the early 2070s". Both these are accompanied by "deep reductions" in non-CO_2 gases over this period, peaking of CO_2 and GHG emissions before 2030, and the same requirements for reductions of CO_2 by 2030 (IPCC, 2022). Reaching net zero GHGs in both these sets of scenarios depends both on reduction in non-GHGs beyond 2050, and the extent of negative CO_2 emissions. Many scenarios feature very large amounts of negative CO_2 emissions after 2050 to achieve their temperature outcomes, which may not be technologically or economically, or even physically achievable. The point at which pathways reach net zero GHGs varies considerably, and is less determinate than the CO_2 pathway in each instance, and the GHG emissions characteristics make a significant difference to the relationship between pathways and temperature change after reaching net zero CO_2 emissions.

Net zero GHG emissions can be reached by either very deep reductions in non-CO_2 emissions[12], and their balancing by net negative CO_2 emissions on a small scale, or by less reduction in non-CO_2 GHGs, and their

[10] See https://www.globalcarbonproject.org/index.htm .

[11] It is important to bear in mind for the discussion below on "fair shares" that most of the carbon budget since the "preindustrial period" has already been used, and mostly by developed countries.

[12] The real challenge is the reduction of methane emissions from agriculture. While there are promising options for some reduction (reducing livestock and/changing livestock dies, and developing less methane-intensive forms of rice cultivation), there are no current options for eliminating methane emissions entirely.

balancing by very large scale net negative CO_2 emissions (using a GWP metric to equate the gases)[13]. Reaching net zero GHGs in the second half of the 21st century generally results in global temperature decline in 1.5 degree scenarios from their 1.5 degree peak (or slight overshoot); notwithstanding, emissions of non-CO_2 greenhouse gases are not projected to reach zero in any of the scenarios up to 2100[14] (see the Illustrative Mitigation Pathways in Figure SPM.5, IPCC, 2022).

The connection between these clear scientific finding and international and national policy on GHG mitigation is complex. The key findings reflected in the Special Reports Summary for Policy Makers clearly identify a strong correlation between limiting warming to 1.5 degrees, CO_2 emissions being reduced by 45% by 2030 compared to 2010 levels, and reaching net zero CO_2 emissions around 2050, *and* remaining within a CO_2 budget of 420-770[15] Gt CO_2. Both the Special Report and the 6th Assessment Report find again that there is an "almost linear" relationship between cumulative CO_2 emissions and temperature rise on account of CO_2's effectively long residence in the atmosphere. The characteristics of CO_2 emissions pathways to 2100 which achieve the 1.5 degree goal are strongly influenced by their starting points (where global CO_2 emissions are at the moment) and the remaining CO_2 budget. Thus there is a very strong connection between the average trajectory of these pathways (45% reduction by 2030, and net zero around 2050) and the remaining available CO_2 budget. The remaining CO_2 budget is also dependent on projections of non-CO_2 gases to 2050 and beyond. Of the key anthropogenic GHGs (CO_2, CH_4, N_2O, artificial GHGs), only CH_4 has a lifetime which is shorter that the timeline to 2050. This has great significance to policy over the next few decades, globally, and also on a national level.

The key outcomes of these findings for international and national climate mitigation policy which are relevant here are that i) global CO_2 emissions between 2017 and the point at which these reach net zero must remain within the remaining carbon budget associated with a 1.5 degree temperature rise, in order to meet the 1.5 degree goal, within the context of the reduction of other GHGs; ii) CO_2 emissions pathways to achieve this are strongly associated with a decline in CO_2 emissions by 45% by 2030 from 2010 levels, and reaching net zero CO_2 emissions around 2050; iii) "deep reductions" will be required to 2050 in non-CO_2 GHG emissions; and the predominant reduction patterns for non-CO_2 gases influences the size of the CO_2 budget. Finally, over a relatively short time period (30 years, which is contrasted to "long" periods of 100 years or more), there is a strong scientific basis for using a GHG emissions budget for national and international climate mitigation policy[16].

2.2. International legal and policy context

The key points of reference for long-term GHG emissions reductions by countries are the United Nations Framework Convention on Climate Change (UNFCCC) and its Paris Agreement. Both the UNFCCC and the Paris Agreement are legally-binding treaties which South Africa has ratified. The Paris Agreement contains several relevant elements for long-term national GHG pathways: i) an agreed global temperature goal (Article 2.1.a), a mitigation goal (Article 4.1); and ii) elements which address the critical question concerning each country's contribution to reaching this global goal, which include provisions on equity and differentiation between developed and developing countries in Article 4 and also in Articles 9-11 on provision of support and Article 13 on transparency.

The global temperature goal is contained in the Paris Agreement's Article 2.1(a), whereby Parties agree on:

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[13] The use of different common metrics would result in different net zero GHG points, including the use of different timespans for the global warming potential metric.

[14] llustrative mitigation pathways for non-CO_2 gases can be found here: (https://www.ipcc.ch/report/ar6/wg3/figures/summary-for-policymakers/figure-spm-5). These show methane. for example declining 58-86% below 2015 levels by 2100 for 1.5-peak pathways.

[15] This range which is reported in paragraph C.1.3 of the Summary for Policymakers of the Special Report, spans i) different probabilities of remaining within 1.5 degrees (50-66%), and the use of different global temperature indicators (global means surface temperature vs global mean surface air temperature).

[16] There are some other important provisos which come with the translation of the global assessment undertaken by the IPCC in its Special Report and Assessment Reports on what action is required globally into national-level actions. The two key provisos are i) that anthropogenic GHG emissions estimation at a global level in some instances uses a different set of methodologies to those used by countries to compile their national GHG inventories as decided by the COP or CMA (this is mainly true in the land sector), and ii) the UNFCCC does not have jurisdiction over GHG emissions emitted by international flights and shipping. Both of these imply that there is an "emissions gap" between all countries reducing their CO_2 emissions to zero by 2050, and the reduction of global emissions to zero by 2050; in other words, the collective effort of all countries to reduce CO_2 emissions to net zero would not result in global net zero CO_2 emissions, unless these two provisos are addressed.

"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, recognizing that this would significantly reduce the risks and impacts of climate change;" (UNFCCC, 2015)

There is an unresolved debate on what "well below 2 °C" means, and from a legal standpoint what the relative balance between the temperature limit is (see for instance Rajamani and Werksman, 2018). The first question is now somewhat irrelevant since whereas the original legal text of the Agreement gives slightly more weight to the "well below 2" temperature limit, there has been a subsequent policy and legal shift internationally towards 1.5°C. This is partly as a result of the findings of the IPCC's Special Report on 1.5 Degrees (requested in the COP[17] decision accompanying the Paris Agreement) concerning the impacts of 1.5 vs 2 degrees temperature rise (which showed that climate risks and impacts would be significantly greater at 2°C compared to 1.5°C (IPCC, 2018), especially on vulnerable countries), which were further confirmed and elaborated by the IPCC's Sixth Assessment Report, as well as a strong shift in the international policy landscape from countries as well as businesses, cities and other groupings of organisations, partly catalysed by the 2019 UN Climate Action Summit. The Glasgow Climate Pact agreed in 2021 (the outcome of COP 26/CMA 3) formally recognises the findings of the 1.5 degree Special Report, and gives greater policyweight to the 1.5°C temperature goal. This language was reaffirmed in the COP 27 outcomes.

The concept of "net zero" is espoused in the Paris Agreement's Article 4.1, in which countries agree to "..achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century.. ..on the basis of equity, and in the context of sustainable development and efforts to eradicate poverty". This is a global goal, and it provides some guidance on how this would be realised in individual countries by differentiating between developed and developing countries in terms of when national GHG emissions peaks are reached, and recognising the important dimensions of equity and sustainable development.

Whereas in 2018, during the Trump Presidency, the COP could not affirm the outcome of the IPCC's Special Report, in Glasgow the language from the report regarding 1.5 degree pathways was incorporated in the Glasgow Climate Pact:

"20. Reaffirms the Paris Agreement temperature 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;

21. Recognizes that the impacts of climate change will be much lower at the temperature increase of 1.5 °C compared with 2 °C and resolves to pursue efforts to limit the temperature increase to 1.5 °C;

22. Recognizes that limiting global warming to 1.5 °C requires rapid, deep and sustained reductions in global greenhouse gas emissions, including reducing global carbon dioxide emissions by 45 per cent by 2030 relative to the 2010 level and to net zero around midcentury, as well as deep reductions in other greenhouse gases[18];" (UNFCCC, 2021)

This provides strong guidance linked to the IPCC's Special Report (and reaffirmed in the IPCC's 6th Assessment Working Group 1 report released in 2021) on an agreed long-term global GHG emissions trajectory. However, it remains for each country to decide what its own national contribution to this will be.

There are two timeframes in terms of which countries indicate their mitigation contribution in terms of the Paris Agreement's architecture: i) in the short-medium term, via each country's "nationally determined contribution" (NDC; (Article 4.2); and ii) in the long-term, via voluntary non-binding "long-term low greenhouse gas emission development strategies" that are "mindful" of Article 2 (i.e. the temperature goal); Article 4.19 and paragraph

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[17] COP stands for "Congress of the Parties" which is the decision-making body of the UNFCCC, and which meets once a year. The decision-making body of the Paris Agreement is referred to in short as the CMA, which stands for "the Congress of the Parties serving as the Meeting of the Parties of the Paris Agreement".

[18] It should be noted that the IPCC, and indeed the Glasgow Climate Pact, call for CO_2 emissions to reach net-zero by (or around) 2050, and "deep reductions" (but not necessarily net-zero) for other GHG emissions.

35 of 1/CP.21[19]. While the concept of an end year for CO_2 or all GHG emissions was successfully proposed in the runup to Paris, in international climate policy the direct link between net zero CO_2 emissions and 2050 was made explicit as a potential national target via the UN Climate Action Summit in 2019. By the end of 2021 at COP 26 in Glasgow, all major economies and the majority of individual countries had made a commitment of some kind to reaching net zero CO_2 emission by between 2050 and 2060. There is now a widespread expectation that countries should adopt long-term net zero targets. COP 26 also directly linked long term strategies to 2050 in a more direct way.

Whereas NDCs are subject to detailed reporting requirements in terms of Article 13 of the Paris Agreement on implementation, and countries are legally bound to "prepare, communicate and maintain" NDCs, long-term strategies are voluntary, and to date, only a small number of countries have submitted these. In addition, long-term strategies do not form part of the Paris Agreement's "ambition cycle" comprising communication of NDCs and a "global stocktake" every five years, which considers amongst other issues collective progress towards the global temperature goal in terms of a synthesis report compiled by the UNFCCC Secretariat. The Glasgow Climate Pact strengthened provisions regarding long-term strategies in paragraph 32, 33 and 34 of 3/CMA.1. Paragraph 32 reads:

> "32. Urges Parties that have not yet done so to communicate, by the fourth session of the Conference of the Parties serving as the meeting of the Parties to the Paris Agreement, long-term low greenhouse gas emission development strategies referred to in Article 4, paragraph 19, of the Paris Agreement towards just transitions to net zero emissions by or around mid-century, taking into account different national circumstances;" (UNFCCC, 2021)

Paragraph 34 provides for the Secretariat to synthesise these, which also brings long-term pathways into the Paris Agreement ambition cycle. There are several ways in which these paragraphs strengthen provisions on long-term strategies. The first is that just transitions are linked to net zero emissions, and countries are urged to include these in LT-LED. Secondly, paragraph 33 clarifies that these should be submitted regularly; the third is that paragraph 32 ties long-term strategies to "net zero emissions by or around mid-century", which is an elaboration of the Paris Agreement and 1/CP.21. Paragraph 33 clarifies that these should be communicated "regularly". Together these represent a shift in emphasis to the long term. While a large number of countries have made some sort of net -zero commitment in a variety of forms (from those that have enshrined a long-term commitment in national legislation on the one hand to those which have announced such a target without yet reflecting it in any form of legislation or policy nationally on the other), one of the key concerns at COP 26 is the inadequacy of the collective mitigation effort for 2030, reflected in countries' NDCs, despite the fact that countries have recently updated their previously-communicated NDCs for 2030. Countries were therefore urged to further update their NDCs by the end of 2022, and a work programme "to urgently scale up mitigation ambition" was established, to address the gulf between collective efforts and a 1.5 degree global pathway.

2.3. "Fair shares" in the context of the UNFCCC and its Paris Agreement

However, neither the Paris Agreement nor its accompanying decision, nor subsequent decisions of the CMA, provides clear quantifiable guidance on what level individual Parties to the Agreement should set their NDC targets at, or which quantifiable characteristics their long-term low emissions development strategies should have; in other words, what the magnitude of each countries' contribution to the global goal should be. Countries are however required to provide, from their second NDCs on, information "for clarity, transparency and understanding" on their NDC targets, in terms of decision 4/CMA.1 in 2018, which includes information on how countries consider their NDCs to be both "fair and ambitious". These are two different requirements; the ambition requirement relates to Article 4.3, whereby Parties' successive NDCs should represent their "highest possible ambition"; fairness relates to the "principle of equity and common but differentiated responsibilities and respective capabilities, in the light of different national circumstances.." (UNFCCC, 2015; United Nations, 1992). In the absence of any agreed guidance, various approaches to quantifying national "fair shares" based on the principles of the UNFCCC and the Paris Agreement have emerged in literature (and indeed been invoked –

[19] The medium term and the long term are defined differently in different literature on climate change. When the Paris Agreement was concluded in 2015, 2030 was regarded as the medium-term point, and 2050 as the long-term. However, since we have now covered roughly half the years between 2015 and 2030, both 2030 and 2050 do not see so far away, especially in the context of investment cycles for large infrastructure projects such as power plants.

often selectively – in countries' NDC communications). These approaches have typically focused on medium-term targets for specific years (initially 2020, but now 2030), and provide very little guidance for long-term trajectories. Moreover, methods for allocation which depend on projecting key indicators (for instance GDP) into the future have very high levels of uncertainty by 2050. When analysts began consideration of this, 2030 was a medium-term target, and 2050 was a long-term target. Since we are now at the end of 2022, there are less than three decades from 2050, which can thus also be considered a medium-term target.

Different approaches to quantifying the principles provided in the UNFCCC and its Paris Agreement have led to a very wide range of outcomes for countries by 2050. This poses both a technical and a policy problem. The technical problem concerns how each country's fair share should be measured (in terms of a GHG emissions budget over a time period, a reduction in GHG emissions from a baseline, a reduction in GHG intensity, a set of decadal targets (2030, 2040, 2050) as part of a low emissions development emissions trajectory, etc.) and concomitantly how to quantify countries' fair shares (which indicators should be used and how these indicators should be linked quantitatively to GHG emissions or other indicators). The policy problem concerns what should be considered in making this allocation, within the broader policy context of the international climate regime. There is therefore an additional moral hazard that countries will use the approach which favours them (in other words, which allocates more emissions space to them, and less to others).

This problem is exacerbated by parts of the literature which have included equity criteria for which there is no basis in international law or any reasonable reading of the UNFCCC and its Paris Agreement. Most notably, some studies use 'grandfathering' (or grandparenting) as a basis for allocating a global carbon budget (e.g. den Elzen 2002; Van den Berg et al 2019). Grandparenting means that the share of historical and/or current emissions is taken as the basis for future allocations, no matter how inequitable the current distribution may be. Others have argued that grandparenting is ethically indefensible, drawing inter alia on moral and political philosophy (Kartha et al 2018 Dooley et al 2021). In addition, and perhaps more incisively, a recent paper assessing different approaches to burden-sharing in terms of their validity in the multilateral climate regime and more broadly in international environmental law "led to the exclusion of approaches based on cost[20] and grandfathering, both usually favourable to developed states" (Rajamani et al 2021).

The result of this tendency for each country to choose an approach which favours itself is that, when adding up less ambitious mitigation targets, the global GHG emissions budget will be exceeded[21]. The relationship between a global goal of net zero CO_2 emissions around 2050 and how this might be achieved in the multilateral system which comprises the UNFCCC and its Paris Agreement, and 198 Parties is therefore not straightforward. Apart from a number of complex accounting problems[22] (not including the exclusion of GHG emissions from international aviation and shipping, which are not covered by the UNFCCC/Paris Agreement), the allocation of GHG emissions reductions to each country is no simpler when attempting to reach a global goal of net zero CO_2 or GHG emissions than it was before – the "burden sharing" problem, or how to allocate the global mitigation effort to each country, has preoccupied policymakers and commentators since the negotiation of the UNFCCC in 1992[23]. The principles for allocation, which were agreed to in the UNFCCC and reaffirmed in the Paris Agreement, are based on equity, and include "common but differentiated responsibility and respective capabilities, in the light of different national circumstances". This INCLUDES the responsibility that developed countries have to

[20] Least-cost based approaches are usually used in integrated assessment models to model global pathways with a specific global mitigation goal or temperature limit as a constraint. The least-cost objective is therefore in a global context. Not only are these global models usually inaccurate on a regional or country level, but they also do not take into account any national circumstances. These are widely recognized as not being a substantive basis for the equitable allocation of emissions space.

[21] This is nicely indicated quantitively by previous versions of the Climate Action Tracker (CAT, 2019), which determined that the impact of each country choosing the most favourable equity approach would be a temperature rise of more than 3 degrees C, even though each approach is based on limiting temperature rise to 1.5 or 2 degrees.

[22] There are large inconsistencies between total global anthropogenic GHG emissions as reporting by Parties to the UNFCCC / Paris Agreement, and total global emissions as assessed by the scientific community and used in integrated assessment models. Many of these stem from different approaches to the assessment of land use emissions. Any global strategy to achieve a particular temperature outcome would need to take cognizance of these (Crisp et al., 2022; Zickfeld et al., 2021).

[23] The "bottom up" solution to setting mitigation targets developed in Paris – "Nationally Determined Contributions" (NDCs) coupled with a periodic international review of collective progress, was agreed in the face of failures to agree any "top-down" allocation process.

provide support to developing countries for the implementation of national mitigation and adaptation policies and measures.

Some policymakers and analysts have argued that it is “too late” to consider differentiating countries’ commitments to mitigation, and that all countries should simply reduce their GHG emissions to zero as fast as possible. While this does serve to outline the urgency necessary in responding to the climate crisis, it also ignores the fact that there are dramatically different costs to similar pathways to net zero in different countries, especially for developing countries. The date at which net zero CO_2 or GHG emissions is reached has also been contested on equity grounds, in practice by China and India (who have pledged to reach net zero CO_2 by 2060 and 2070 respectively), the largest developing country emitters currently[24]. Thus, while there is a wealth of literature on burden-sharing, it remains an essentially contested problem in international climate policy. The term “possible” is also highly context-specific. Nevertheless, countries need benchmarks to assess how “fair and ambitious” their mitigation contributions are. To “make a fair contribution to the global effort” is entrenched in South Africa’s national climate change policy (DEA, 2011), and is shortly expected to be embedded in legislation (DFFE, 2022b). Both the national mitigation policy framework and subsequent mitigation policy development, including the most recent developments concerning the just transition by the National Planning Commission and currently by the Presidential Climate Commission[25], provide guidance as to what national characteristics South Africa’s long term decarbonization pathway should possess, which are related to the specific nature of the South African economy and emissions-related infrastructure, and the development challenges the South African state faces (the “triple challenge” of poverty, unemployment and inequality). The concept of “fairness” and “a fair contribution” cannot be easily separated from a detailed understanding of national circumstances, given the principles of the Convention and the Paris Agreement.

As demonstrated below in the modelling analysis, a net zero CO_2 target can be associated with a large number of pathways, with significant variation in total CO_2 emissions over the relevant time period. Since this latter quantity is of central importance in addressing climate change, countries’ “fair shares” need to be defined both in terms of a long-term outcome, and in terms of a cumulative GHG emissions budget. There is as noted above, a strong case for including other GHGs in such a budget, in addition to CO_2. This is the approach which will be used here.

2.4. Quantification of South Africa’s long-term fair share

Approach

As outlined above, a long-term GHG emissions trajectory for South Africa which comprises the country’s fair share in the context of the Paris Agreement should fulfil a number of criteria, which include both differentiation based on historical responsibility and respective capabilities, informed by national circumstances, and consistency with a global mitigation objective – which at present is constituted by the goal to keep global warming within 1.5 degrees. As above, the question of “fair shares” is the subject of a large body of literature, which is reviewed below. Whereas the scientific assessment of the requirements for a 1.5 degree global GHG emissions pathways is presented in terms of the trajectory of global CO_2 emissions, and its associated cumulative budget (which includes CO_2 emissions from the land sector), as well as “deep reductions” of other gases, the equity analyses referenced below generally use GHG emissions levels in specific years (which usually exclude land use emissions). In this study, a cumulative GHG emissions budget has been derived, consisting of all GHGs considered in the current GHG inventory, from 2021-2050, as a proxy for South Africa’s fair share to the global effort. In addition, using a cumulative GHG emissions budget in the context of an analytical approach which includes the relative costs of existing high-carbon infrastructure, provides a more accurate reflection of the economically optimal timing of mitigation investments (which are not well reflected in global models at all), while preserving the fairness of South Africa’s contribution.

While there is a strong scientific basis for using a budget approach for the allocation of CO_2 emissions space to 2050, including other gases does not have the same scientific validity, especially over periods which significantly exceed the residence in the atmosphere of non-CO_2 GHGs. A GHG budget, both as an analytical proxy for a

[24] In absolute terms- on the basis of per capita emissions, China is still significantly below many developed countries, and India has one of the lowest per capita emissions rates of any country.

[25] The Presidential Climate Commission recently completed its *Just Transition Framework*, which is currently awaiting Cabinet approval, and contains a clear statement of a net zero CO_2 goal.

country's fair share, and also as an instrument of national policy, leads to the possibility of trading off reductions in CO_2 against reductions in other gases over the timeframe in question. As evidenced below, this does have a significant impact on the timing of decarbonization, and therefore potentially leads to higher CO_2 emissions during the modelled period and beyond[26]. Meinshausen el al. however argue that over the time period to 2050, there is a strong case for using GHG budgets as a basis for mitigation policy:

> "As much of the preceding analysis has shown, there is a difference between applying carbon budgets and emissions budgets. Mostly, the literature outlines carbon budgets rather than emissions budgets. This is because assuming a linear relationship between carbon emissions and induced warming is more robust than assuming, as we have done, a 1:1 relationship between cumulative greenhouse gas emissions and induced warming. Over long timescales our assumption does not hold because several non-CO_2 gases that contribute to warming have finite lifetimes. However, when considering relatively low temperature thresholds like 1.5°C and 2°C, there is a strong case for looking at emissions between now and the time that warming peaks – which is why a short time-horizon to 2050 is appropriate. That in turn means that looking at emission budgets rather than carbon budgets can be a superior option. This is because carbon budgets inherently depend on non-CO_2 emission assumptions - while emission budgets actually include those non-CO_2 emissions in the approximation." (Meinshausen et al., 2019)

Modelling a cumulative GHG emissions constraint is therefore also a good proxy for national mitigation policies which are consistent with the current international climate regime. Therefore, GHG emissions budgets for the cumulative carbon-constrained emission scenarios were determined based on estimations for "fair" South African emissions pathways reported in available burden-sharing studies. These studies either allocate GHG emissions space in the specific years (initially 2020, and latterly 2030) which are particularly important from an international policy perspective, allocate a CO_2 or GHG emissions budget over the longer term, or allocate a mitigation share of the required global mitigation response, all in relation to a set of long-term global pathways derived from global climate modelling studies which would result in meeting the Paris Agreement's temperature goals. There is little consensus on the best approach to determining a country's fair share and no guidance agreed multilaterally – the failure to reach such a consensus is what resulted, after 20 years of non-consensus, in the bottom-up architecture of the Paris Agreement. Absent this, countries have historically used various approaches, and a variety of indicators to substantiate, with varying levels of detail (if at all), why, for example, their Nationally Determined Contributions are fair and ambitious (Winkler et al., 2018).

A number of international studies (Baer et al., 2008; CAT, 2022; Höhne et al., 2014; Holz et al., 2019; Raupach et al., 2014; Robiou du Pont et al., 2017; Sælen et al., 2019; van den Berg et al., 2020) have developed various frameworks to calculate a country's "fair share" of emissions relative to a global emission pathway, or their fair share of mitigation effort (percentage of global emissions reductions below a baseline pathway), based on varying interpretations of the principles of equity and common but differentiated responsibilities and respective capabilities in the light of national circumstances (from the Convention and the Paris Agreement) which quantify these principles in various ways. These frameworks yield very different national emission pathways and the corresponding cumulative emission budgets for South Africa, and some of these only apply up to 2030. A selection of these climate equity tools was explored in some detail, and this analysis informed the decision in this study to model a series of (net-zero CO_2) emissions pathways based on cumulative GHG carbon budgets of 9, 8, 7 and 6 Gt CO_2-eq (i.e. increasing levels of ambition) as proxies for what will potentially be expected of South Africa over the next three decades. None of these studies directly address the problem policymakers face in operationalising the "fair and ambitious" requirements of the Paris Agreement, and especially not to net zero; this is a key area for further work – hence the use of a range, which it may be possible to narrow with more analysis.

Sources and methods

Four sources were considered:

- The Climate Action Tracker (CAT, 2022)

[26] Given the different characteristics of GHGs in the atmosphere, over a timeframe longer than the basis for analysis, equating CO_2 and other GHGs using GWP values may result in different temperature outcomes.

- The Climate Equity Reference Calculator (CERC, Holz et al., 2019; Kemp-Benedict et al., 2019)
- The 1.5°C National Pathway Explorer (1.5-NPE, Climate Analytics, 2022)
- The Paris Equity Check tool (PEC, Robiou du Pont et al., 2017)

CAT and CERC were applied previously in technical analysis that informed South Africa's first NDC update in 2021 (Marquard et al., 2021). The CAT tool gathers emissions projections for a country from a range of independent modelling studies (based on varying equity criteria) and cites the median value in each year as the country's "fair share" emissions level for that year. In more recent versions, the CAT tool also develops "modelled domestic pathways" for each country i.e., an assessment of a country's full domestic decarbonisation potential irrespective of capability (CAT, 2021), based on the use modelled global pathways (see below). Where a country's fair share emissions amount exceeds its modelled domestic pathway, the implication is that the country should receive additional international support to bridge its "ambition gap"; and where a country's fair share is lower than its modelled domestic pathway, it should fund the "additional" mitigation in other countries. It should however be noted that these "modelled domestic pathways" do not consider equity in any way, and are based purely on a global least-cost methodology. These do not therefore address the question of fairness at all.

The CERC calculates a global emissions baseline up to 2030, and what global mitigation effort will be required from that baseline to conform with 1.5°C or 2°C temperature pathways. CERC then distributes the global mitigation effort to each country in the world, in proportion to a "responsibility-capability index" that is calculated for each country based on its national circumstances (population, economic size and income distribution) and historic responsibility (cumulative emissions relative to a base year ranging from 1850 to 1990).

The 1.5°C National Pathway Explorer cites global emission scenarios collected from a set of economy-wide Integrated Assessment Model (IAMs) greenhouse gas emissions trajectories from the IPCC SR1.5 database – specifically AIM-CGE (Fujimori et al., 2017), IMAGE 3.0 (Stehfest et al., 2014) and REMIND (Kriegler et al., 2017). These are then "downscaled" to national level based, essentially, on a country's historic emissions data (Climate Analytics, 2022)[27]. This is therefore NOT an equity-based analysis, although both CAT and NPE use the results in analyses which imply this.

Table 1 – Emission levels and cumulative (2021 – 2050) budgets for South Africa for each modelled option in Mt CO_2-eq, adjusted to include land use[28].

Scenario / Pathway	Cumulative (2021-2050)	2025	2030	2050
CAT: 1.5 Fair Share	10 012	415	338	263
CAT 1.5: Modelled Domestic Pathway	8 766	484	354	137
1.5-NPE: AIM/CGE [SSP1][Low CDR reliance]	6 856	384	248	92
1.5-NPE: IMAGE [SSP1][High CDR reliance]	5 830	370	238	61
1.5-NPE: REMIND_1.7 [High energy demand][Low CDR reliance]	5 895	369	243	59
SR15 range IPCC Special Report on 1.5C - 50th percentile (high)	7 648	435	315	97
SR15 range IPCC Special Report on 1.5C - 5th percentile (low)	5 791	390	239	55
SR15 range IPCC Special Report on 1.5C - 25th percentile (mid)	7 196	412	294	83
PEC: Greenhouse development rights	13 139	488	473	316
PEC: Capability	3 269	216	148	17
PEC: Equal cumulative per capita	2 838	216	145	-21
PEC: Equal per capita	5 406	288	231	57
CERC: 1.5-LED	NA	408	304	NA
CERC: 1.5	NA	387	337	NA

[27] See the "From global to national pathways" section of 1.5°C National Pathway Explorer methodology page at https://1p5ndc-pathways.climateanalytics.org/methodology/ (accessed 24 August 2022).

[28] Land use emissions are excluded from all of these equity analyses, on account of the associated uncertainty, and because different countries choose to account for land use emissions differently. These results have been adjusted for South Africa to take the land sink into account, which is estimated at a constant 10 Mt during the whole period. Actually including land use for all countries in the analyses itself would probably result in a slightly more favourable allocation to South Africa.

Finally, the Paris Equity Check compares national emissions reduction pathways according to five different methods of allocation, namely :

i. "capability" – emissions allocated in proportion to countries' population normalised by average per-capita GDP

ii. "equal cumulative per capita" – emissions allocated in proportion to a countries' population and historic emissions since 1990)

iii. "Greenhouse Development Rights" – a framework developed by Baer et al. (2008) for allocating emissions based on preserving developing countries' right to sustainable development; the GDR was subsequently further developed into the CERC, which is described above.

iv. "equal per capita" – emissions allocated to countries' populations)

v. "constant emissions ration" – emissions allocated according to present-day distributions of countries' emissions, also known as "grandfathering"[29].

It should be noted that the authors of the Paris Equity Check describe these as "the five IPCC allocation categories" (Robiou du Pont et al., 2016). However, this description seems to be unfounded: (i) the IPCC has not taken an official position on "allocation categories", and these are therefore NOT "IPCC allocation categories"; (ii) the five categories do not include responsibility as an exclusive principle, despite responsibility being a core principle of the UNFCCC (Kartha et al., 2018), and comprising the central principle of several equity analyses; and (iii) no equity proposals directly include grandfathering/grandparenting – a diametric opposite of the "polluter pays" principle – which, when applied as a principle of equity, has been described in one publication as "morally perverse" (Dooley et al., 2021), and which the Check's website notes is not an acceptable equity principle to any country. This does not, strangely, seem to deter its use. Option v in the PEC **has therefore been excluded from this analysis**, since this is centred on an approach to burden-sharing which is widely regarded as inequitable.

All global emissions pathways considered here are aligned with a 1.5° global goal (with a 50% probability), although some of them are out of date, and thus do not take into account the latest science, and the lack of mitigation over the last half decade or so. The "modelled pathways" are not based in an equity analysis either; these are included on account of their integration into CAT, in which these are used to draw normative conclusions regarding the allocation of emissions space to countries.

Finally, it is also important to note that both the equity check and CAT model a range of approaches, using their implementation of these approaches in their model. This leads to some inconsistencies – for instance, the CERC/GDR approach is modelled in three places – the CERC analysis itself, the CAT interpretation of the CERC approach, and the Paris Equity Check interpretation of the GDR/CERC approach.

Emissions pathways and cumulative budgets

Table 1 shows cumulative emissions budgets for the period 2021-2050, as well as 'milestone' emission levels in years 2025, 2030 and 2050, as determined from a range of pathways developed from the sources described above. The ranges bounded by the GHG emissions pathway from each approach is further illustrated in Figure 1. The overall range of emissions from the sources above is particularly wide, ranging from 2.8 Gt CO_2-eq (from the Paris Equity Check's 'cumulative equality per capita' metric) to 13.4 Gt CO_2-eq (from the application of the GDR). However, the upper end of this range, using the Greenhouse Development Rights approach, is based on a previous iteration of the GDR. Since CERC is the successor to the GDR, the updated version of CERC is a more accurate reference point, and post COVID and using updated 1.5 degree pathways, South Africa's allocation is

[29] It should be mentioned that the authors of the Paris Equity Check describe these as "the five IPCC allocation categories" (Robiou du Pont et al., 2016). However, this seems to be completely unfounded: (i) The IPCC has not taken an official position on "allocation categories", and these are therefore NOT "IPCC allocation categories"; (ii) the five categories do not include responsibility as an exclusive principle, despite responsibility being a core principle of the UNFCCC (Kartha et al., 2018); and (iii) the categories do include grandfathering – a diametric opposite of the "polluter pays" principle – which, as a principle of equity, has been described in one publication as "morally perverse" (Dooley et al., 2021), and which the Check's website notes is not an acceptable equity principle to any country. This does not however seem to deter its use.

much lower. While there is a lot of divergence between approaches, there are several key features which are worth focusing on.

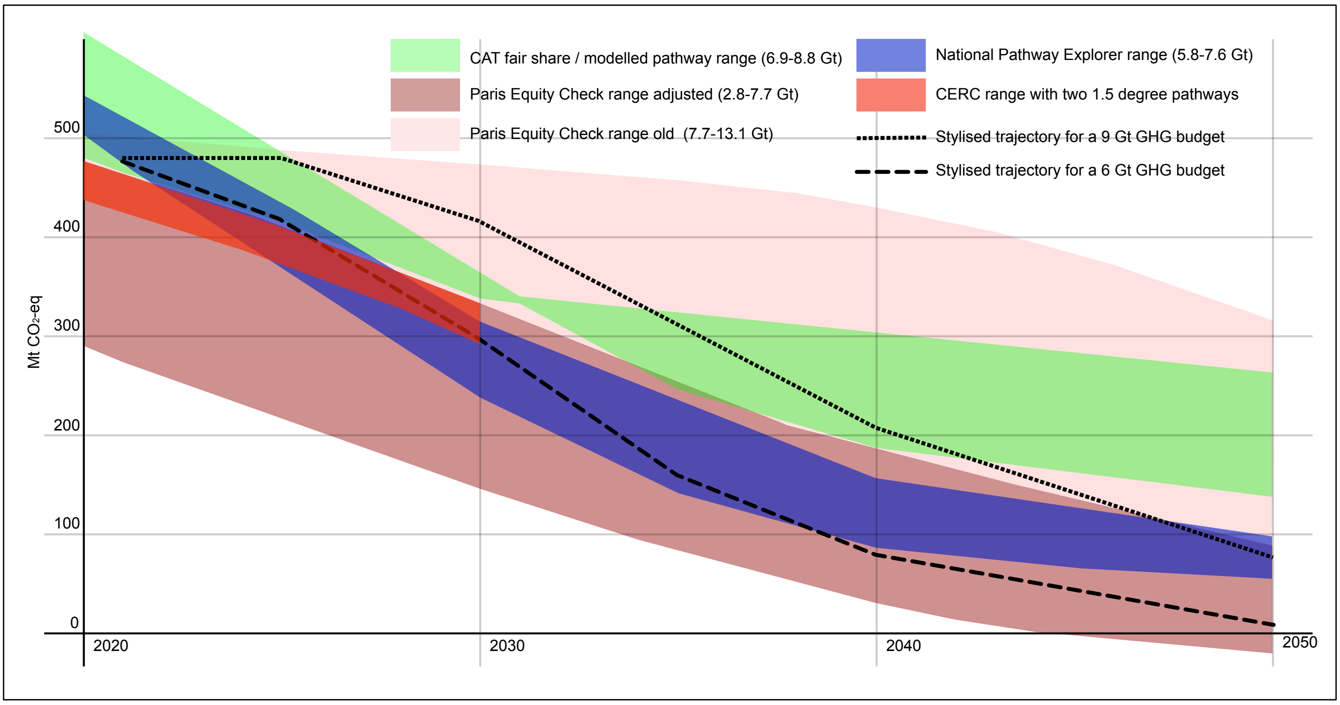

Figure 2 – Emissions pathway ranges for CAT, PEC, and NPE to 2050, plus two stylized pathways for 6 and 9 Gt CO2-eq cumulative GHG emissions from 2021-2050, and CERC values to 2030.

What is notable about the trajectories presented in Figure 2 is that only about 50% of these can be matched with a net zero CO_2 outcome, and require more rapid reductions earlier in the 30-year period. This is partly because most of these analyses focus on 2030, and have much higher ranges of uncertainty towards 2050. Nevertheless all approaches have a similar profile, i.e. rapid and ambitious reduction of emissions in the first two decades, followed by a more gradual shift later on. What is also notable about these is the broad range of estimates for what are now historical GHG emissions in 2020, which is partly on account of divergences between international GHG emissions data sets and South Africa's own national GHG inventory estimates, and partly on account of the application of these burden-sharing analyses from 2010 on. This rapid early reduction is a feature of global pathways which keep warming to 1.5 degrees (or minimal overshoot), and a simple arithmetical outcome of the relationship between current GHG emissions levels and the long-term target.

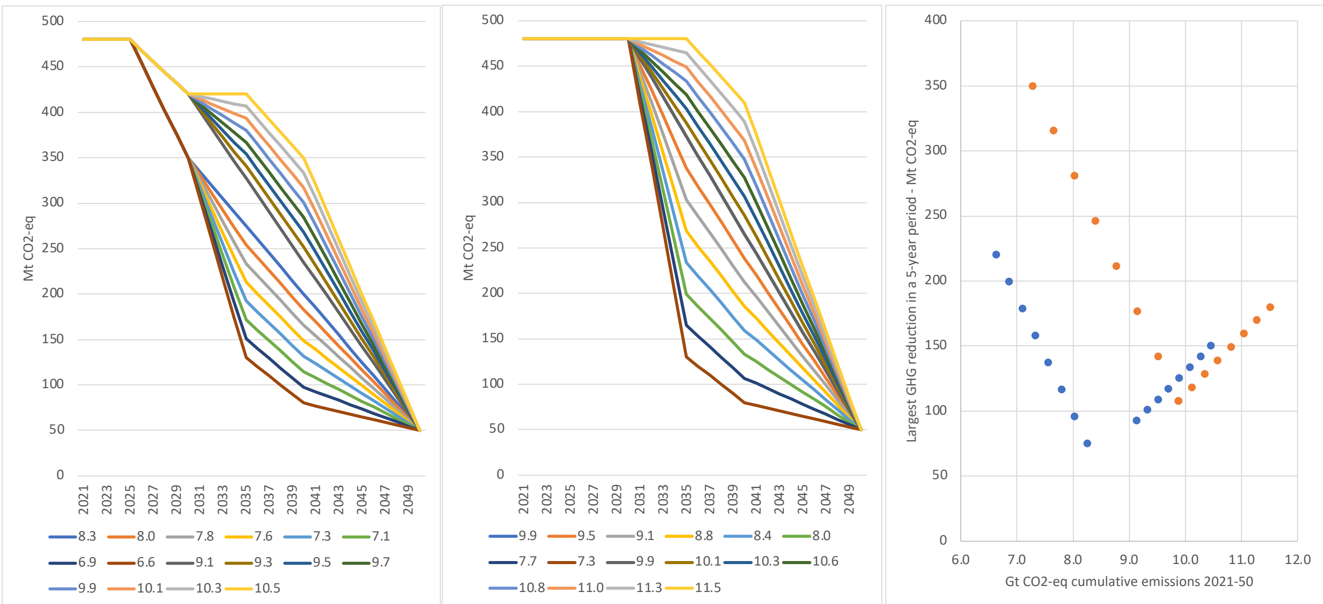

Figure 3 – Stylized GHG emissions pathways with corresponding GHG budgets to net zero CO_2 (estimated at 50 Mt CO_2-eq here in 2050 (consisting of non-CO_2 gases)). The figure on the right presents the most rapid reduction in a five-year period required for each pathway on the left.

This relationship is presented in Figure 3, which consists of stylised pathways to net zero with varying budgets. The figure on the left presents pathways which achieve the 2030 NDC target (both ends of the range). With a simple linear reduction from current GHG emissions levels in 2025 to the NDC target range in 2030, between 4.4 and 4.6 Gt (upper and lower NDC ranges) of South Africa's long-term GHG budget would have been used, leaving two decades to use the remainder. If the NDC target is not met and GHG emissions remain constant until 2030, 4.8 Gt will have been used. Both more and less ambitious pathways below and above a range of 8.3-9 Gt (corresponding to the NDC target range in 2030) require much steeper reductions in each 5-year period after 2030; some of these are probably not possible, meaning that a net zero CO_2 target is compatible with a relatively small range of cumulative GHG budgets to 2050. In order to explore the technical implications of this, a range of 6-9 Gt cumulative GHG emissions budgets between 2021 and 2050 have been modelled; stylized versions of these are included in Figure 2.

3. Key methodological issues and assumptions

3.1. Characteristics of net zero pathways for this study

As outlined above, a “net zero pathway” for South Africa is for the purposes of this study assumed to be constituted as follows:

- CO_2 emissions will reach net zero in 2050, which means that the sum of sources and sinks of CO_2 emissions will be equal to zero by 2050
- GHG emissions pathways will have a cumulative emissions budget range for all gases modelled here (the five gases[30] currently reported in South Africa’s National Inventory), consisting of the sum of annual GHG emissions for the five gases from all sectors for the years 2021-2050

GHG emissions outcomes beyond 2050 have not been modelled here, but will be discussed in the “recommendations” section.

3.2. Modelling approach

The modelling approach to this project is exploratory and is aimed at providing a basis for further more detailed work on this. The modelling framework which was used for this project is SATIMGE, consisting of the following linked modules:

- SATIM – the South African TIMES model, which is a partial equilibrium, linear optimization model, representing the South African energy system, associated GHG emissions and also industrial process emissions;
- ESAGE – the energy-enhanced version of the South African Computable General Equilibrium model, modelling the whole economy;
- Two spreadsheet-based models which capture GHG emissions from the AFOLU and waste sectors.

The modelling framework is integrated to guarantee consistency between technology and economic elements of the modelling framework.

SATIM optimizes for discounted system costs subject to user-defined constraints and a user-defined useful energy demand, and chooses both supply and demand-side technologies to meet demand based on a linear-least cost optimisation algorithm. ESAGE adjusts sectoral growth rates, and thus demand, based on the economy-wide impact of investments made in SATIM, and these models iterate to provide consistent sectoral growth rates and the corresponding optimal energy system. The overall modelling framework does not optimize for selection of measures in the AFOLU and waste sectors. These are therefore specified exogenously, and sensitivity analyses are used to understand the impact of various choices (which change the available cumulative emissions budget for the other sectors) - more details on sectoral assumptions are provided below.

The waste and AFOLU sectors are integrated with the rest of the modelling framework via consistent major drivers (GDP, population), but the selection of mitigation measures in these sectors is exogenous to the model[31]; with some variation in subsectors depending on economic growth, this implies that the size of the potential CO_2 land sink during the modelled period is determined exogenously. There are two potential shortcomings with this approach: (i) the measures in the AFOLU sector to maintain sinks of this size to 2050 may be more expensive than seeking lower- or zero CO_2 options in the rest of the; and (ii) the uncertainties in land sector emissions are very high, both in terms of potential changes in estimation methodology and in terms of outcomes, especially towards 2050, by which time climate impacts are likely to have a very significant effect on land sinks. Therefore, several scenarios for GHG emissions trajectories for the AFOLU sector were developed and applied in this study, as described further below.

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[30] Carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydroflourocarbons (HFCs) and perflourocarbons (PFCs).

[31] This is partly because in the absence of mitigation policies and measures in these sectors, there is very little information on how much these measures would cost to implement.

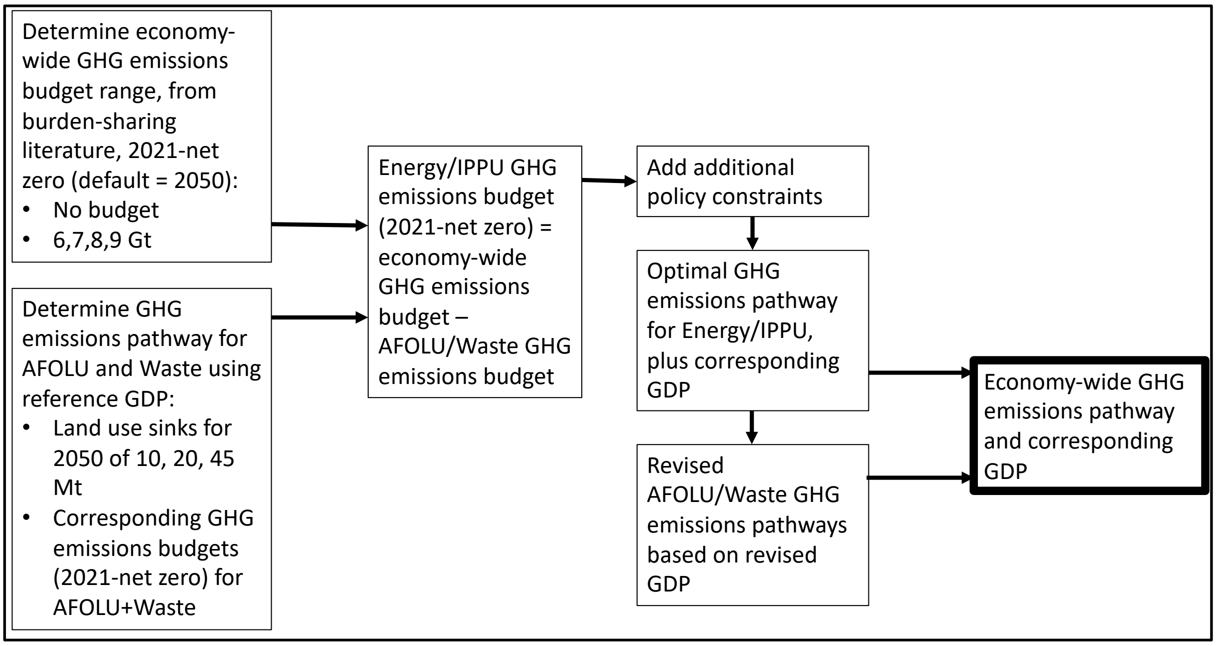

Figure 4 – Modelling approach for the cases modelled

3.3. Cases modelled, and associated scenario assumptions

In total 64 different cases were modelled, based on the following scenario variations:

- Two economic growth rates
- Three variations on AFOLU emissions, corresponding to different levels of policy implementation to enhance carbon sinks
- With / without demand-side policies and measures (energy efficiency, transport)
- With and without a large export industry in green hydrogen and green iron
- Five variants on a cumulative emissions constraint from 2021 to 2050 of all GHGs, as described above (four constraints and one variant without a constraint)

Each of these variations is described in more detail in the sub-sections below.

The goal of this set of scenarios is to provide an initial exploration of possible pathways to net zero CO_2 by 2050 for the South African economy. A more elaborate and detailed scenario matrix will need to be developed for a more detailed, policy-relevant exploration of pathways to net zero, which also considers options for later net zero target years, and a more refined approach to modelling medium-term targets (the NDC). The IRP 2019 was specifically NOT modelled here in any of these scenarios, but comparisons with the IRP 2019 are undertaken below, to indicate the extent to which the IRP is consistent with these pathways.

Economic growth rates

Two economic growth rate scenarios are considered – one reference economic growth rate scenario, in which the economy grows relatively slowly from 2021 to 2030 at around 2%, and accelerates slowly after this to reach just under 4% by 2050, and one high growth rate scenario in which the economy growth at a high rate of around 4% from 2021 to 2050. Both growth scenarios experience the same negative growth shock in 2020 due to the COVID epidemic. The growth rate and the relative size of the economy are presented in Figure 5, for the reference case. Fluctuations in the growth rate are as a result of modelled investment requirements, which are uneven due to the pattern of retirement rates for existing infrastructure.

The reference growth rate leads to a doubling of the size of the economy by 2050, and the high growth rate leads to growth of just under three times its current size. The growth rates presented in Figure 5 are the base rates, and these vary per modelled case when the relevant cases follow pathways with different investment patterns.

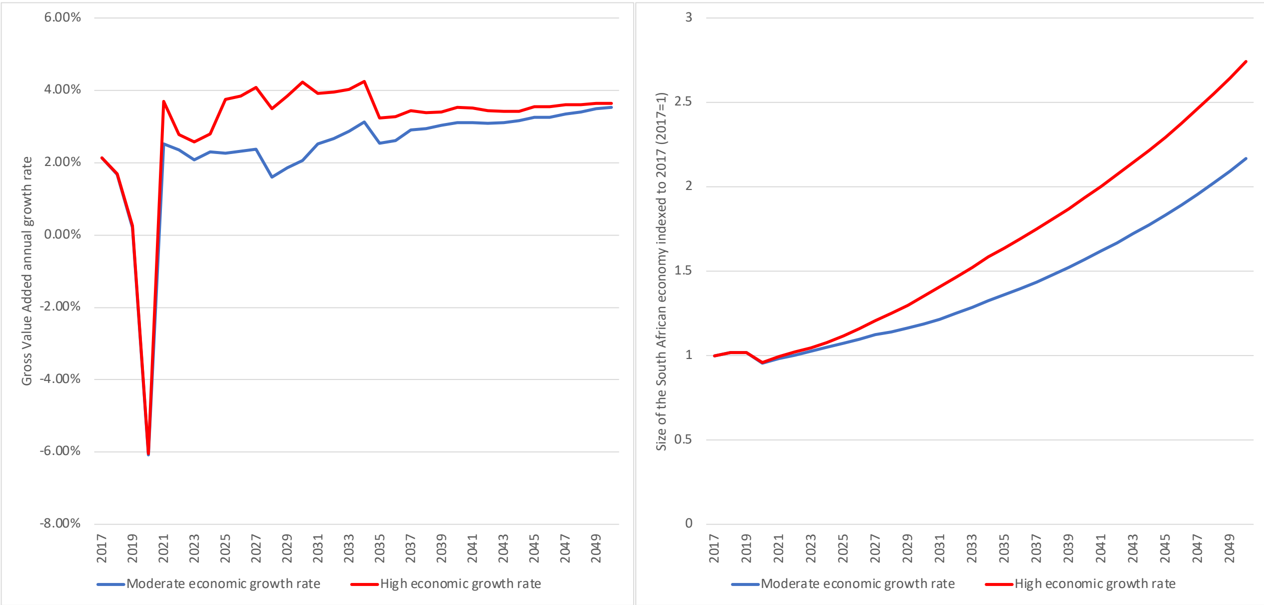

Figure 5 – GVA (gross value added) growth rate (left) and relative size of the economy (2017=1) in the reference case.

Inclusion / exclusion of policies and measures (PAMs)

We consider two scenarios – one in which only current PAMs (up to 2021) are included in the modelling, which includes committed capacity in the REIPPPP and the completion of Medupi and Kusile in the electricity sector, and the carbon tax as currently implemented; and one in which demand side PAMs are implemented and achieved – the draft post-2015 national energy efficiency strategy, and the green transport strategy. The way in which these have been implemented is described in (Marquard et al., 2021). The inclusion of these demand-side measures results in lower energy demand and modal shifts in the transport sector.

Green exports

We consider two scenarios for green exports (of iron and steel produced with zero-carbon hydrogen, and of ammonia) – one with no additional exports and the other with a large-scale exports of both commodities.

Carbon sink scenarios to 2050

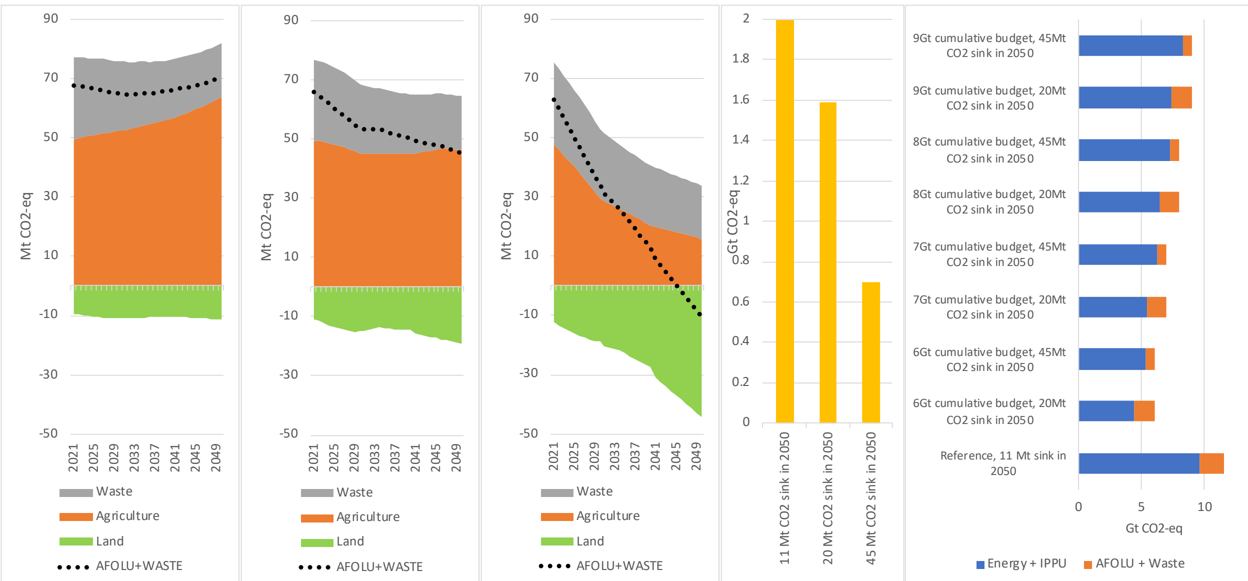

Figure 6 – Three options for South Africa's land-based carbon sink to 2050 (reference on the left, 20Mt centre left and 45Mt centre), the cumulative emissions from AFOLU and waste with different land sector sinks in 2050 (centre right, as a result of different policy trajectories), and the impact of different scenarios for the land sink on cumulative GHG budgets (right).

Three scenarios were considered for the land sector. The first reference scenario assumes minimal policies in the sector. The second assumes a moderate policy programme to reduce CO_2 emissions and enhance CO_2 sinks, and the third assumes a comprehensive set of mitigation policies in the land and agricultural sectors. These three scenarios for the land and agriculture sectors result in three different net CO_2 sink levels from now until 2050 as presented in Figure 6. This results in a 12 Mt CO_2 sink in 2050 for the reference approach, a 20 Mt sink for the moderate policy scenario, and 45 Mt for the comprehensive scenario.

These scenarios have an impact on two aspects of this analysis. The first concerns the carbon sink available in 2050, which in turn determines the maximum amount of CO_2 which can be emitted in 2050 in order to reach net zero – a larger carbon sink means that there is more emissions space elsewhere in the economy. The second concerns the overall GHG emissions budget over the period from 2021-2050. A larger sink during this period effectively means that there will be more GHG emissions space for other sectors, with the same net GHG emissions outcome. The implications of this will be explored further below.

GHG cumulative emissions budgets for 2021-2050

Five scenarios are considered, corresponding to a range of possible "fair shares" for South Africa, the uncertainty of which was discussed above. These consist of a scenario in which there are no GHG emissions constraints (the reference scenario), as well as scenarios in which the cumulative GHG emissions budget from 2021-50 is 6, 7, 8 or 9 Gt CO_2-eq. Each cumulative emissions scenario (6-9 Gt CO_2-eq) is modelled using two land sink levels – 20Mt and 45Mt in 2050. The consequences of a smaller sink therefore affect the rest of the GHG emissions budget significantly, as presented in Figure 6 (right). Assuming a smaller sink does not therefore only restrict CO_2 emissions in 2050, but also the overall GHG emissions space available to the rest of the economy.

Modelled cases

These scenarios are modelling in a combination of cases, all of which are detailed in Table 5, and graphically presented in Figure 68.

3.4. The challenge of decarbonization

Unlike previous studies, this study is focused on one long-term policy goal – to reduce CO_2 emissions to net-zero (i.e. to abate CO_2 emissions to such an extent that any remaining, or "residual", emissions are balanced by land sinks, as per the three land sink scenarios described above).

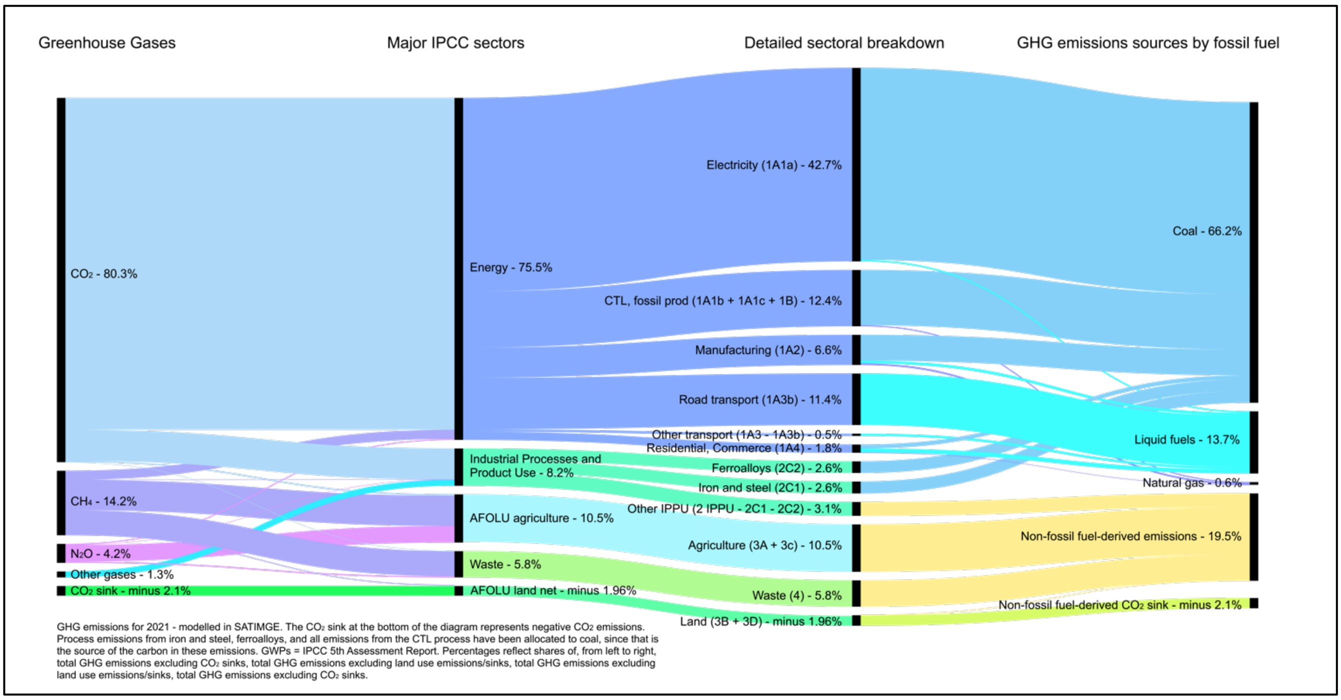

Figure 7 – Modelled[32] South African annual greenhouse gas emissions in 2021, from left to right, categorized by gases, by major IPCC sectors (energy, industrial processes and product use, agriculture and land use, and waste), by key emitting sectors, and by fossil fuel source. The percentages indicate the percentage for each category of net GHG emission, i.e. including land use – hence the CO_2 sink (the bottom green line) has a negative value. The codes in the detailed sectoral breakdown indicate IPCC emissions categories. The land use sink is included on the diagram to compare it to CO_2 emissions – thus, NET CO_2 emissions on the left are actually 80% of the net total.

[32] Figures for 2021 emissions here and below are modelled estimates, and not verified in South Africa's national GHG inventory as yet. The latest version of the national GHG inventory is for the year 2017. A draft GHG inventory for 2019 is currently available.

It is thus useful to consider the sources of CO_2 in the economy at present. This is presented in Figure 7, which correlates greenhouse gases with GHG emissions sources, in the form of major IPCC sectors, key emitting sectors, and GHG source.

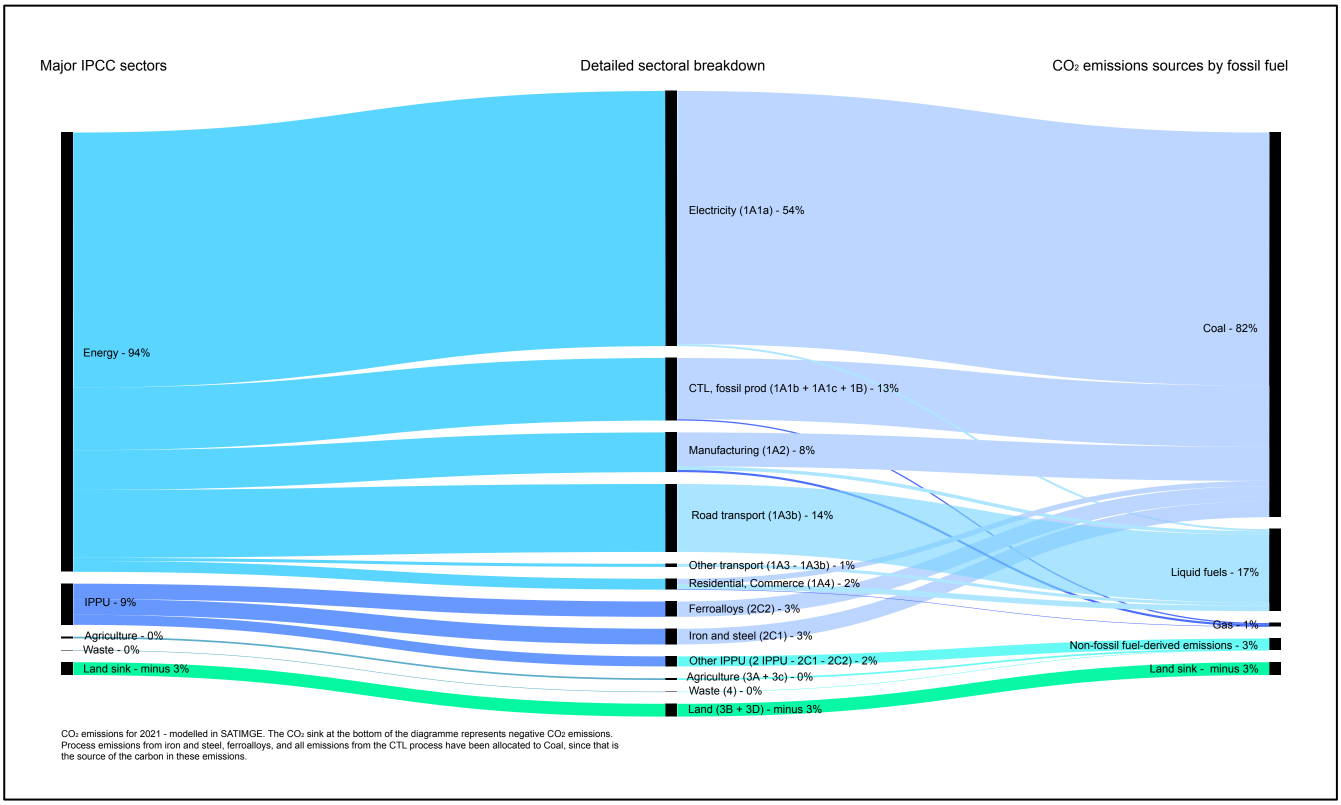

Figure 8 – Modelled South African annual CO_2 emissions in 2021, from left to right, by major IPCC sectors (energy, industrial processes and product use, agriculture and land use, and waste), by key emitting sectors, and by fossil fuel source. The percentages indicate the percentage for each category of net CO_2 emissions, i.e. including land use – hence the CO_2 sink (the bottom green line) has a negative value. The codes in the detailed sectoral breakdown indicate IPCC emissions categories. The land use sink is included on the diagramme to compare it to CO_2 emissions. CO_2 sinks are indicated by the term “minus” to avoid confusion.

Figure 8 presents CO_2 emissions only. CO_2 comprised a net 80% of GHG emissions in 2021, and has three primary sources:

- Combustion and fugitive emissions from fossil fuel use, which include the processing of coal to produce liquid fuels; (94% of net CO_2 emissions)
- Process emissions, primarily in the manufacture of iron and steel, ferroalloys and cement; (9% of net CO_2 emissions)
- Land use and land use change; (-3% of net CO_2 emissions)

In addition, around 10 Mt CO_2-eq of the remaining GHGs are associated with CO_2 emissions (via combustion or fugitive emissions), and would be mitigated by mitigating (or anthropogenically removing) CO_2 emissions.

By far the largest source of CO_2 is the electricity sector (1A1a) comprising 54% of net CO_2, followed in order by road transport (14%), the manufacture of liquid fuels from coal (1A1c + 1B3) (13%), general manufacturing (1A2) (8%), and with process emissions from minerals processing (mainly iron and steel and ferroalloys), and a much smaller contribution from process emissions from cement and other industrial processes (3% and 2% respectively). Almost all of these CO_2 emissions result from the use of fossil fuels, mostly from combustion, with a further small but significant contribution from ore reduction. Since around 30% of these liquid fuels are produced from coal, more than 82% of South Africa’s CO_2 emissions are associated with coal use, and will involve either the replacement of coal-based technologies in the relevant sectors with zero-carbon technologies, the storage of emitted CO_2, or the phasing or shutting down of the relevant sector. There are also complex interactions between these sources – for instance, the decarbonization of the transport sector will mean that there is no demand for liquid fuels, which will mean that the coal-to-liquids process will cease to operate, thereby also removing emissions sources associated with this sector. The goal of achieving net zero CO_2 emissions therefore is largely, but not completely dominated by the problem of phasing down coal use in the economy to

2050. In a net zero scenario, any CO_2 emissions arising from continued coal use would need to be stored (CCS) or offset via an increase in the country's natural carbon sink[33].

[33] We have left carbon capture and utilization off this list, since if the resulting products such as jet fuel are combusted, the carbon would still be emitted to atmosphere (albeit as a result of more efficient use).

4. Baseline GHG emissions

4.1. Economy wide GHG emissions

Baseline GHG emissions were modelled without specifying any additional policies and measures, and with a reference growth rate (see Figure 5; sensitivity to growth rate is presented in Figure 12). This case is referred to as the "reference case" below, and EXCLUDES the IRP 2019 expansion plan – new electricity plant is identified by the model on a least-cost basis, with no further constraints, in order to allow comparison with policy-based cases. An overview of results is presented here, and more detailed comparisons with net zero-constrained cases is provided in the next section.

Total GHG emissions decline in the absence of further policy, as a result of the retirement of high-carbon infrastructure and its replacement by low-carbon infrastructure, where it is cheaper. Most of this decline is in CO_2 emissions, which decline to 61% of their 2021 level by 2050; other gases only decline to 96% of their 2021 level. The waste and agriculture sectors produce a very small share of CO_2 and are not considered again in this analysis in relation to CO_2.

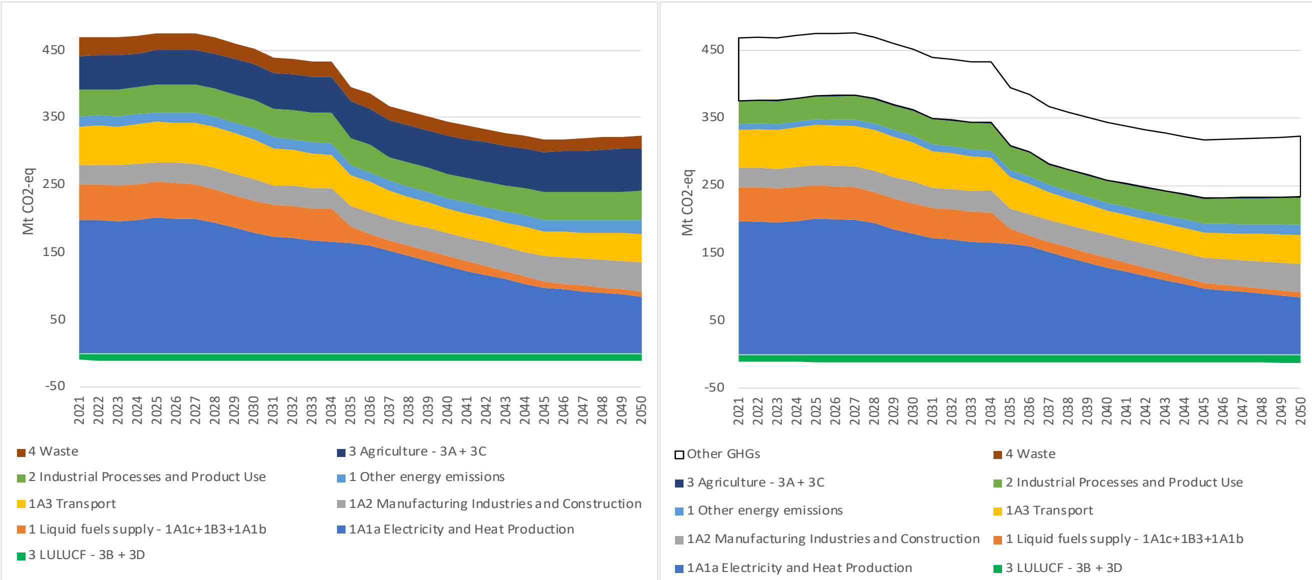

Figure 9 – Left: CO_2-eq emissions per sector, all gases for the reference case; Right: CO_2 emissions only per sector, with all other gases contained in the transparent area at the top of the graph.

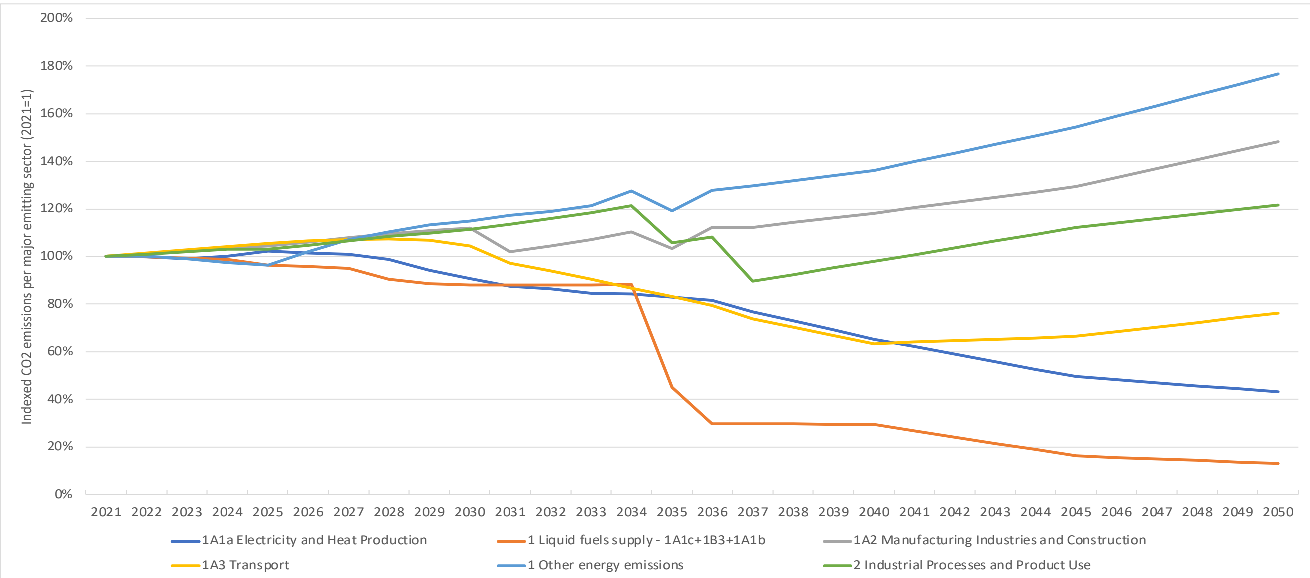

Figure 10 – indexed CO_2 emissions for key emitting sectors (2021=100%)

Figure 10 presents indexed CO_2 emissions (2021=100%). Decline in CO_2 emissions is driven by the decarbonization of the electricity sector (via the replacement of retiring coal plants with renewable energy and gas), a shift in the transport sector to low-carbon vehicles, and as the result of reduction in demand for liquid fuels, curtailment of the coal-to-liquids process. CO_2 emissions continue to grow in manufacturing (in both combustion and process emissions), since there are no lower-carbon emissions which are more cost-effective over the modelling period in these sectors than coal. These will be examined below in more detail.

4.2. Energy use

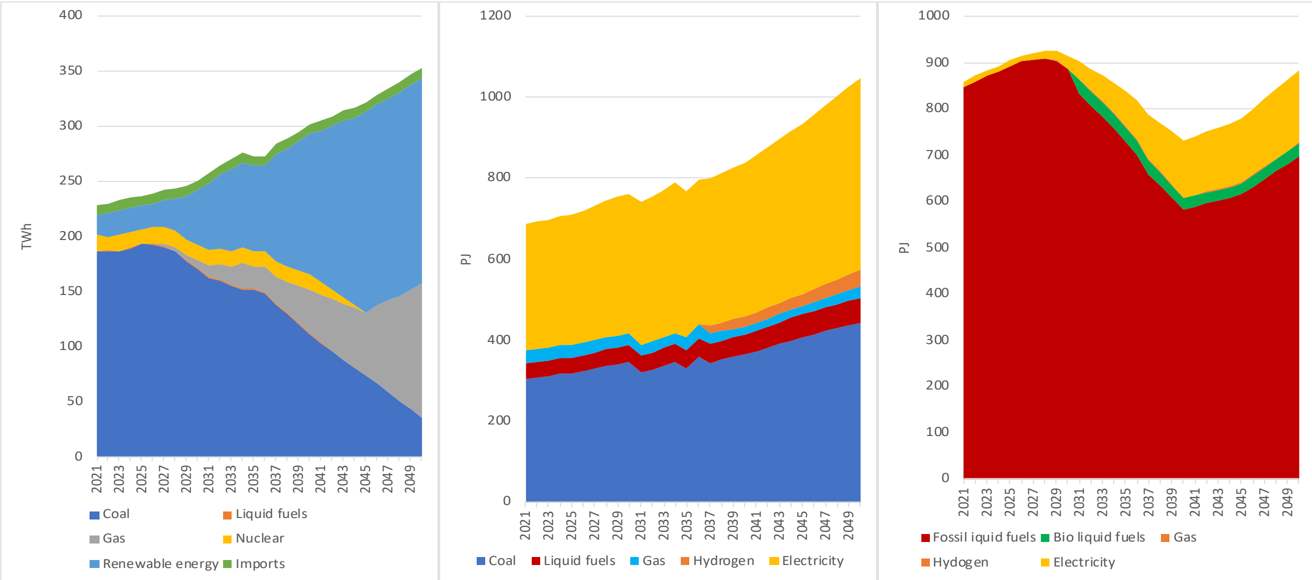

Figure 11 – Electricity sent out by source (left), energy demand in industry (centre), energy demand in transport (right)

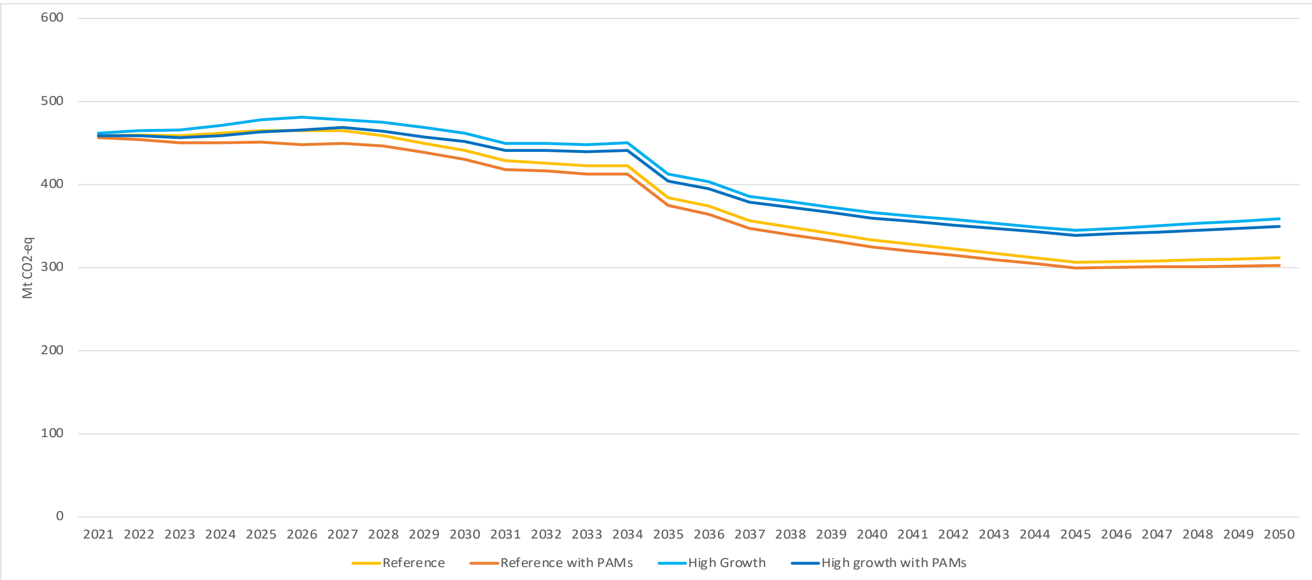

Figure 12 – Sensitivity to growth rate and demand-side PAMs

Since there is no GHG constraint in the reference case, the model identifies a pathway based only on total discounted system cost, on the basis of the existing stock of infrastructure. The results show that in the electricity sector, new coal plants are not competitive with other generation technologies, and neither are nuclear plants. In this context, the trajectory of coal use follows the retirement of the existing coal fleet. The use of natural gas expands significantly from 2021, especially in the last period, which is partly due to the decreasing gas price assumption. The energy mix in the industrial sector remains relatively unchanged apart from the addition of hydrogen in relatively small quantities in the late 2030s for iron and steel. Gas does not play a major role in the sector. In the transport sector, electric mobility expands from 2030, but stagnates around 2040 in favour of growing liquid fuels demand. There is no hydrogen or natural gas use in the transport sector, but a small amount of biofuels blended into the petrol and diesel supply as a result of current policies. Very little transformation takes place in industry (Figure 11, centre) and energy use in industry continues to be dominated by coal and electricity in 2050, with a small amount of hydrogen being used in the iron and steel sector. Transport energy use continues to be dominated by fossil-derived liquid fuels (Figure 11, right), with a relatively small shift to electric mobility. These will be explored in more detail below.

The sensitivity to economic growth and demand-side policies is presented in Figure 12. The high growth rate results in a 15% increase in GHG emissions by 2050, and the impact of demand-side policies and measures on GHG emissions is slight for both growth rates towards 2050. The impact of economic growth comes mainly from sectors where low-carbon technologies are not yet competitive with fossil fuel-based technologies – specifically in the industry and transport sectors.

5. Net zero CO_2 emissions pathways

Adding a single goal for net zero CO_2 for 2050 results in steep emissions reductions from 2035 onwards, as presented in Figure 13, for two different carbon sink values – 20 Mt and 45 Mt, corresponding to different mitigation pathways in the land sector, as presented in Figure 6.

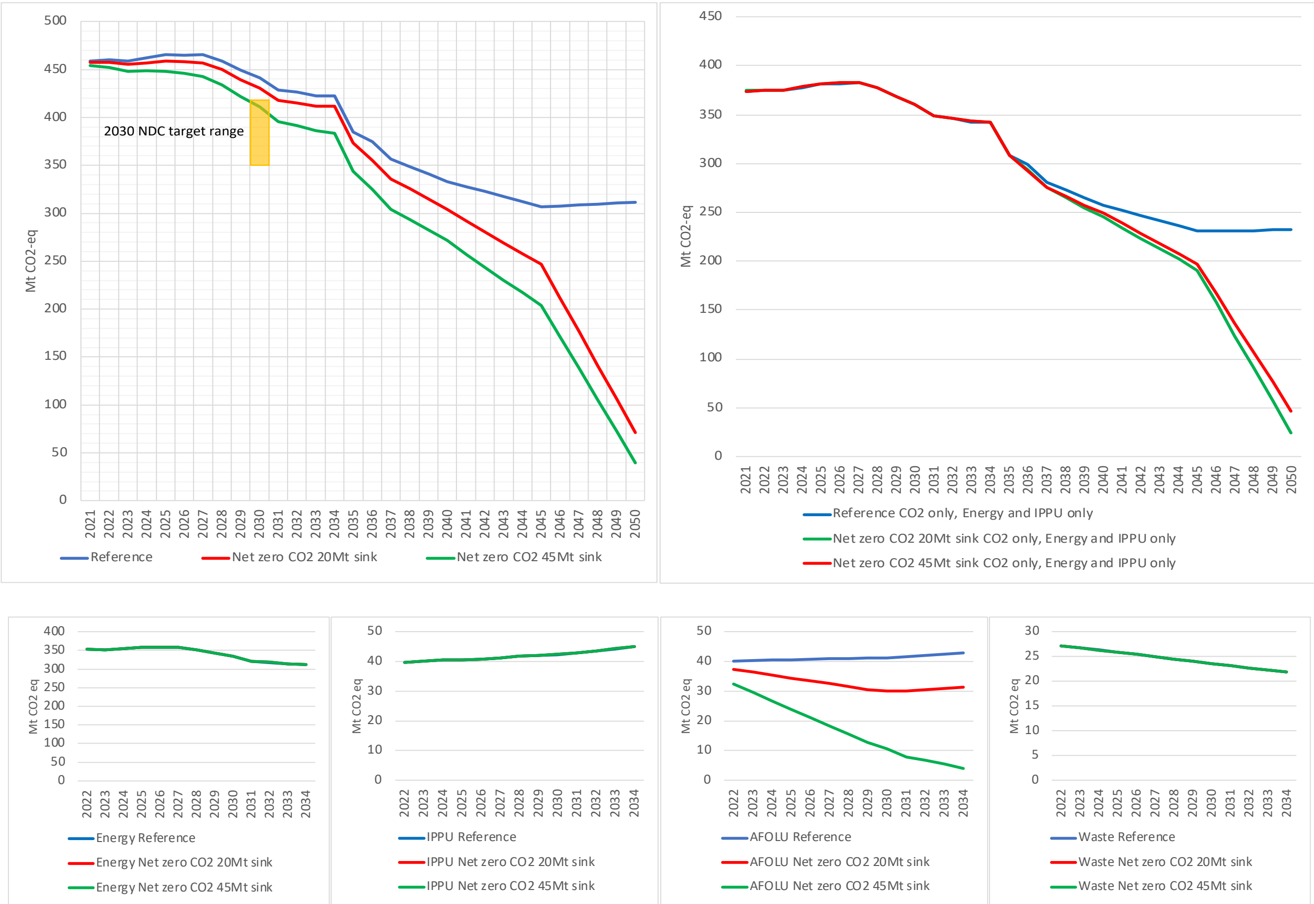

Figure 13 – Reference case with two modelled pathways with net zero CO_2 goals by 2050, with carbon sinks in the land sector of 20 and 45 Mt in 2050 respectively, with all GHGs (left) for the whole economy, and CO_2 only in the energy and IPPU sectors (right). The bottom row of figures show GHG emissions for these three cases per IPCC sector.

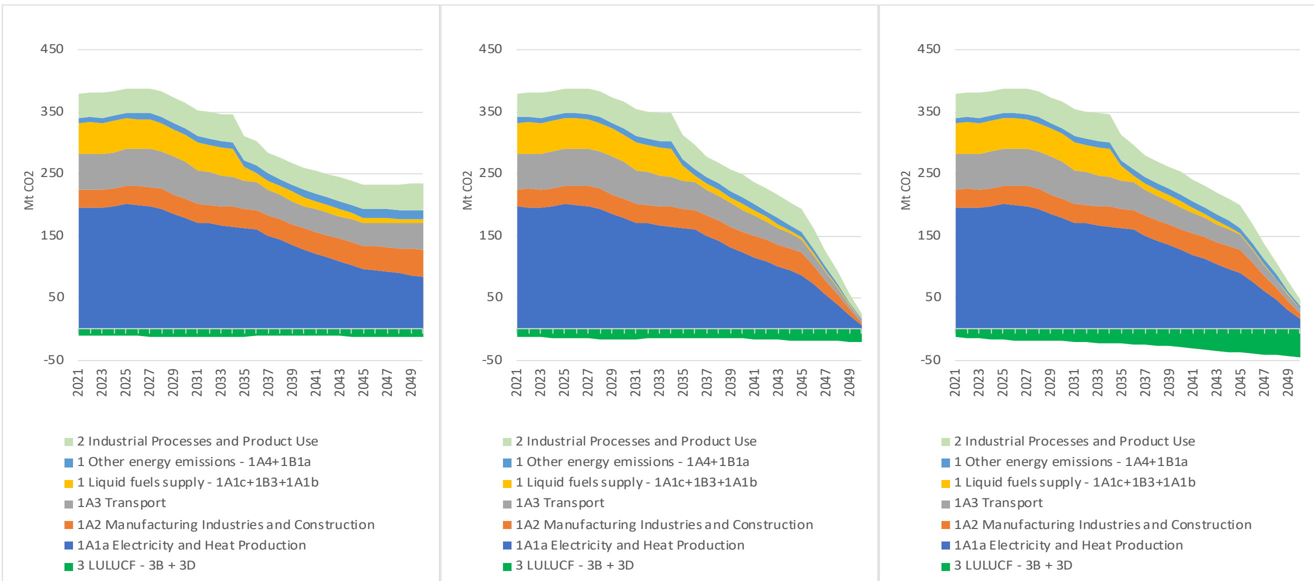

Figure 14 – CO_2 emissions by major emitting sector for the reference (left), net zero CO_2 20Mt sink (middle) and net zero 45 Mt sink (right)

With only a 2050 net zero goal and no other GHG emissions constraints, the CO_2 emissions in the energy and IPPU sectors only begin to diverge from the reference case in around 2035, followed by extremely steep reductions from 2045 to 2050, which, as will be apparent below, may not be feasible either technically or economically since these depend on extremely large investments in the electricity sector in the last five years before the net zero target. GHG emissions for these three cases is presented in Figure 13. The divergence in GHG emissions as a whole is driven by mitigation in the AFOLU sector associated with different land sinks in 2050, rather than by the net zero target itself. The graph to the right, which presented CO_2 emissions from energy and process emissions, illustrates that there is no divergence in CO_2 emissions before 2035 as a result of the 2050 target. Only the net zero 45Mt case meets the 2030 NDC target, and this is only on account of the measures assumed to apply to the AFOLU sector to achieve a 45Mt sink. As presented in Figure 14, deviation from the reference case occurs ONLY as a result of mitigation in the AFOLU sector. Merely having a net zero target does not result in medium-term action in itself.

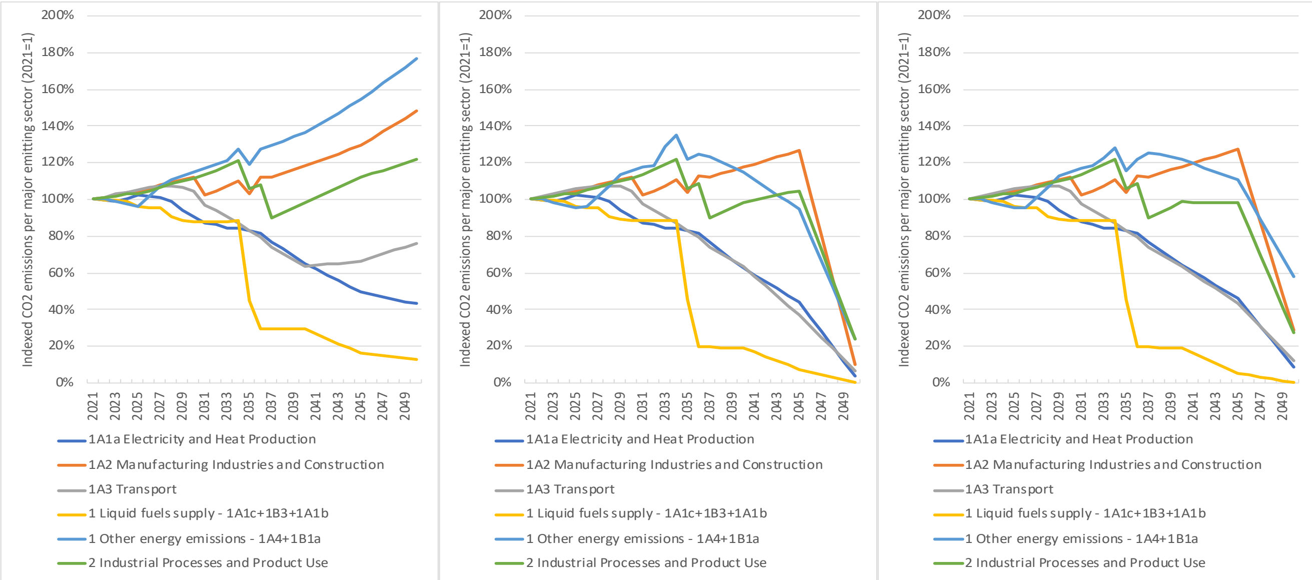

Figure 15 – Indexed CO_2 emissions for key emitting sectors (2021=100%), for the reference case (left), net zero 20 Mt sink (centre), and net zero 45 Mt sink (right) cases

CO_2 emissions by sector in the three cases are presented in Figure 14, and indexed emissions per sector are presented Figure 15. While emissions from liquid fuels manufacture, electricity and transport decline in the reference case (more detail below), emissions from industry rise in the reference case in the absence of any other constraint. The addition of a 2050 CO_2 emissions cap (of either 45 or 20 Mt CO_2, for difference CO_2 sink scenarios) leads to dramatic reductions in CO_2 emissions, but only in the last five years.

5.1. Electricity

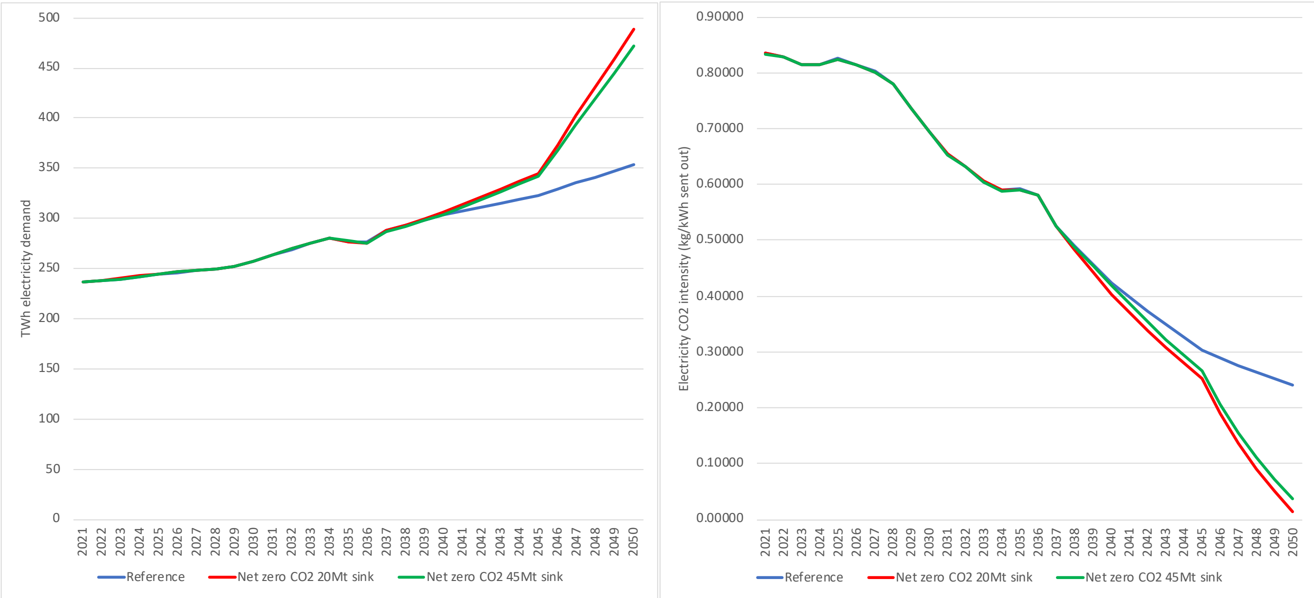

Figure 16 – total electricity demand (left) and CO_2 intensity of electricity (right) in the reference, net zero 20 Mt sink, and net zero 45 Mt sink cases

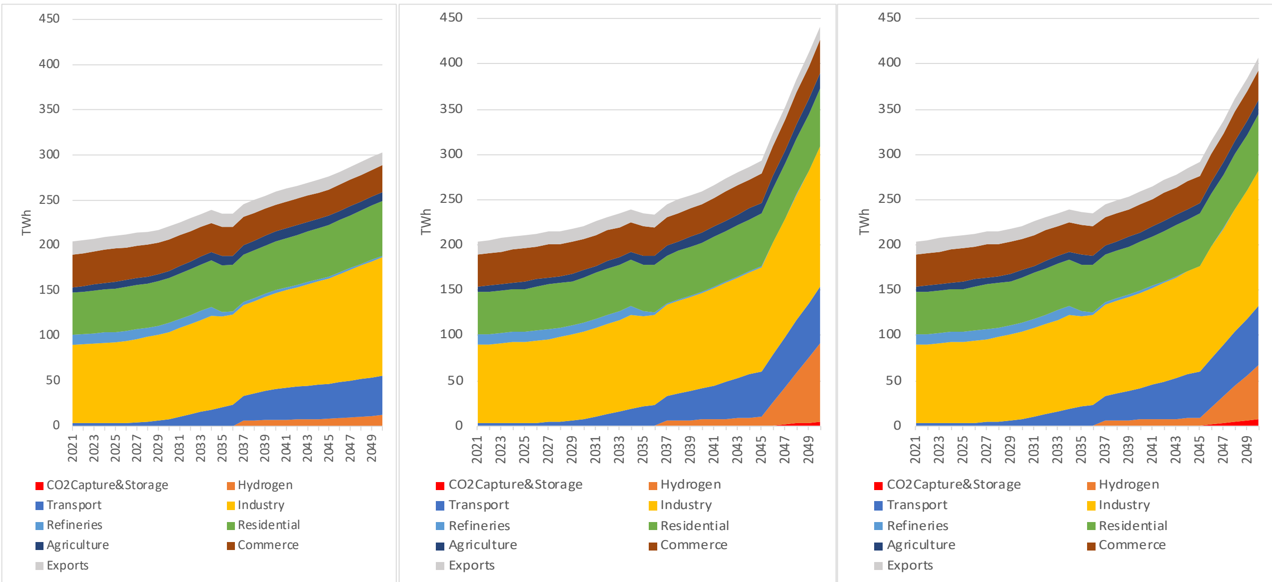

Figure 17 – Electricity demand by sector in the reference case (left), net zero 45 Mt sink case (centre), and net zero 20 Mt sink case (right)

Electricity demand grows rapidly in the net zero scenarios in the 2040s, as presented in Figure 16, so that demand is around 20% higher in 2050 than in 2045, and in relation to the reference case. The reasons for this, presented in Figure 17, are that industrial electricity demand is 10% higher than in the reference case, but most notably there is a growth of 50% in electricity demand for transport as a result of the electrification a large proportion of the vehicle fleet. The biggest impact on electricity demand however is hydrogen production.

This results in a very steep rate of investment in low-carbon electricity generation, presented in Figure 19 in terms of new capacity, and in Figure 33 on the actual investment cost in the sector. The additional investment in the electricity sector and the resulting total installed capacity of the national electricity system is dramatically higher for these cases, and also features very little use of natural gas compared to the reference case. New capacity required in the 2045-50 years is over 30 GW per year in the -45 Mt sink case, and over 40 MW in the -20 Mt sink case. Total installed capacity is more than double the reference case in the -20 Mt case. In these cases (with only a constraint on CO_2 levels in 2050), the difference between the -20 and -45 Mt sink cases is around R20 billion a year in additional investment. Investment rates from 2045 to 2050, as presented in Figure 18, are unrealistic, and getting to these levels of generation capacity by 2050 will require more investment in the decade before, which in turn will result in earlier decarbonization. This is further explored in the section below exploring the consequences of imposing a GHG budget over the three decades from 2021-2050.

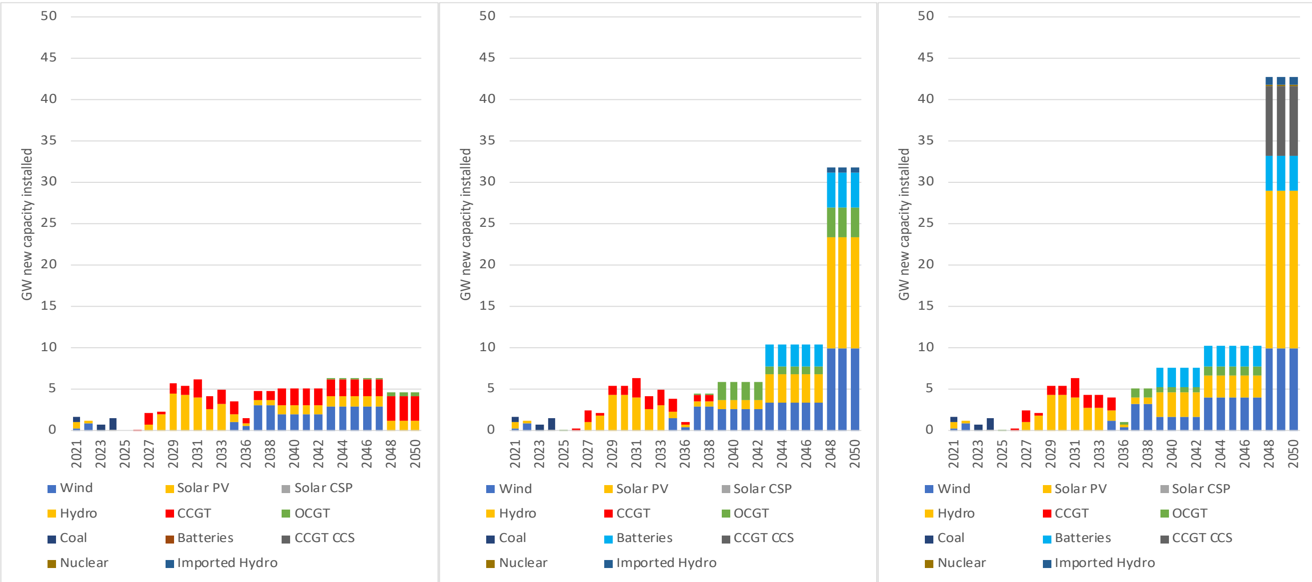

Figure 18 – New generating capacity added annually by technology in the reference case (left), net zero 45 Mt case (centre), and net zero 20 Mt sink (right)

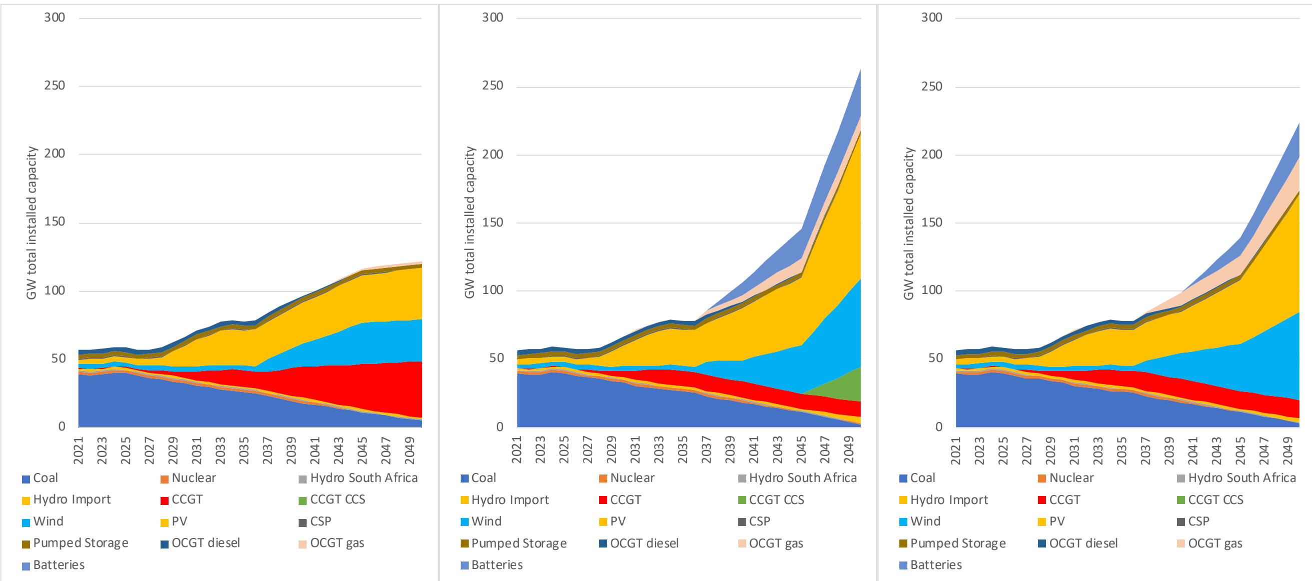

Figure 19 – Total installed capacity in the reference case (left), net zero 45 Mt case (centre), and net zero 20 Mt sink (right)

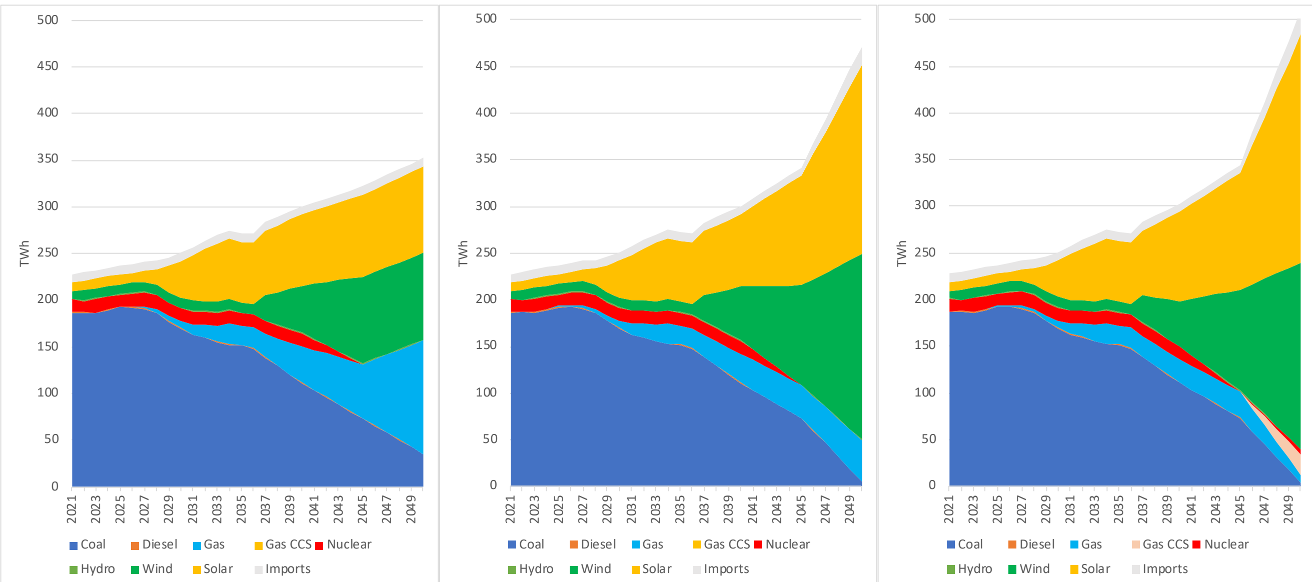

Figure 20 – Electricity by source in the reference case (left), net zero 45 Mt case (centre), and net zero 20 Mt sink (right)

Whether electrification of industry, transport and other sectors results in decarbonization depends on the GHG emissions intensity of the electricity grid, which is presented in Figure 17. On the other hand, marginal increases in electricity demand are met by investing in zero-carbon generation and storage technologies in the net zero cases, except for a small amount of gas-fired peaking capacity – in other words the marginal impact of any additional electricity demand after the completion of Medupi and Kusile is limited to any additional fossil-fuelled CCGT or OCGT plants. The same applies to the carbon intensity of hydrogen production from grid electricity. GHG emissions in the electricity sector reach very low levels in the net zero cases, as described further below.

5.2. Industry

CO_2 emissions from industry are presented in Figure 21, including industrial process emissions. The majority of CO_2 emissions are combustion emissions to provide process heat, with the largest share of process emissions stemming from iron reduction, ferroalloys manufacture, and lime and cement production. Energy use in the industry sector is presented in Figure 22, including coking coal. Direct GHG emissions from the industry sector are mainly associated with the use of coal and coking coal. In the net zero cases, coal use is phased down rapidly after 2045. This is replaced by electricity, gas and hydrogen, and a small fraction of biomass. The reduction in overall energy demand in industry is a result of the reduction in thermal losses from on-site combustion of coal rather than a reduction in energy demand.

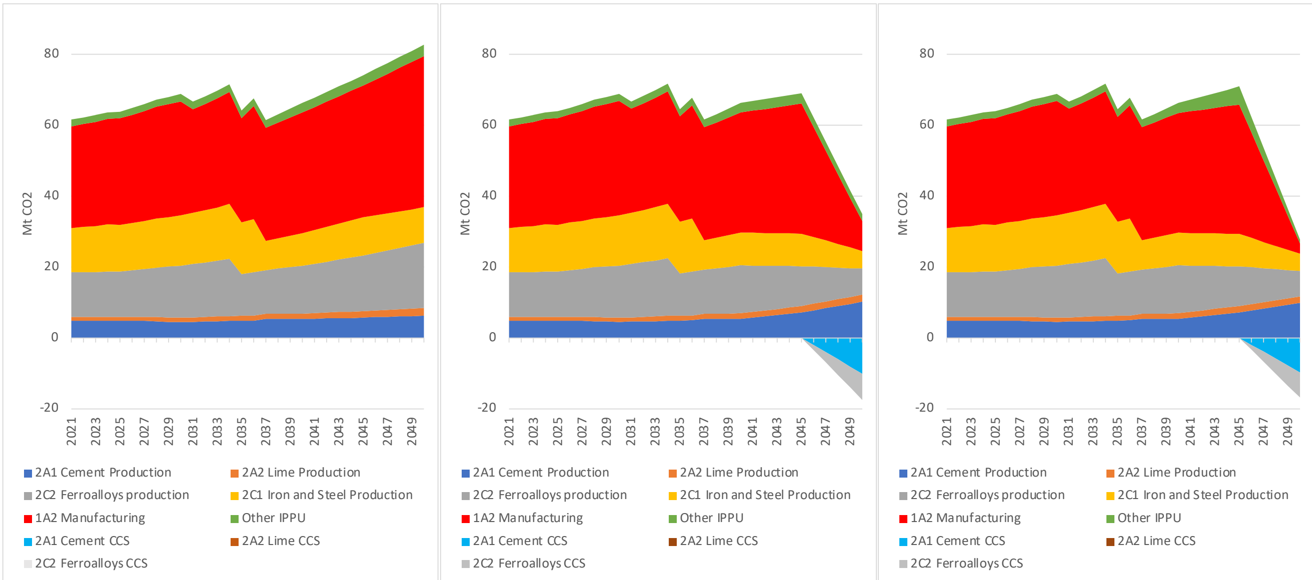

Figure 21 – CO_2 emissions from Manufacturing (1A2) and industrial process emissions for key emissions sources. Negative CO_2 emissions represent the use of CCS. NET CO_2 emissions are therefore emissions-CCS.

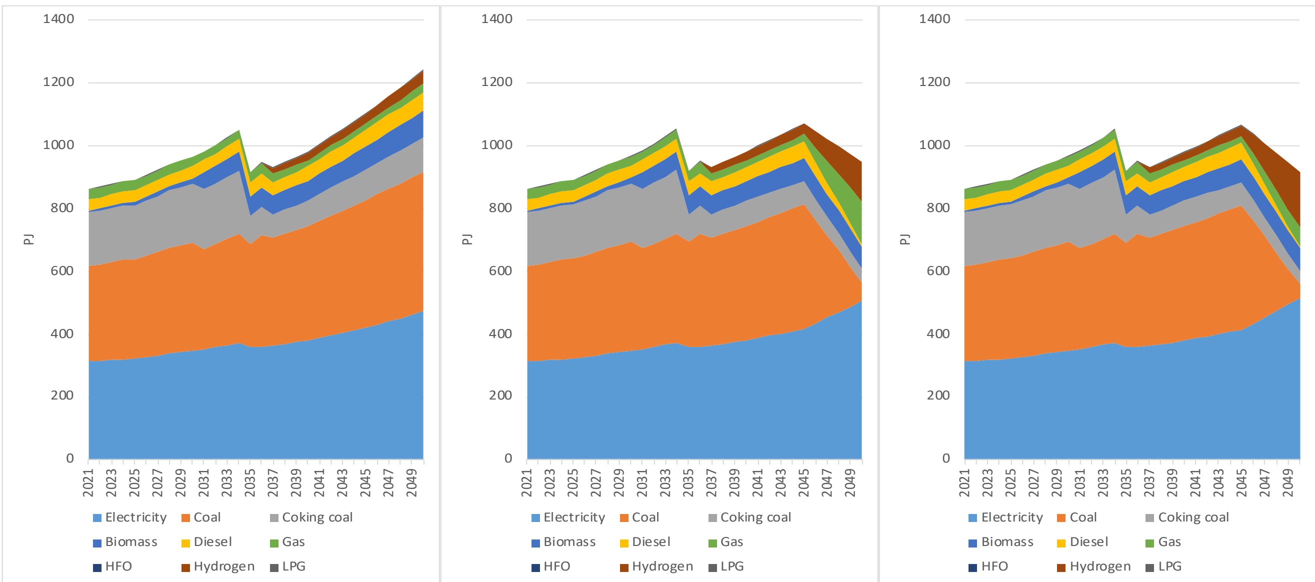

Figure 22 – Energy demand by energy carrier in industry in the reference case (left), net zero 45 Mt case (centre), and net zero 20 Mt sink (right) (includes coking coal used in the iron and steel and ferroalloys industries).

5.3. Transport

Transport demand, for both freight (ton kilometres) and passenger (passenger kilometres), the technology mix used to meet this demand, and the associated CO_2 emissions, are presented in Figure 23 and Figure 24. The shares of the demand for ton kms and passenger kms which are met by rail vs road in the case of freight, and public vs private transport in the case of passenger transport, are specified exogenously and are therefore inflexible in the modelling framework. In the absence of further policy incentivising either rail for freight or public transport for passenger transport, the ratio of demand satisfied by road transport vs rail in the case of freight, and private passenger transport vs public transport for passenger transport, increases in favour of road transport and private passenger transport. The impact of modal shifts in both freight and passenger transport is explored below.

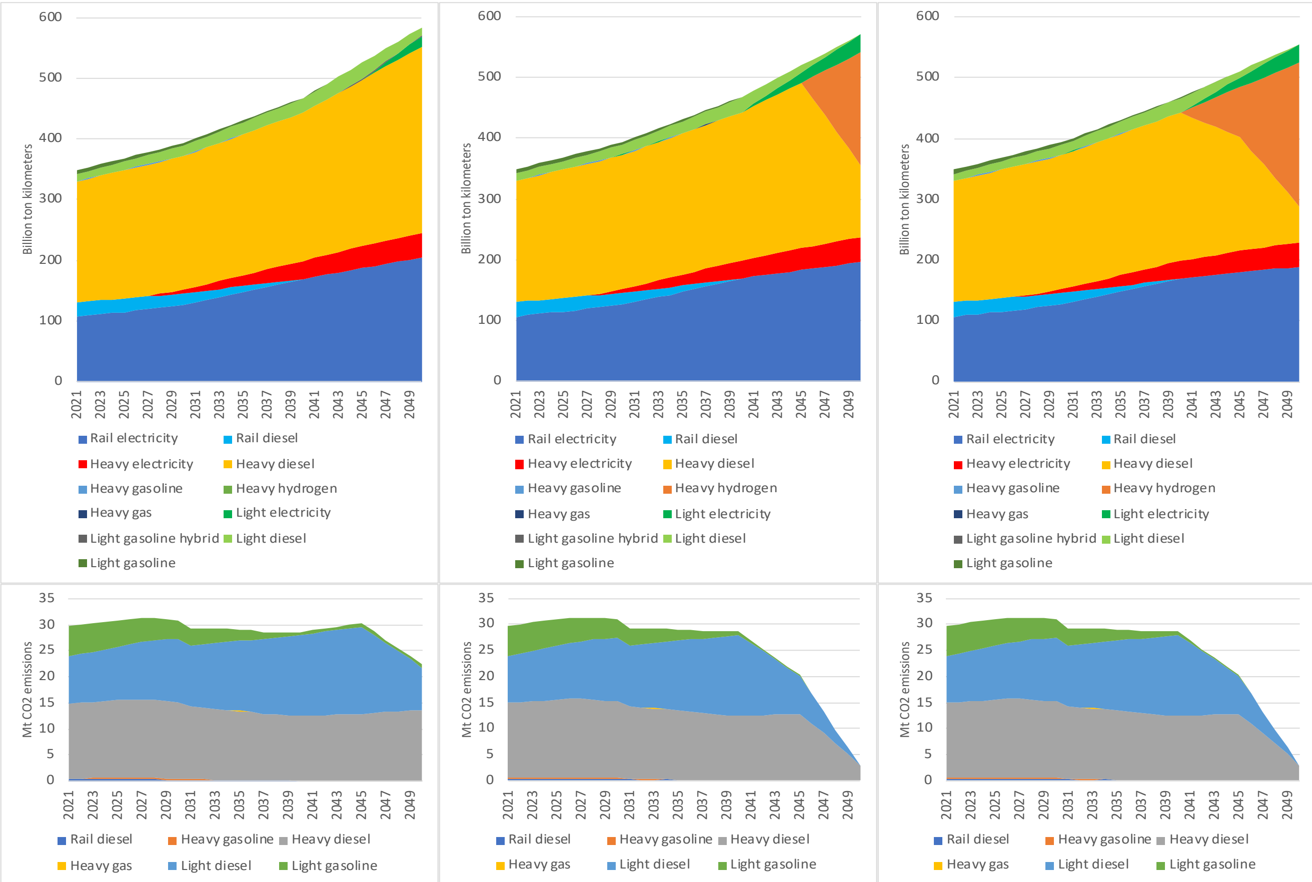

Figure 23 – Surface freight transport demand in billion ton kilometers in the reference case (top left), net zero 45 Mt sink case (top centre), and net zero 20 Mt sink case (top right), and corresponding CO_2 emissions for freight transport in the reference case (bottom left), net zero 45 Mt sink case (bottom centre), and net zero 20 Mt sink case (bottom right) (all divided into rail and heavy and light commercial vehicles (road)).

Freight transport is dominated in the reference case by electric rail transport and diesel-fuelled heavy-duty vehicles, with a very small contribution from heavy-duty electric vehicles. Light-duty vehicles are also primarily fuelled by fossil-based liquid fuels. Corresponding GHG emissions result from combustion of diesel and gasoline. In the net zero cases, there is a shift in the 2040s from diesel to hydrogen, with some diesel use still occurring by 2050 in the net zero cases. This is however as presented in Figure 25 biodiesel (with no net CO_2 emissions) in the net zero cases. Light-duty freight vehicles shift rapidly to electricity and do not emit any CO_2 by 2050.

For passenger transport, private passenger transport is dominated by diesel and gasoline vehicles (smaller cars and SUVs) initially, with an almost complete shift to electric vehicles from the later 2020s on. In the reference case, there is a shift back to diesel cars as a result of the low oil price. In the net zero cases, the private vehicle fleet is entirely electrified by 2050. In public transport, the underlying economics result in a shift in the reference case from diesel buses and diesel and gasoline minibuses, to complete electrification of both buses and minibuses by 2050. This patter is almost identical for both the reference and net zero cases.

This pattern corresponds to total energy use in the sector, as presented in Figure 25, which includes kerosene usage for air travel. Kerosene demand is differentiated into demand for domestic flights (which depart and arrive in South Africa, and the GHG emissions of which are accounted for as part of South Africa's national GHG inventory) and international flights (which are fuelled in South Africa, and depart from South Africa but arrive in another country, the GHG emissions of which are noted in South Africa's national GHG inventory, but are not accounted for in total GHG emissions for South Africa).

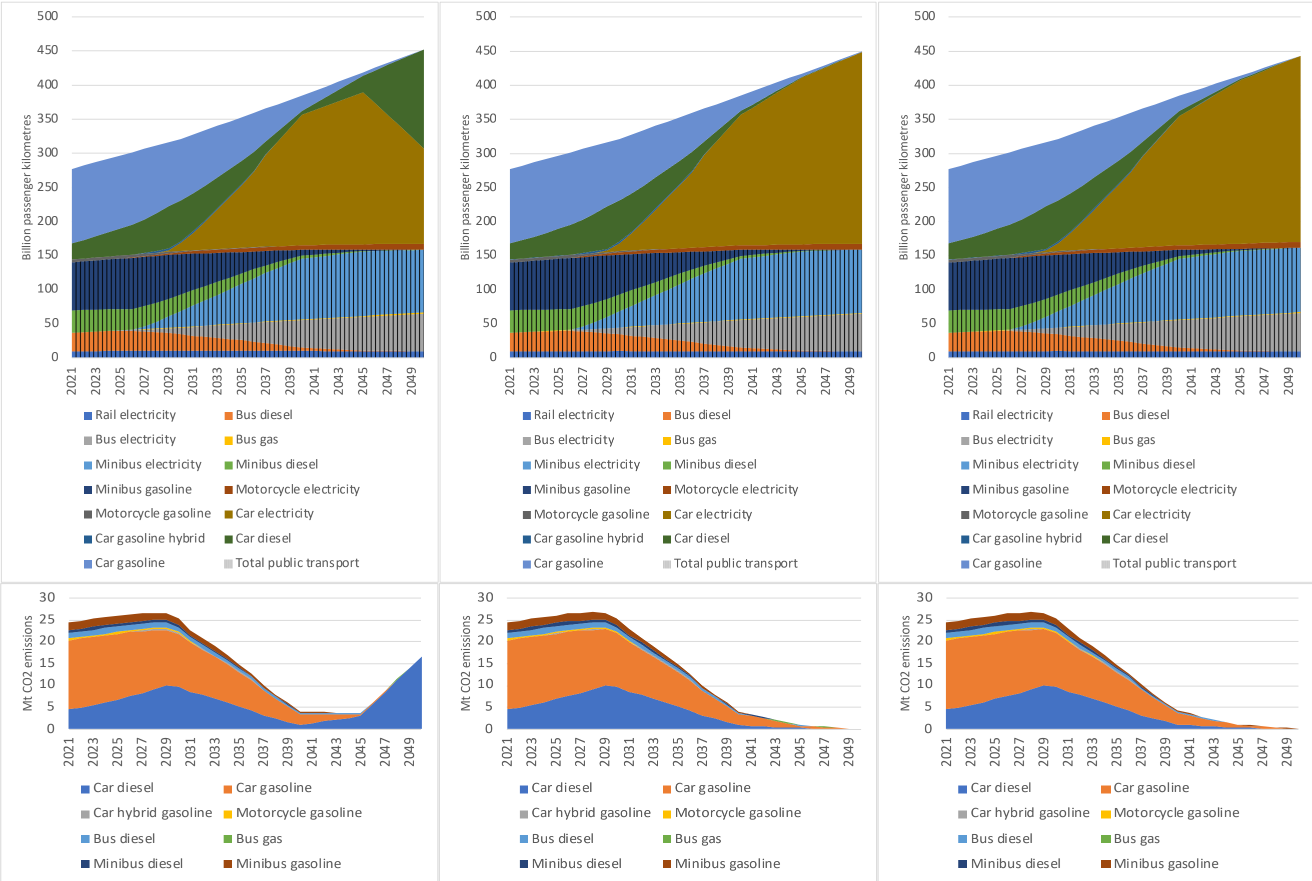

Figure 24 – Road passenger transport demand in billion passenger kilometres in the reference case (top left), net zero 45 Mt sink case (top centre), and net zero 20 Mt sink case (top right), and corresponding CO_2 emissions for passenger road transport in the reference case (bottom left), net zero 45 Mt sink case (bottom centre), and net zero 20 Mt sink case (bottom right). The share of passenger km provided by public transport in the upper graphs is shaded with vertical bars.

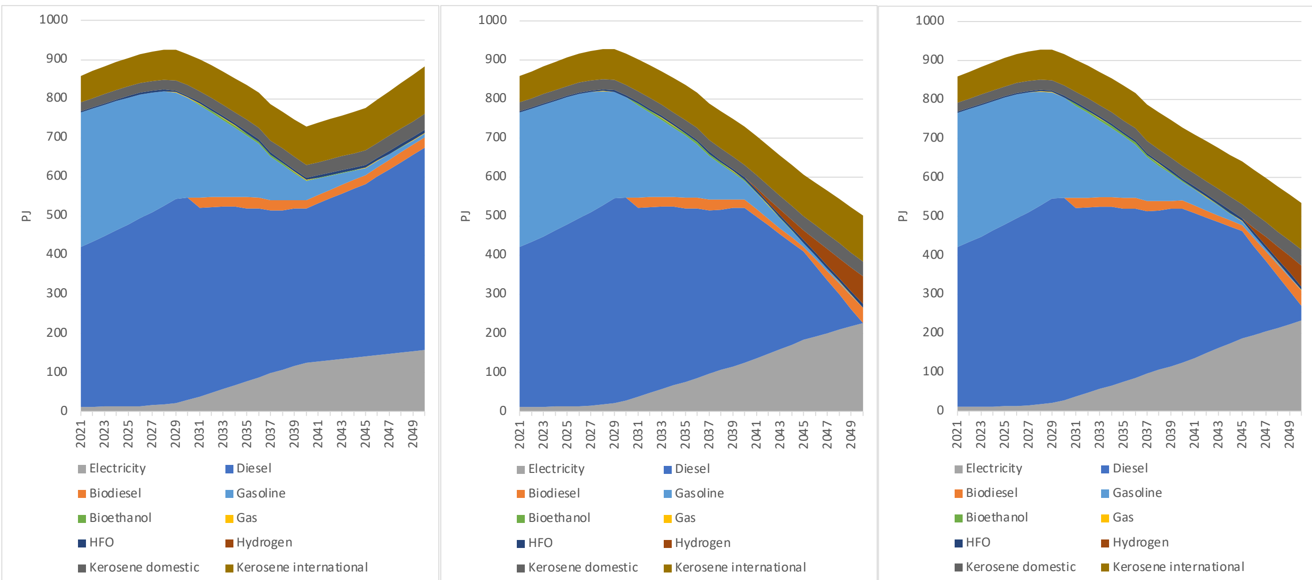

Figure 25 – Energy demand in the transport sector by energy carrier in the reference case (left), net zero 45 Mt sink case (centre), and net zero 20 Mt sink case (right). Kerosene demand (in the transport sector for jet aircraft), is divided into demand for domestic flights (which is included in South Africa's GHG inventory) and international flights (which is not).

A net zero CO_2 target in terms of the Paris Agreement would EXCLUDE GHG emissions from international flights. As for electricity, the total energy consumption level as well as the ratios between fuel types are misleading, since the direct use of liquid fuels in transport (via an internal combustion engine) results in a large quantity of waste heat, which is not the case for electricity . In the reference case, diesel use persists to 2050 with a far smaller role for electricity and a very small fraction of biofuels. For the net zero cases, diesel use decreases to very low levels (which are dominated by biofuels), and electricity predominates, with a small contribution from hydrogen.

5.4. Liquid fuels supply (fossil fuel-derived)

Liquid fuels demand, and the corresponding supply, as presented in Figure 26, declines until the late 2030s, when the economics of the transport sector lead to a growth in demand for diesel, in the reference case. This is mostly imported, as a result of unfavourable economics and the required product profile. South African crude refineries and the CTL process cease production by 2035 in all scenarios (including the reference case); in the net zero scenarios, the recovery of diesel demand does not happen.

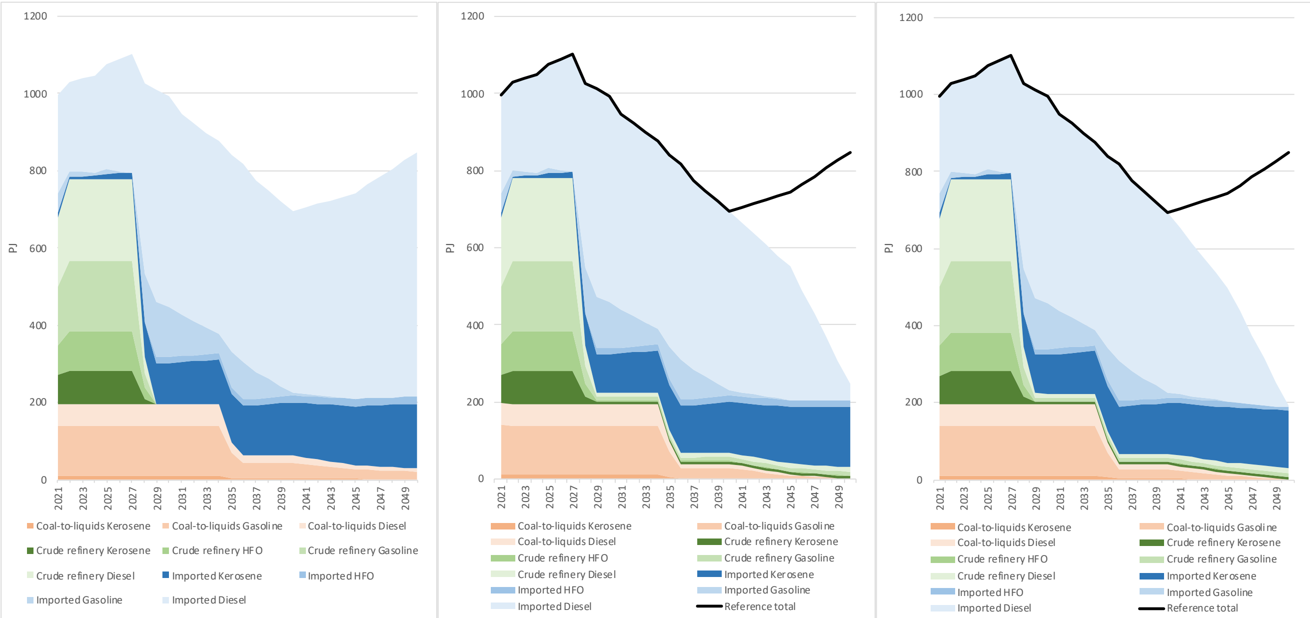

Figure 26 – Fossil fuel -derived liquid fuel supply by fuel and source for the reference case (left), net zero 45 Mt sink case (centre), and net zero 20 Mt sink case (right). The black line corresponds to total liquid fuels demand in the reference case (in PJ).

5.5. Remaining CO_2 emissions in 2050 and the uptake of CCS

Table 2 presents the state of CO_2 emissions In the reference case and 20 and 45Mt carbon sink cases. Total CO_2 emission in 2050 are above 200Mt of CO_2, which is only a 40% reduction of CO_2 emissions 2021. Without any carbon constraint, there is no reason to use CCS options, which are inherently more expensive than other technology options. In the net zero cases, CO_2 emissions reach close to net zero in 2050, with the use of CCS, which is discussed in more detail below. Remaining CO_2 emissions in 2050 in the current results are as a result of interactions between the different sectoral model components, which will be addressed in the next version of the modelling framework (mainly due to resolution of iterations between the energy and economic models).

Table 2 – CO_2 emissions in 2050 in the reference, 45Mt and 20 Mt sink cases

	Reference	**Net zero 45 Mt sink**	**Net Zero 20 Mt sink**
Total CO_2 emitted in 2050	232.1 Mt	75.1 Mt	53.7 Mt
Total CO_2 stored in 2050	0 Mt	28.8 Mt	29.9 Mt
Net CO_2 emissions in 2050 from energy and IPPU	232.1 Mt	46.3 Mt	23.8 Mt
Net CO_2 emission from AFOLU and waste in 2050	-10.7 Mt	-43.8 Mt	-18.7 Mt
Total net CO_2 emissions in 2050	221.4 Mt	2.5 Mt	5.1 Mt

Figure 27 presents CO_2 emissions still remaining in the economy in 2050 per emitting IPCC category for energy and IPPU CO_2 emissions, as well as the extent to which CCS is used by the modelling framework in 2050. There are no mitigation options for ferrochrome, lime production or cement production, and hence CCS is used extensively in these sectors for the net zero cases. Remaining GHG emissions in the electricity sector result in the reference case from three large coal plants still in operation (Medupi, Kusile and Majuba). In the net zero cases, CO_2 is emitted by only one coal plant (Kusile) and from natural gas-fired power plants. CCS options are taken up by cement and ferrochrome (presented in detail in Figure 28), for which there are no other mitigation options in the modelling framework at present, and by electricity, in different configurations. Because of the cost of CCS this is only taken up in the last five years to meet the net zero target.

Figure 27 – Remaining CO_2 emissions in 2050 in the reference case (top), net zero 45 Mt sink case (middle), and net zero 20 Mt sink case (bottom), and use of CCS. The overall length of the bars in each category are the CO_2 produced by that sector in 2050; the red section of each bar is the amount of CO_2 which is stored, and the blue section is the amount emitted to atmosphere.

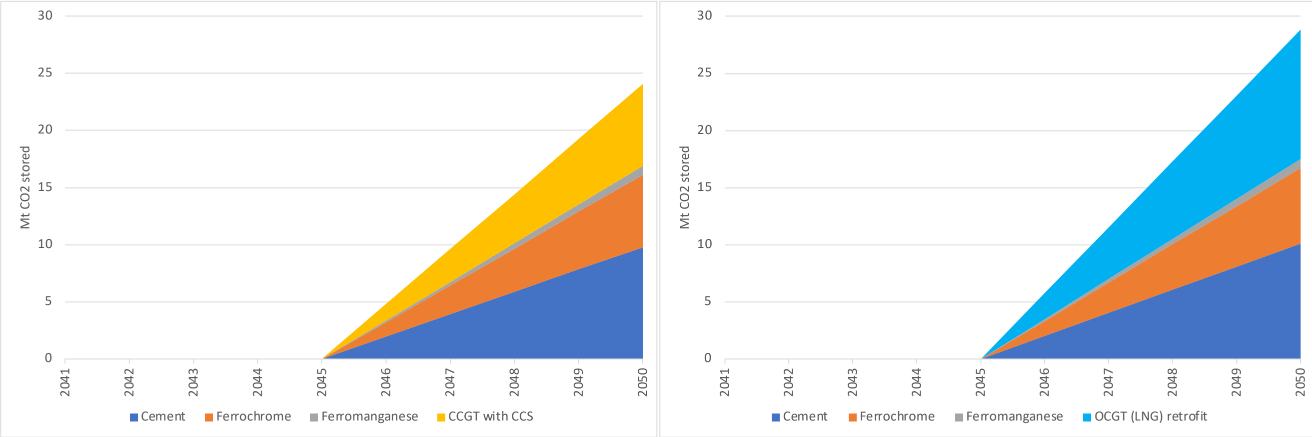

Figure 28 – Use of CCS by sector/technology in the net zero 45 Mt sink case (left), and net zero 20 Mt sink case (right) (CCS is not used in the reference case).

5.6. Natural gas and hydrogen utilization

Without an emissions constraint and with the gas price assumptions used in this study, the use of natural gas is extensive as presented in Figure 29. Gas use in the power sector is scaled back significantly in the net zero cases, and used in combination with CCS.

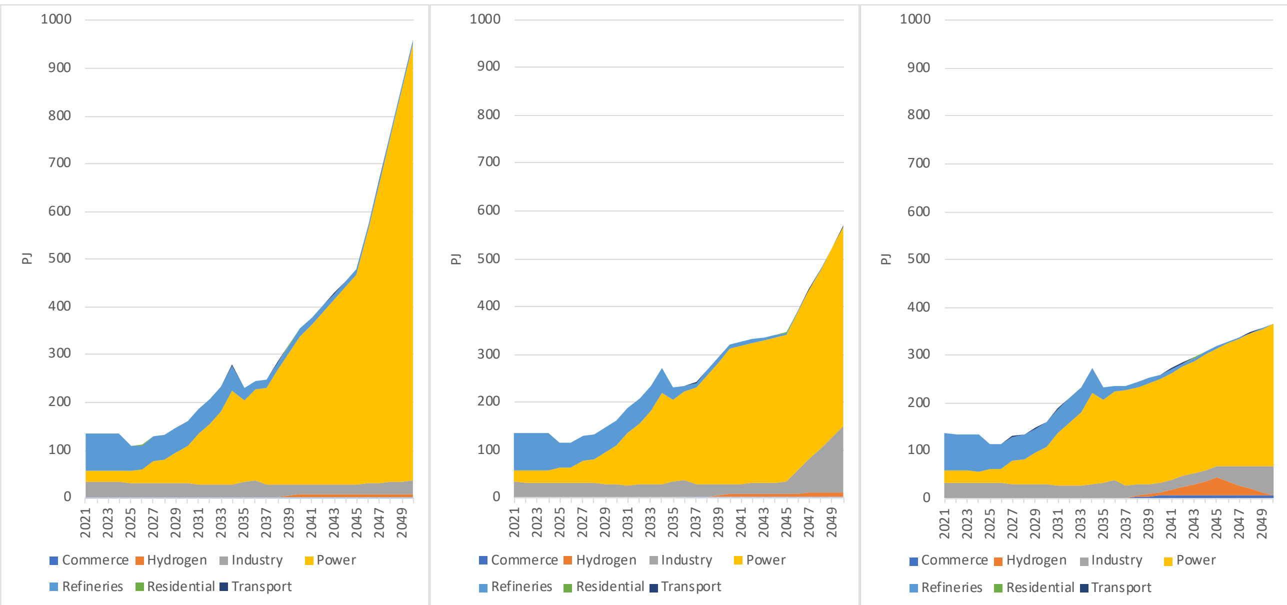

Figure 29 – Natural gas utilization in the reference case (left), net zero 45 Mt sink case (centre), and net zero 20 Mt sink case (right). “Hydrogen” = hydrogen manufacture from natural gas

Hydrogen sees significant use only from 2036 in both the reference and net zero cases as presented in Figure 30. In the reference case it is manufactured wholly from natural gas, which results in additional CO_2 emissions. In the last five years, and five years earlier in the net zero 20 Mt case, the net zero cases feature hydrogen use for heavy freight transport.

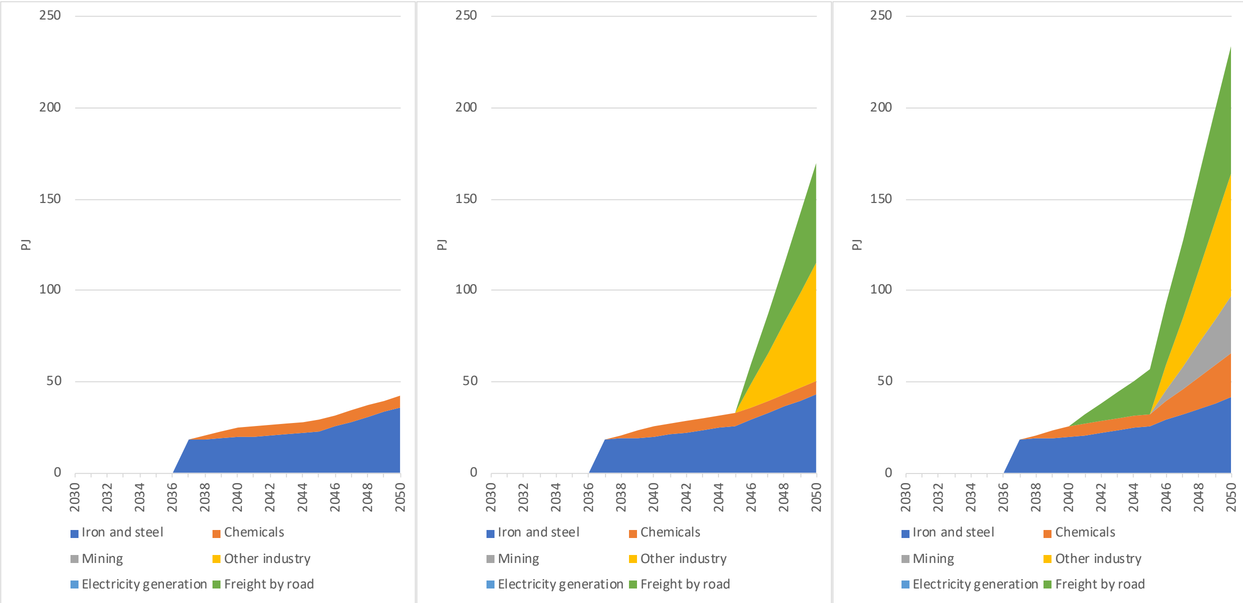

Figure 30 – Hydrogen production utilization for the reference case (left), net zero 45 Mt sink case (centre), and net zero 20 Mt sink case (right).

5.7. Investment requirements and economic impacts

There are a number of key indicators which can be used within the modelling framework to explore the economic impact of cases. The first is the total system cost, derived from the energy model, which considers the cost of capital, operations and fuel (where applicable) over the modelled period. The second is the effect of additional constraints on economic growth, measured in terms of Gross Value Added (GVA), as a proxy for the size of the economy. The third useful indicator is the capital requirements for decarbonization. Here we report only the capital requirements of the electricity sector.

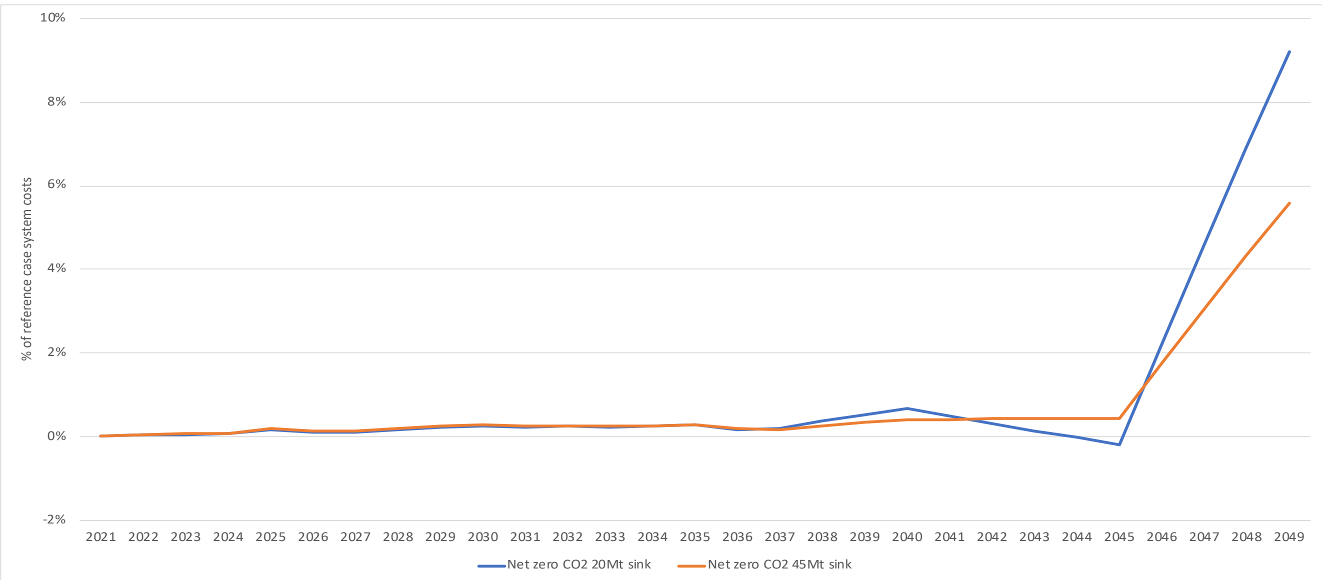

Figure 31 – Percentage increase in total undiscounted system costs (energy and IPPU) relative to the reference case

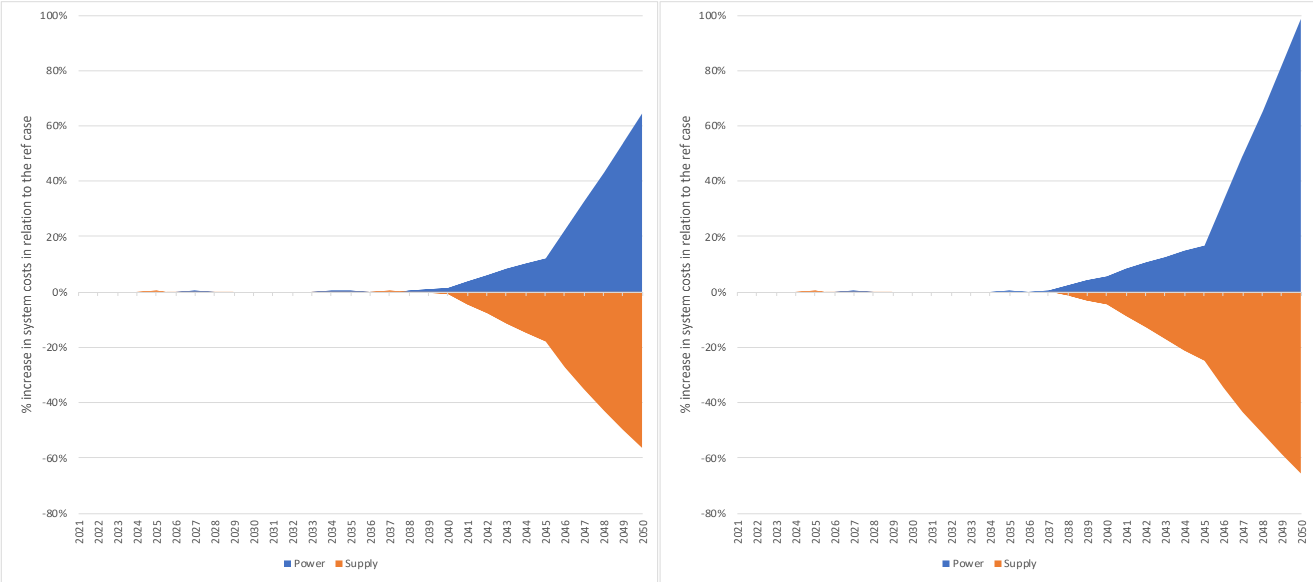

Figure 32 – Percentage undiscounted system cost difference between the reference case and the net zero 45 Mt sink case (left), and net zero 20 Mt sink case (right) for the power sector and the fuel supply sector (which includes the cost of fuels (coal, liquid and nuclear fuels) supplied to the power sector). These two sectors account for an average of 89% of cost differences between cases.

Increases in total system costs for the net zero cases is below 10%. The two sectors which account for most of this are power and fuel supply – as expected, additional capital costs in the power sector (due to a faster exit from coal) are offset by savings on fuel supply including coal.

Investment requirements in the power sector rise extremely rapidly, by about six times, in the net zero cases from around 2045 as presented in Figure 33. It is doubtful whether the country's technical and economic capabilities would be able to support such a rapid rise in investment in reality. The requirements of this investment programme are also the main driver for the lower growth rate (the size of the economy in relation to the reference case is presented in Figure 34), which is the result of a crowding-out effect. This economic impact may be offset by measures such as the large-scale use of international climate finance at concessional interest rates, assuming it is available at this scale, but this rapid shift is also incompatible with other policy goals such as green industrialisation, and given that other countries have the same CO_2 target, supply bottlenecks may render this impossible. In addition, by 2049, investment in the electricity sector comprises 6.2-7.1% of total GVA, up from just over 1% in the reference case. The result of this is that the economy is smaller in the net zero cases by 3-6% as presented in Figure 34 due to the crowding out effect.

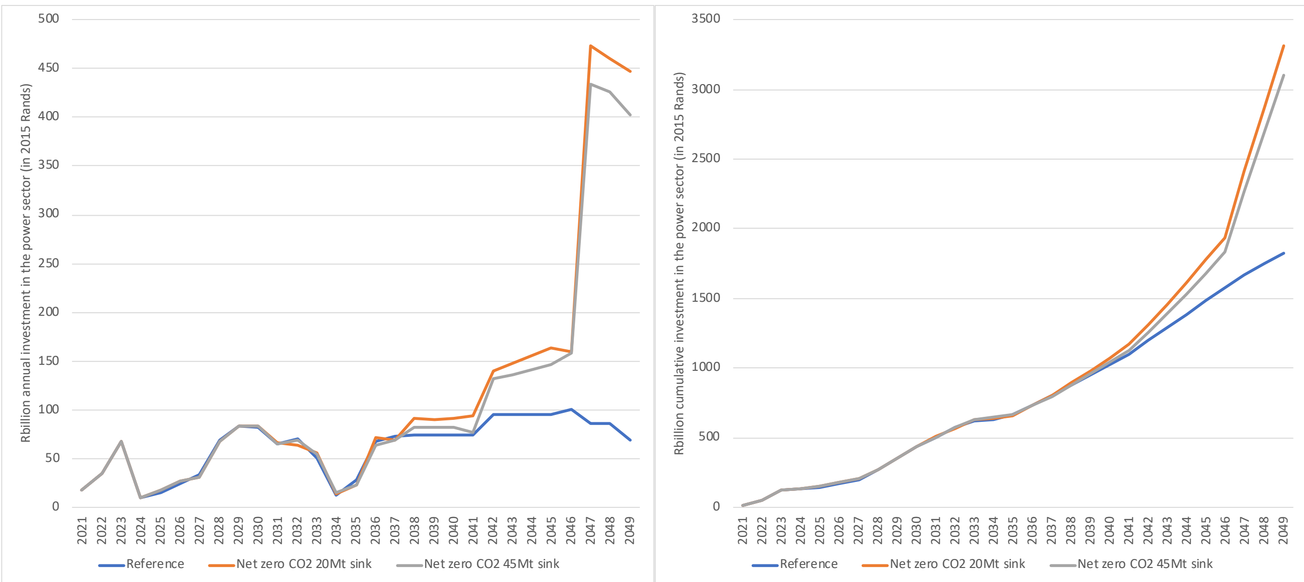

Figure 33 – Annual (left) and cumulative (right) investment requirements in the electricity sector, 2021-49, for the reference and net zero cases.

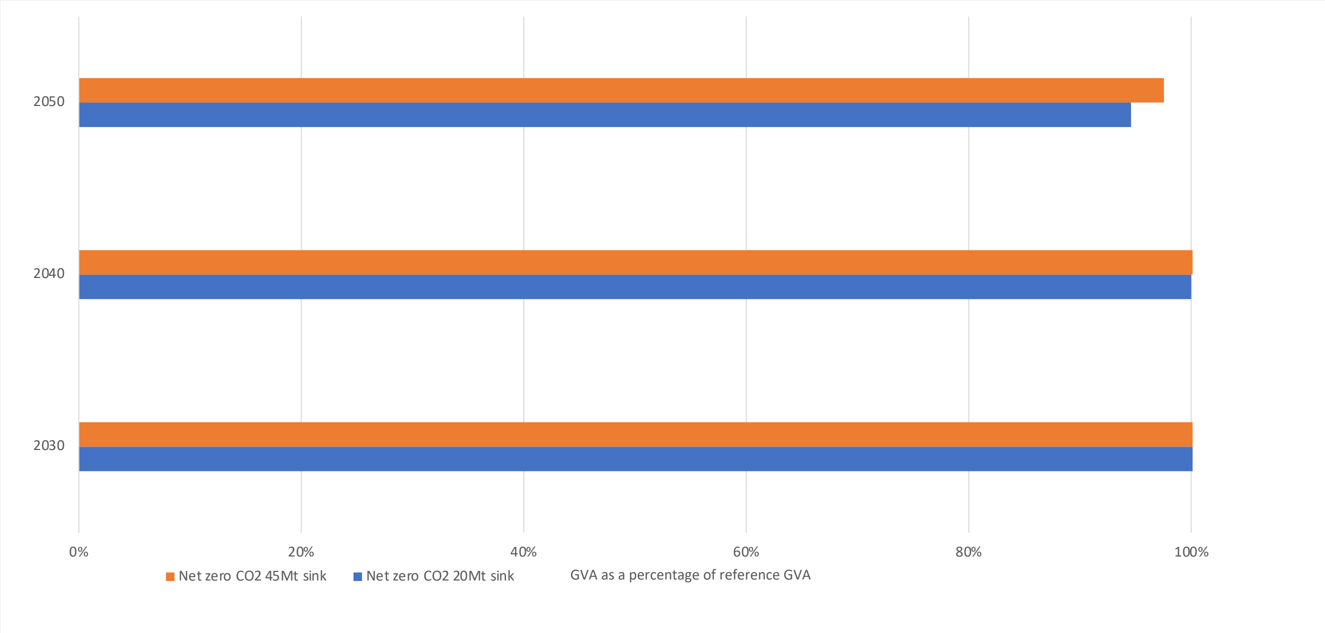

Figure 34 – Gross Value Added (GVA) for each case as a percentage of GVA for the reference case, for the specific year.

5.8. Cumulative GHG emissions

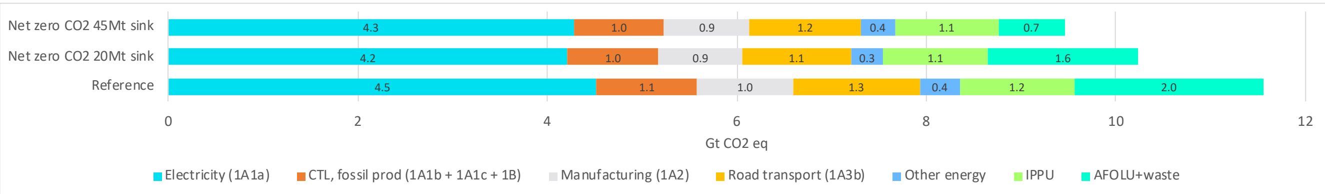

Figure 35 – Cumulative GHG emissions, 2021-50, for key emitting sectors, in Gt CO_2-eq.

The reference case has cumulative emissions of 11.56 Gt CO_2-eq (2021-2050), whereas the 20 Mt sink net zero case has cumulative emissions of 10.24 Gt. The 45 Mt sink case has cumulative emissions of 9.46 Mt. The key difference between net zero cases, in the absence of the inclusion of other policies and measures is the additional mitigation in the AFOLU sector over the whole period; in the 45 Mt sink cases this leads to a 1.3 Gt GHG emissions savings over the 2021-50 period, and in the 20 Mt cases a 0.4 Gt saving. The net zero cases, in the absence of any further GHG constraint, mitigate a relatively small amount of GHG emissions in the energy sector compared to the reference case.

6. Imposing a GHG emissions budget

For a number of reasons, the net zero cases discussed above are probably outliers in practice. Not only are the investment requirements in the last five years implausible, but these are arguably not consistent with either South Africa's fair share over the longer term, or with a medium term GHG emissions outcome which would constitute a fair contribution to the global effort, and also meet the 2030 NDC mitigation target. In this section we report on the results of modelling long-term cumulative GHG constraints as well as reaching net zero CO_2 emissions by 2050. Results will be reported for four cumulative GHG emissions budgets, from 2021 to 2050, of 9, 8, 7 and 6 Gt. This range is an outcome of the discussion above on the existing literature on national mitigation burden-sharing, to evaluate a series of cumulative budgets in terms of what would be required for each budget in the medium and long term.

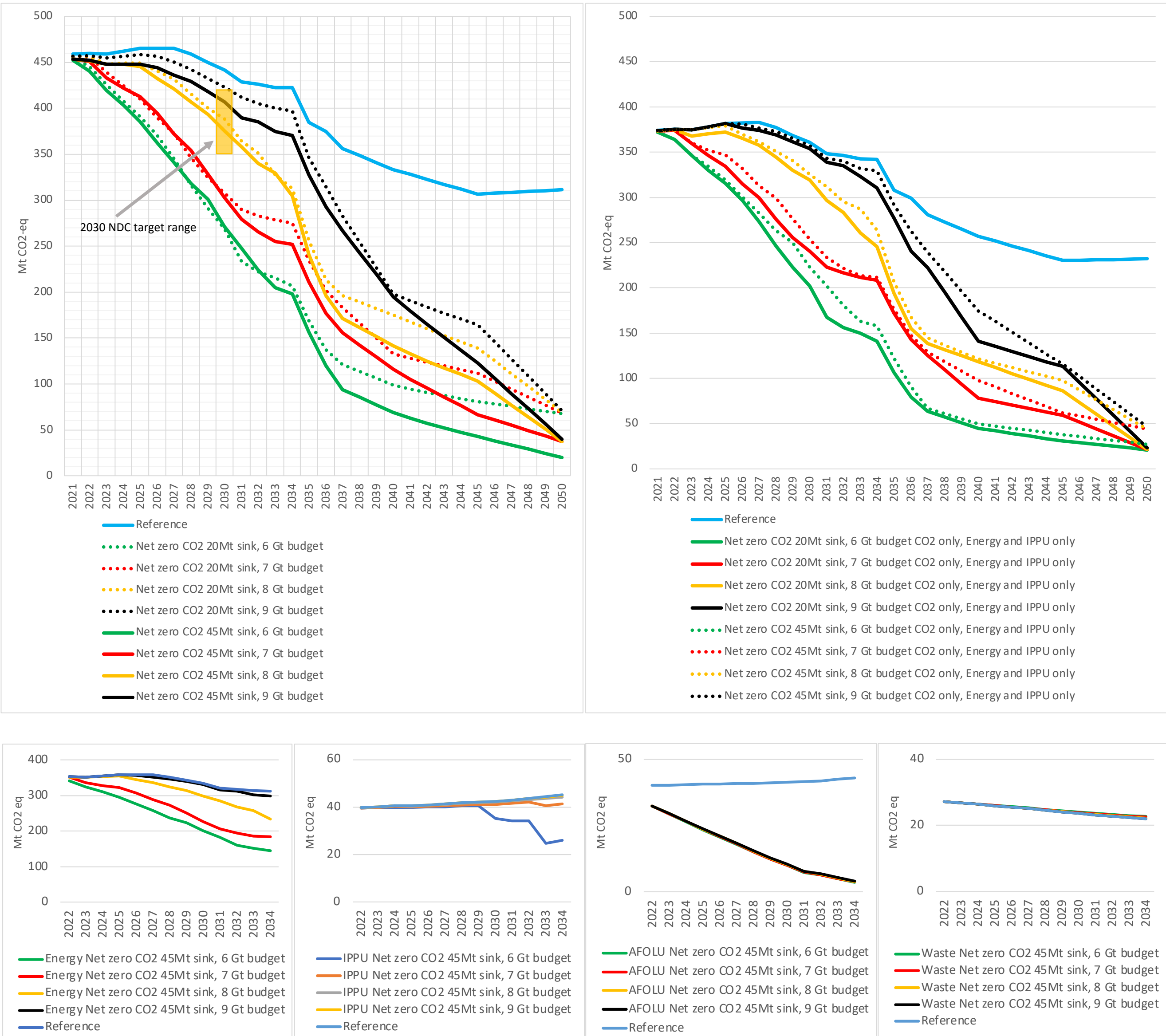

Figure 36 – Reference case with eight modelled pathways with net zero CO2 goals by 2050, with carbon sinks in the land sector of 20 and 45 Mt in 2050, with GHG budgets of 6-9 Gt,, with all GHGs (left) for the whole economy, and CO_2 only in the energy and IPPU sectors (right). The bottom row of figures presents GHG emissions for the energy (left), IPPU (centre left), AFOLU (centre right) and waste (right) sectors for these cases.

The impact on GHG emissions constrained by these budgets, as presented in the sectoral figures in Figure 36 on medium term effects, is negligible in the AFOLU and waste sectors, because there is limited feedback within the modelling framework, and for these cases, measures to achieve a 45 Mt sink are assumed. There is a more pronounced variation later in the modelled period due to changes in GDP. The large impact which the constraint has is on the other two sectors – energy and industrial process emissions, and keeping GHG emissions within these budgets requires ambitious mitigation action within this decade.

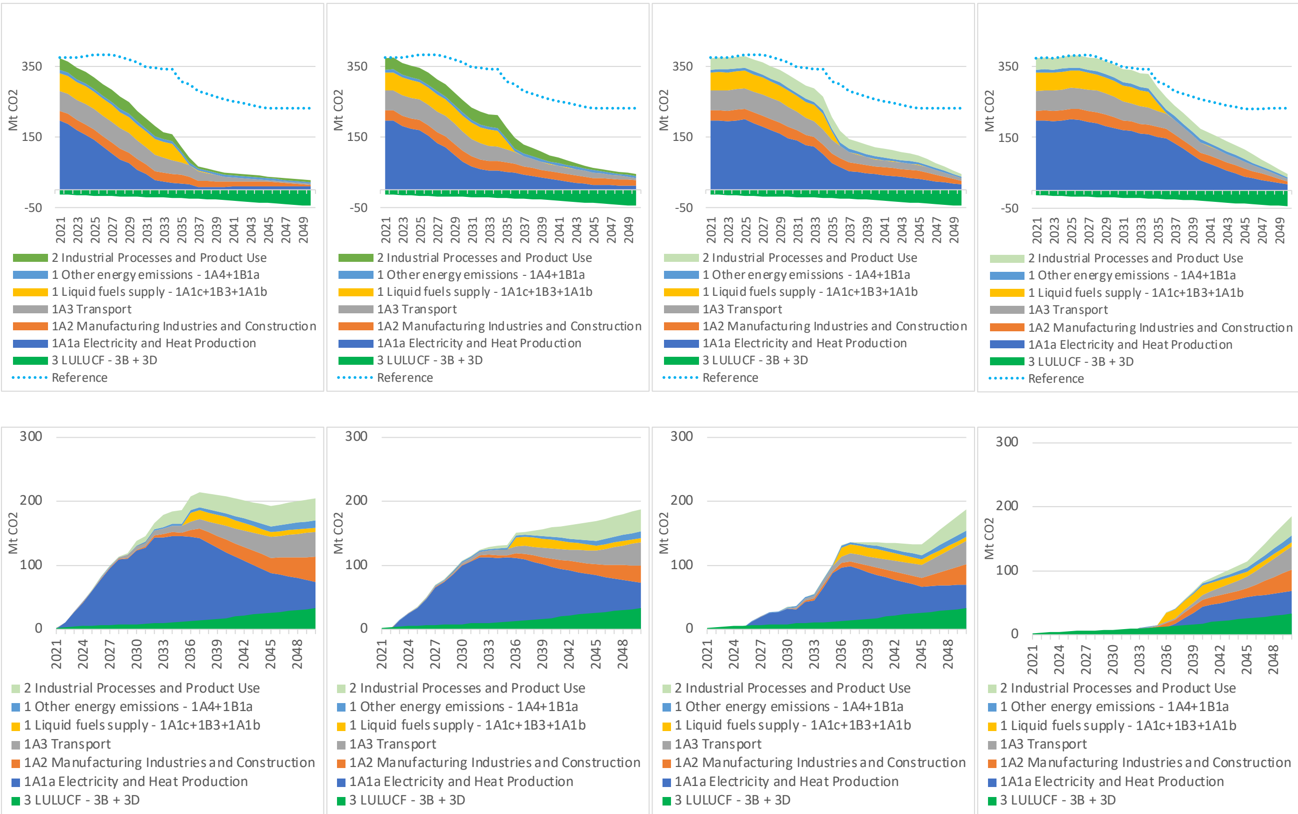

Figure 37 – CO_2 emissions by major emitting sector with a 45 Mt sink in 2050 for the 6-9 Gt GHG budget cases (top), and mitigation by sector in relation to the reference case for the 6-9 Gt cases (bottom). All cases with a 45 Mt sink in 2050.

This is more precisely presented in Figure 37, which presents CO_2 emissions for the largest emitting IPCC categories, and the scale of mitigation for each sector. The more constrained budgets result in far earlier mitigation action at scale – whereas in the 8 and 9 Gt budget cases there is not much acceleration of decarbonization in the 2020s, this is necessary for more stringent budgets to meet the constraint. Moreover, even in the extremely ambitious 6 Gt case, the electricity sector is the only sector in which decarbonization is accelerated up to 2030. Since this is relative to the reference case, it needs to be borne in mind that the reference case itself does decarbonize the transport sector partially, starting in the 2020s, as well as the electricity sector. Imposition of GHG budgets would accelerate this process. As in the reference case, the liquid fuels supply sector curtails activity and thus emissions around 2030, but in all the budget cases it ceases production in 2035.

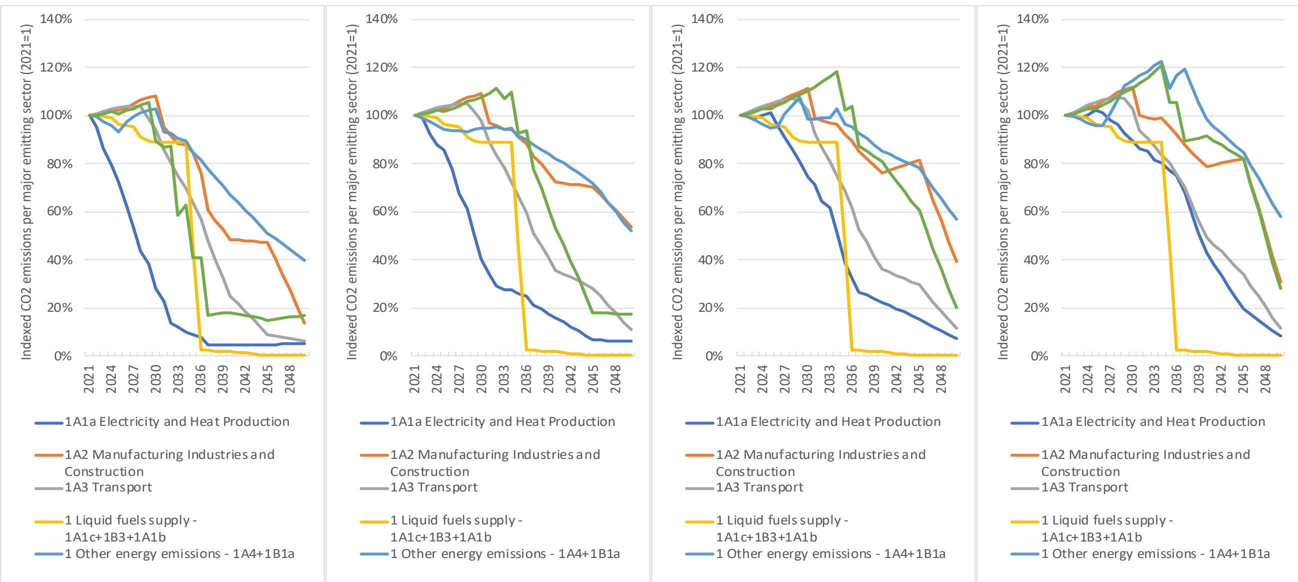

Figure 38 – Indexed CO_2 emissions for key emitting sectors (2021=100%), with a 45 Mt sink in 2050, for 6-9 Gt budgets (left to right).

Decarbonization is rapidly accelerated in the energy and transport sectors, as well as in industry, with tighter emissions budgets, since more rapid reductions are necessary to stay within the cumulative budget. In the case with the most stringent budget (6 Gt), the electricity sector is almost entirely decarbonized by 2030.

6.1. Electricity

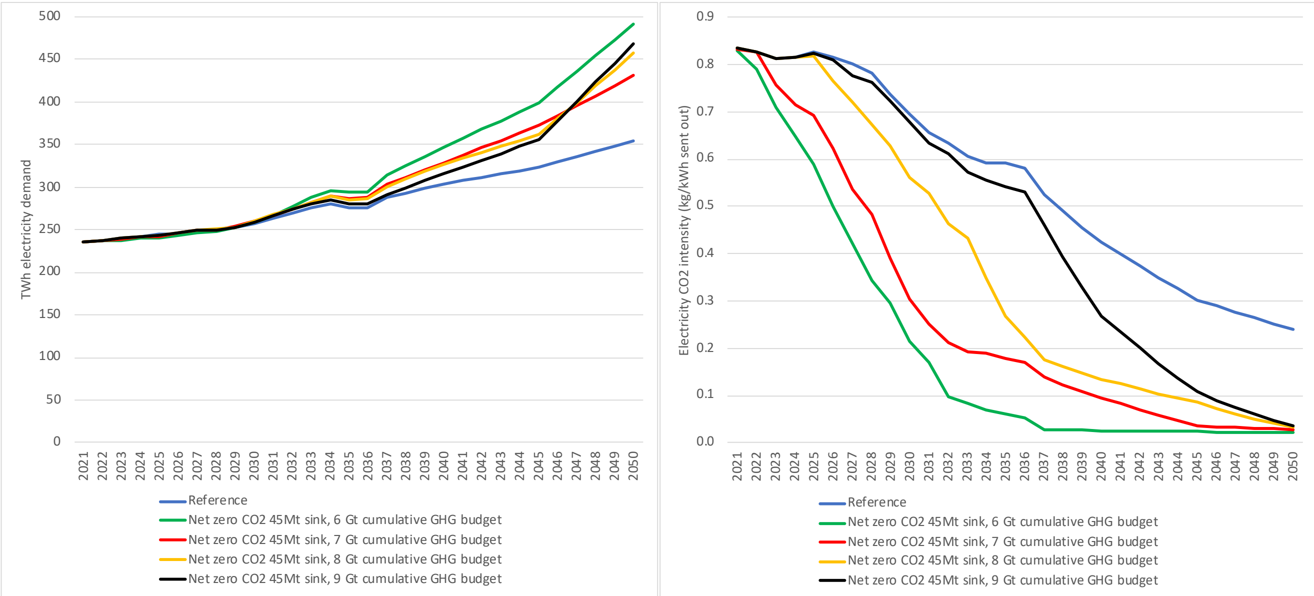

Figure 39 – Total electricity demand (left) and CO_2 intensity of electricity (right) in the reference and net zero 45 Mt sink cases with GHG budgets of 6-9 Gt

Electricity demand is considerably higher in the emissions-constrained cases from 2030 onwards, as presented in Figure 39, because of the need to decarbonize earlier. This increase in demand, which is broken down by sector in Figure 40, is driven by additional electrification to that which occurs in the reference case in the industrial and transport sectors (with smaller contributions from the commerce and residential sectors), and electricity use for both hydrogen production, and carbon capture and storage. Figure 41 presents the percentage of electricity use in each sector, as a proportion of total final energy use in that sector, which is a good indicator of additional electrification[34]. In the residential sector, in the reference case the level of electrification rises from 58% in the reference case to 68% in 2050 to 72-5% in the net zero cases. In the commerce sector, the proportion of electricity use actually drops in the reference case, and in most of the net zero cases as well.

In the industry sector, electrification follows a complex pattern as the GHG budget reduces. In the reference case the share of electricity in this sector remains more or less the same, whereas in the net zero cases without a GHG budget, electrification grows only slightly to 2040, and grows very significantly in the last decade to meet the net zero constraint. In the cases with a GHG budget, the extent to which electrification options are taken up varies in a complex way as the GHG budget decreases. The share of electricity starts at 36% in 2021, and increases slightly in the reference case to 38% in the reference case. In the net zero cases without a GHG budget, it does not increase relative to the reference case, but increases dramatically in the last decade to 55-58%, depending on the value of the carbon sink. In the GHG budget cases, the pattern is complex, and in order to meet the constraint, the model decarbonizes the electricity system a lot earlier, and shifts to electricity earlier – around 45-48% compared to 39% in the reference case in 2040, and in 2050 both the 9 and 8 Gt cases reach around 54% of energy provided to the industry sector coming from electricity by 2050, whereas the 7 Gt case features a LOWER electrification rate in 2050 than the higher cases, and the 6 Gt case reaches an electrification rate of 60%. This is because the 7Gt case begins to decarbonize the electricity sector earlier, which also lowers the GHG intensity of electrified sectors. This is very likely to be sensitive to a change in the discount rate, which was not explored in this study.

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[34] The shift from fuels which are combusted in the respective sectors (for instance liquid fuels or coal, or biomass) to electricity is distorted by the large thermal losses from fossil fuel combustion, and the degree of distortion varies significantly by sector – for instance the efficiency of liquid fuel use for transport is very low, whereas the efficiency of coal use in industry is relatively high (since it is used mainly for supplying heat.

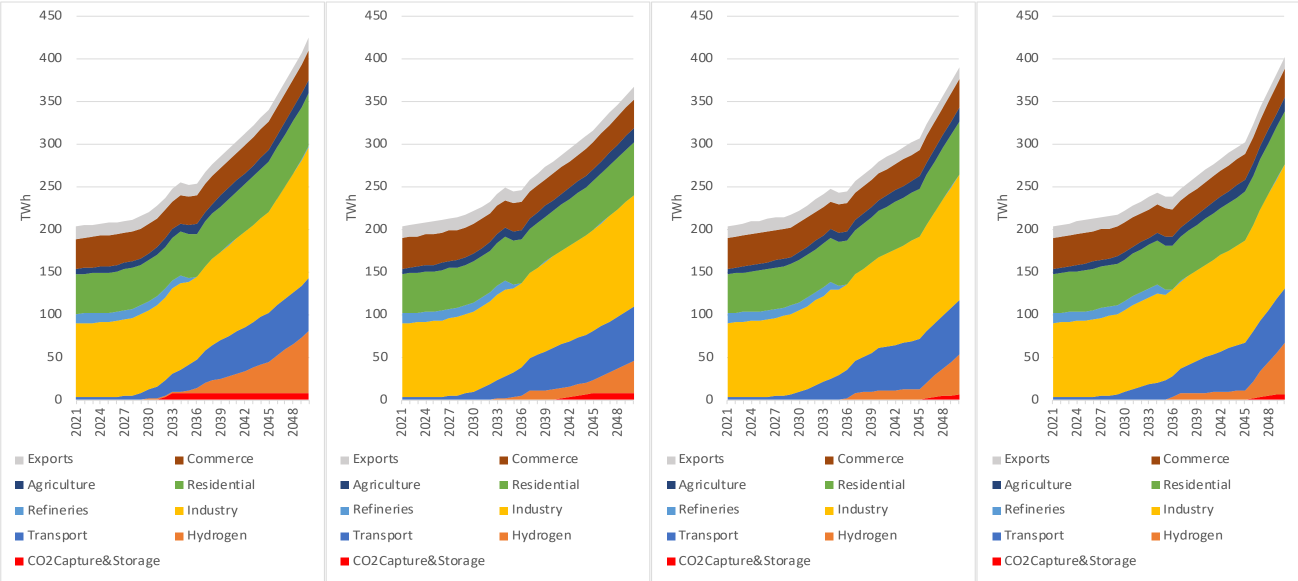

Figure 40 - Electricity demand by sector in net zero 45 Mt sink cases with GHG budgets of 6-9 Gt (left to right)

Figure 41 – Share of electricity demand as a percentage of energy demand in each sector, for each case in 2021, 2040 and 2050

On the supply side, the size of the grid expands from its current value of just over 50 GW to just under 250 GW by 2050, with investments in zero carbon electricity capacity happening much earlier in the cases with lower cumulative GHG emissions, as presented in Figure 42 (new capacity) and Figure 43 (total capacity) as opposed to just over 100 GW in the reference case. These cases still feature a massive increase in the rate at which new capacity is added in the last 2 years before 2050 to meet the net zero constraint. In this analysis, there are no constraints for the addition of new capacity, and there are a number of constraints to increasing the investment rate dramatically (from technical constraints to financial constraints) which should be tested in future analyses. The new capacity which is added to the electricity system is predominantly solar PV and wind capacity, with OCGT (natural gas fired) and batteries providing ancillary services. It should be borne in mind that batteries require additional generation capacity (since these are charged with electricity). Some CCGT (natural gas) is invested in, but this fades away to almost nothing from the 9 (11 GW) to 6 (1 GW) Gt cases, and with no new CCGT capacity beyond 2038.

It is also worth noting that the build rate has not been optimised for localisation of parts of the wind, solar PV and battery value chains. Figure 42 indicates that the model runs in this analysis result in considerable annual fluctuations in the investment rates for new zero carbon technologies, which would not optimally support a high degree of localisation or national construction capacity in the electricity sector. The existing coal fleet is modelled with endogenous retirement: the default case is that existing coal plants retire at the latest at the specified date in IRP 2019, but these will be retired if the annual utilization falls below 20%. In the GHG unconstrained cases, this does not occur other than in the net zero cases in the last five years, whereas in the 6-9 Gt cases, as presented in Figure 44, this occurs more and more rapidly until in the 6 Gt case, most of the current coal fleet has retired by 2038.

Table 3 – Percentage electricity generated by fuel source over the period 2021-2050 (excluding imports)

Fuel source	Reference	Net zero CO_2, 45Mt sink, 6 Gt	Net zero CO_2, 45Mt sink, 7 Gt	Net zero CO_2, 45Mt sink, 8 Gt	Net zero CO_2, 45Mt sink, 9 Gt
Coal	48.74%	18.27%	24.20%	32.41%	41.71%
Diesel	0.23%	0.27%	0.26%	0.24%	0.23%
Gas	12.11%	5.31%	5.53%	6.13%	6.62%
Nuclear	3.72%	3.81%	3.68%	3.68%	3.72%
Hydro	0.26%	0.23%	0.24%	0.24%	0.25%
Wind	14.33%	38.43%	35.74%	30.16%	23.65%
Solar	20.62%	33.67%	30.35%	27.14%	23.83%

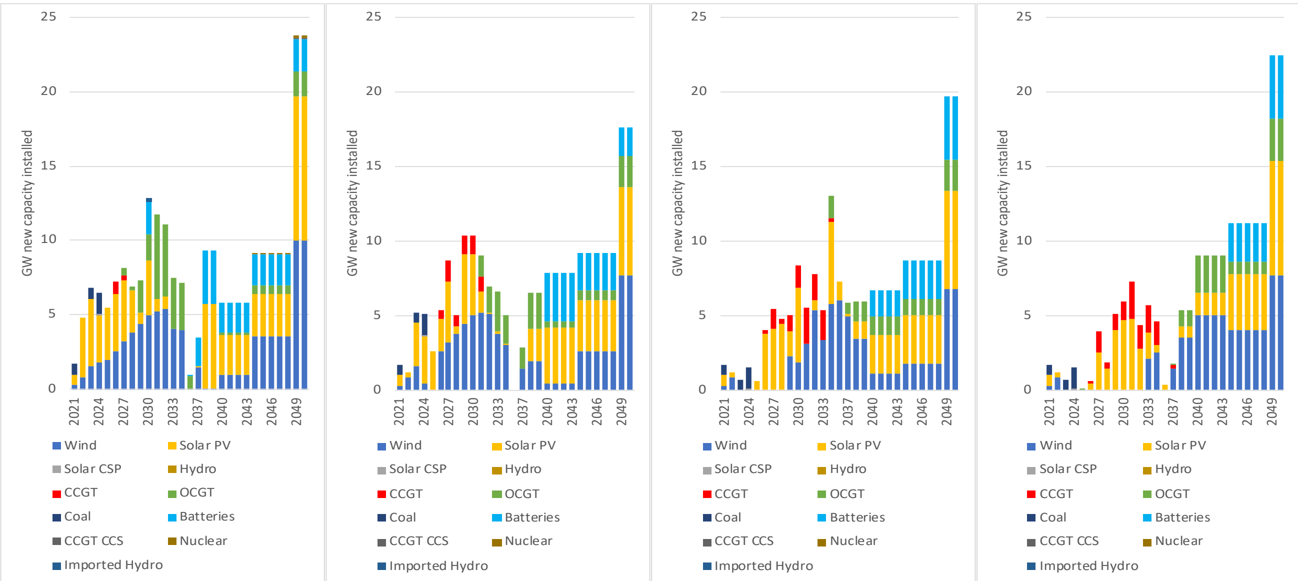

Figure 42 – New generating capacity added by technology in the net zero 45 Mt sink cases with GHG budgets of 6-9 Gt (left to right)

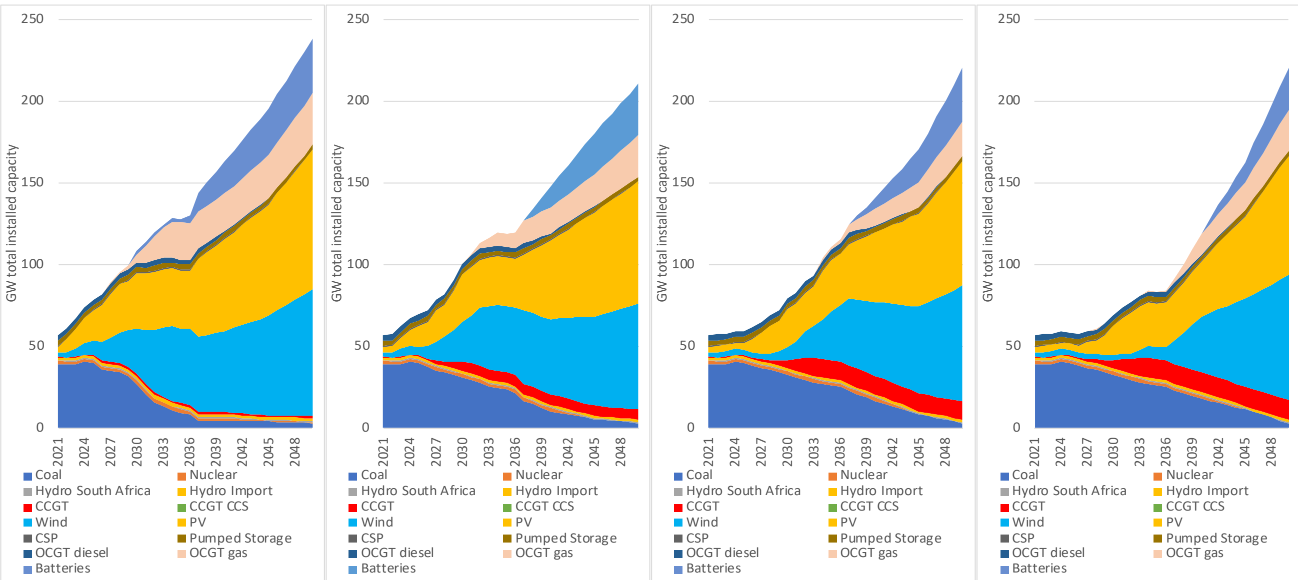

Figure 43 – Total installed capacity in the net zero 45 Mt sink cases with GHG budgets of 6-9 Gt (left to right)

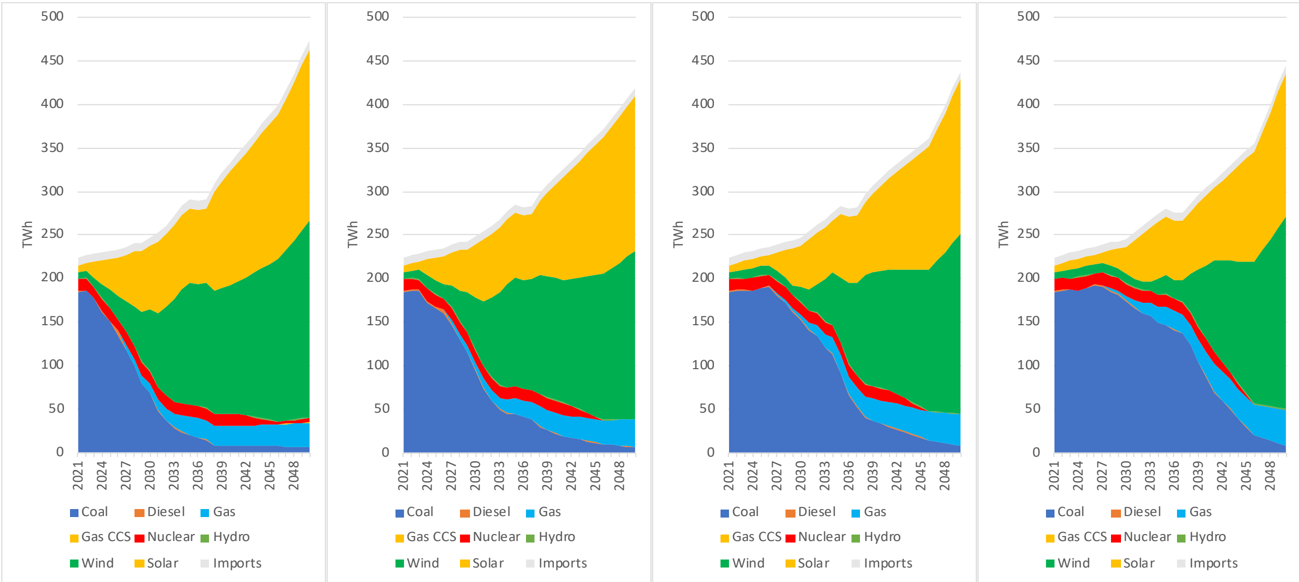

Figure 44 – Electricity production by source in the net zero 45 Mt sink cases with GHG budgets of 6-9 Gt (left to right)

The share of total electricity generated by source, which roughly parallels a CO_2 budget, over the period 2021-50, is presented in Table 3; the share of coal-fired electricity generated is around 48% in the reference case, but this drops to only 18% in the 6 Gt case. The amount of electricity generated by zero carbon sources increases in inverse proportion, whereas the amount of electricity sourced from natural gas is at a relatively high level in the reference case (12%), but drops to around 6% in the GHG-constrained cases, and as discussed below, some of this gas generation is retrofitted with CCS later in the period. The proportions are presented graphically in Figure 44, in which it is clear that the most economically efficient pathway to meet more stringent carbon constraints, as well as the net zero target, is large-scale investment in wind and solar PV generation. Existing coal capacity is still cheaper to run in the short and medium term, given the assumptions used in this analysis. Capacity is curtailed in response to the GHG constraint.

6.2. Industry

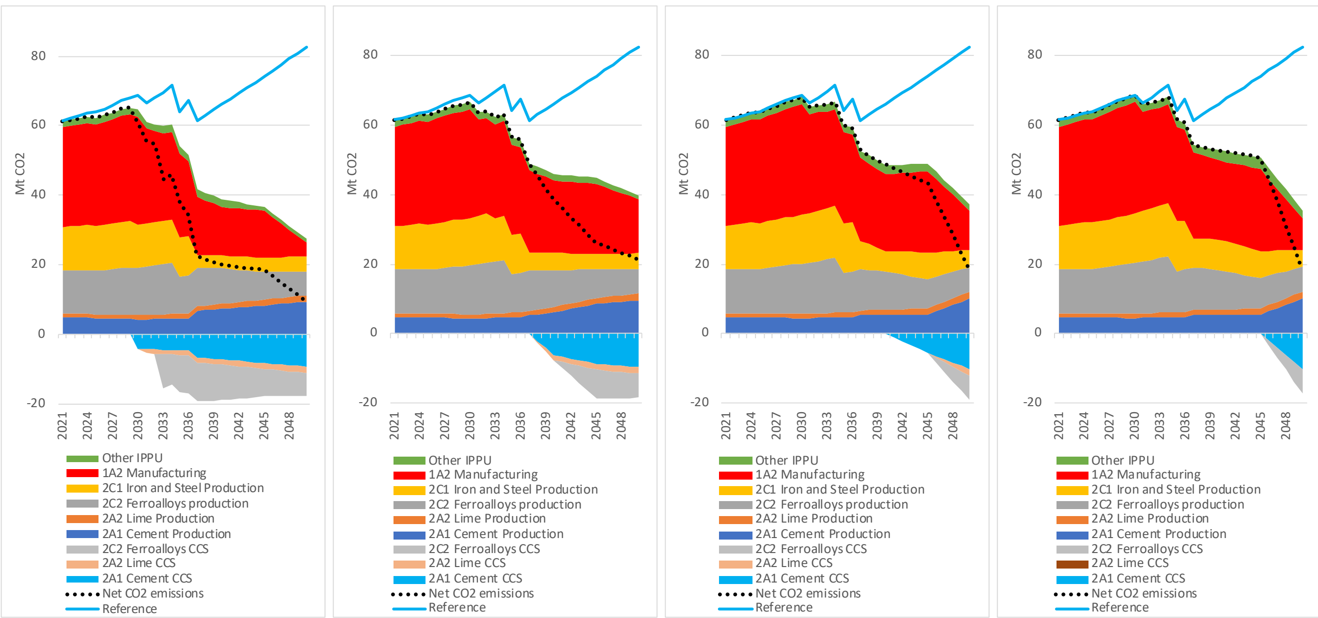

Figure 45 – CO_2 emissions from Manufacturing (1A2) and industrial process emissions in net zero 45 Mt sink cases with GHG budgets of 6-9 Gt (left to right). Total net CO_2 emissions for the sector (gross emissions – stored emissions) are show by a dotted line and CO_2 emissions in the reference case are shown for comparison.

Whereas in the unconstrained cases, emissions from industry (including industrial process emissions) continue to grow until the last five years, in the GHG constrained cases, this occurs from the early 2030s on, as presented in Figure 45. The CO_2 emissions in figure 42 are gross CO_2 emissions, and the corresponding application of CCS is presented below the x axis. There are two sources of GHG emissions reduction in the sector: i) switching to zero- or lower-carbon technologies, and ii) carbon capture and storage, in the case of sectors which are unable to switch. The latter is relatively expensive and is only chosen by the model as the result of a GHG constraint (cumulative or net zero). The uptake of CCS is discussed in more detail below, and is taken up to store process emissions in the cement, ferroalloys and lime subsectors. There are some technology shifts in the metals sector, of which the most significant is the shift from using carbon as a reductant to using hydrogen in the reduction of iron ore. The rest of the decarbonization in the sector are as a result of fuel switching, which is presented in Figure 46, both from fossil fuel to electricity, and from coal to gas and hydrogen, which occurs earlier in the more stringent cases. The substitution of coal with natural gas is an effective mitigation option except in the most stringent GHG constraint case (6 Gt) in which gas is displaced towards 2050 by hydrogen.

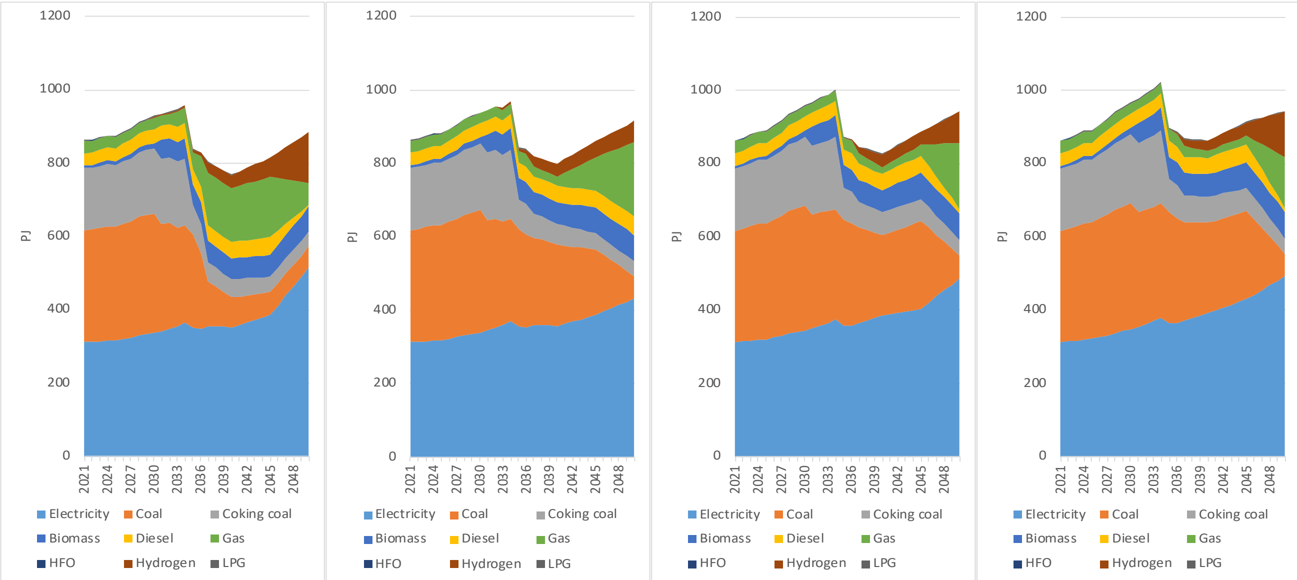

Figure 46 – Energy demand by energy carrier in industry in net zero 45 Mt sink cases with GHG budgets of 6-9 Gt (left to right)

6.3. Transport

CO_2 emissions from the transport sector for the 6-9 Gt cases are presented in Figure 47 and Figure 48 for freight transport and for passenger transport respectively, as well as via which technology the demand for freight transport (in ton kilometres) and passenger transport (passenger kilometres) is satisfied.

The share of rail of total freight transport does not change between cases as this is exogenously specified in the modelling framework, and the indirect CO_2 emissions from the transport sector arising from the use of electric rail depend on the CO_2 intensity of the electricity system, as presented in Figure 39, which implies that there are less attributable CO_2 emissions as a result of this fixed share in the lower GHG budget cases than in the higher or reference cases. Whereas the unconstrained GHG cases only deviate from the use of liquid fuels in the freight sector in the last decade before 2050, and specifically in the last five years, the constrained cases deviate earlier, and the key shifts are from diesel to hydrogen, biodiesel and electricity in heavy freight transport and almost complete electrification in light freight transport, as presented in Figure 49. Whereas the 7-9 Gt cases have a fairly constant share of hydrogen-fuelled heavy transport, the switch to hydrogen happens earlier and in larger magnitude in the 6 Gt case. The residual diesel vehicles use biodiesel towards 2050, as presented in Figure 49.

The shares of road passenger transport demand (passenger kilometres) met by specific technologies and associated energy carriers, as well as the associated CO_2 emissions, are presented in Figure 48. These are strikingly similar, since most of the shift to low- or -zero CO_2 transport technologies has already taken place as a result of the falling costs of electric vehicles. CO_2 emissions are therefore also very similar. Current model constraints prevent much faster shifts, and since the modal shares for passenger transport are specified exogenously, this does not alter between scenarios. The impact of a modal shift will be explored further below in the section on sensitivity analyses.

The transport sector's energy consumption is presented in Figure 49, for both freight and passenger transport, as well as for marine and air transport[35]. The shift in the use of transport fuels between the cases with more and less stringent cumulative emissions budgets arises primarily from technology shifts in the freight sector. The key differences are in the higher and earlier use of more biodiesel, hydrogen and electricity in freight transport.

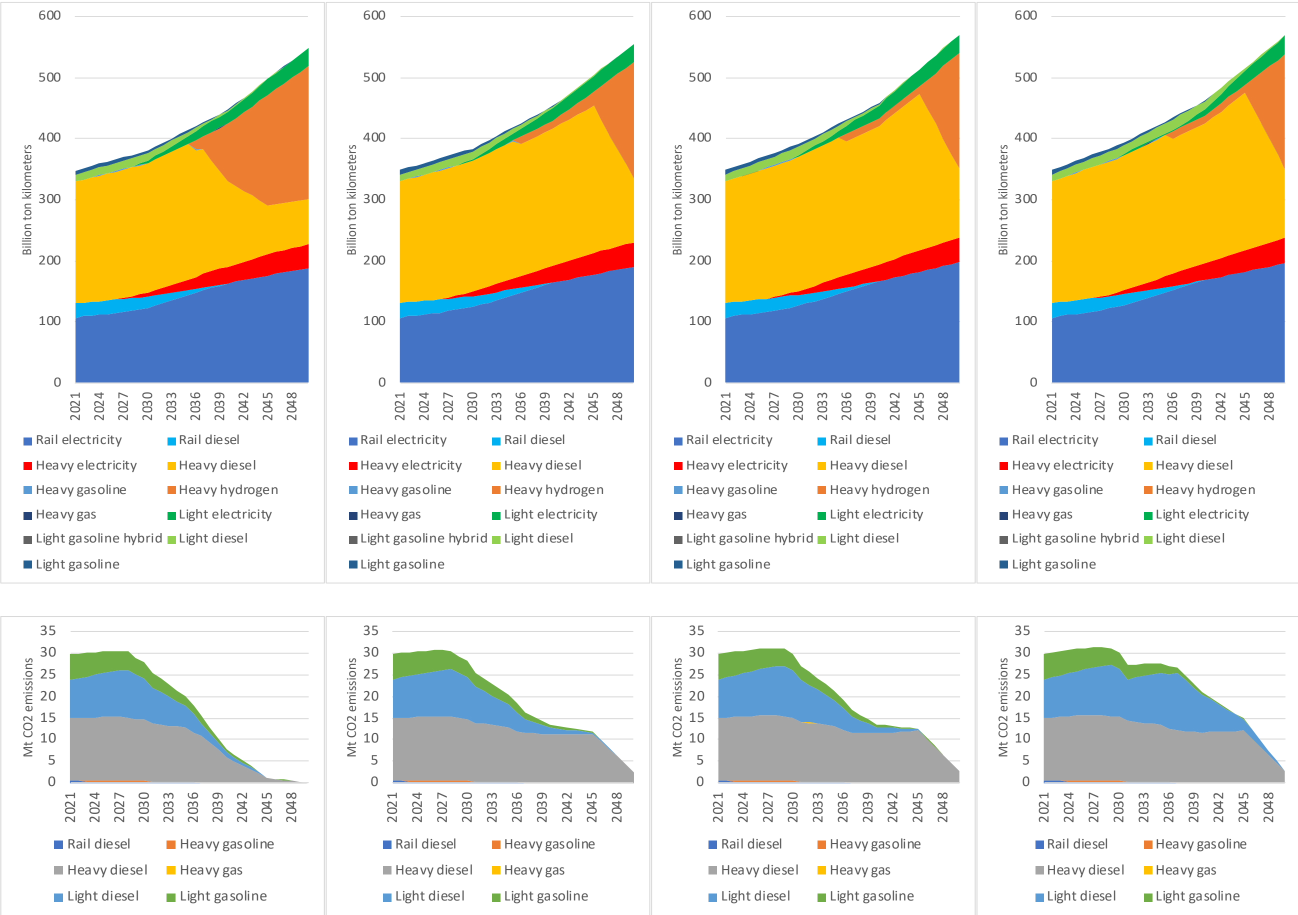

Figure 47 – Surface freight transport demand in billion ton kilometres in net zero 45 Mt sink cases with GHG budgets of 6-9 Gt (top left to right), and corresponding CO_2 emissions for freight transport in net zero 45 Mt sink cases with GHG budgets of 6-9 Gt (bottom left to right) (all divided into rail and heavy and light commercial vehicles (road)).

[35] The kerosene share is used for jet fuel, and divided into national and international air travel. In terms of GHG inventory methodology as well as the structure of the international climate change regime, CO_2 emissions from international air travel are not accounted for as a component of South Africa's national GHG emissions, and will not be accounted for in assessing South Africa's achievement of its NDC target.

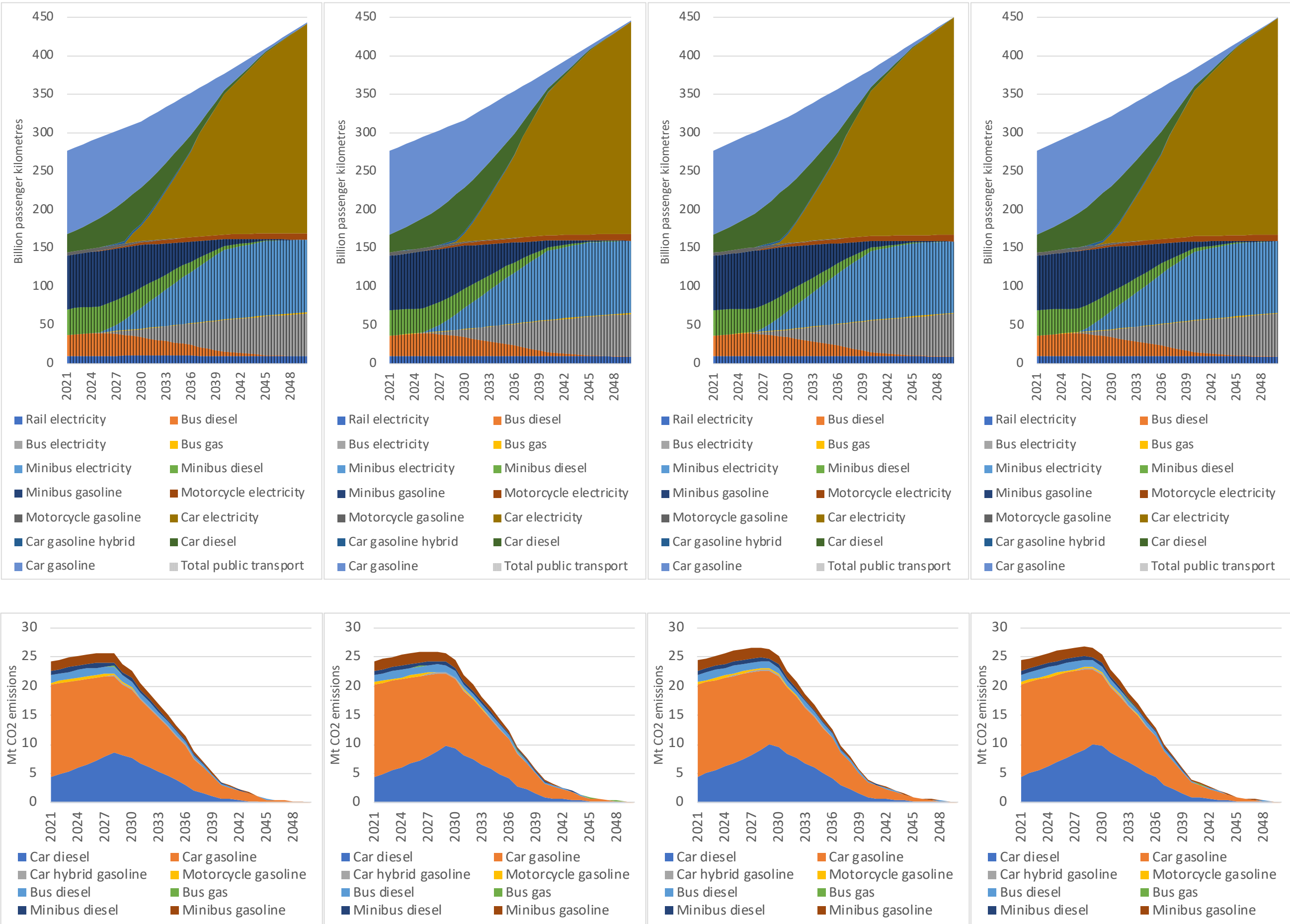

Figure 48 – Road passenger transport demand in billion passenger kilometres in net zero 45 Mt sink cases with GHG budgets of 6-9 Gt (top left to right), and corresponding CO_2 emissions for passenger transport in net zero 45 Mt sink cases with GHG budgets of 6-9 Gt (bottom left to right). The black cross hatching designates public transport.

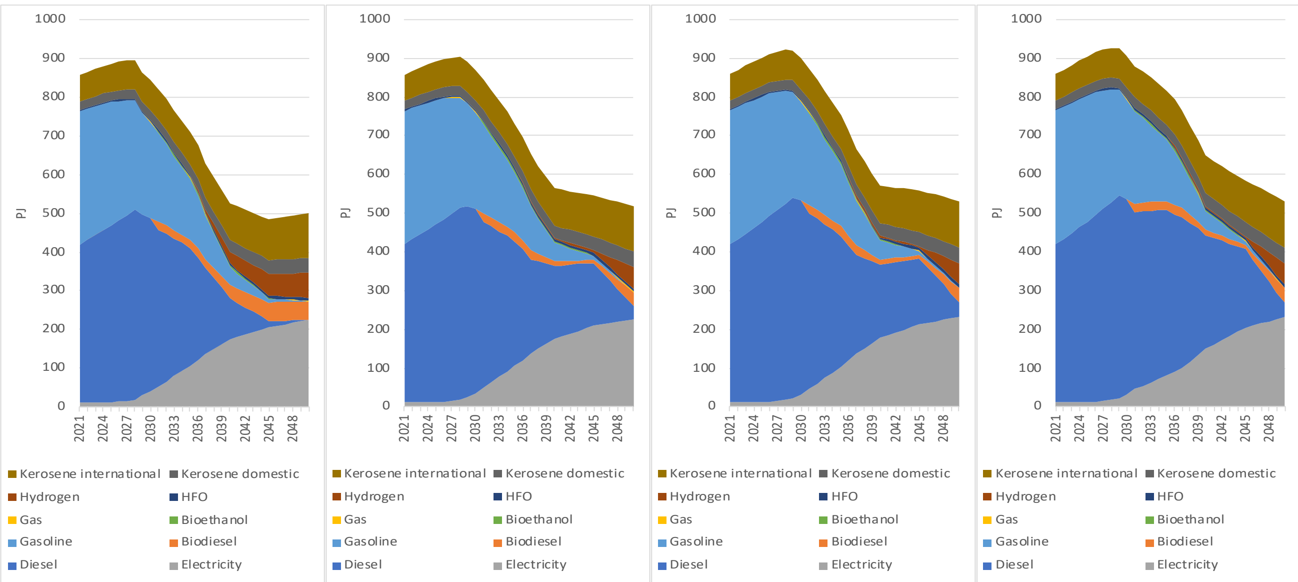

Figure 49 – Energy demand by energy carrier in transport in net zero 45 Mt sink cases with GHG budgets of 6-9 Gt (left to right)

6.4. Liquid fuels supply (fossil fuel-derived)

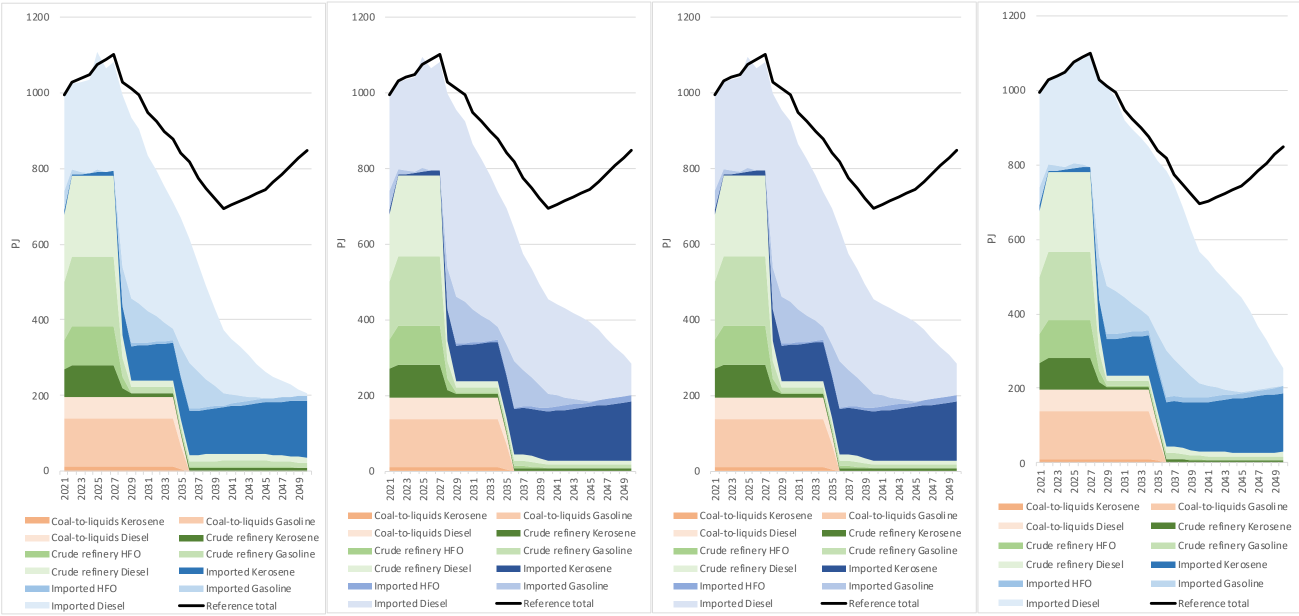

Figure 50 – Fossil fuel -derived liquid fuel supply by fuel and source for the net zero 45 Mt sink cases with GHG budgets of 6-9 Gt (left to right) (for diesel, gasoline, HFO and kerosene only, and excluding PetroSA production, which is assumed to cease in 2024).The black line corresponds to total liquid fuels demand in the reference case (in PJ).

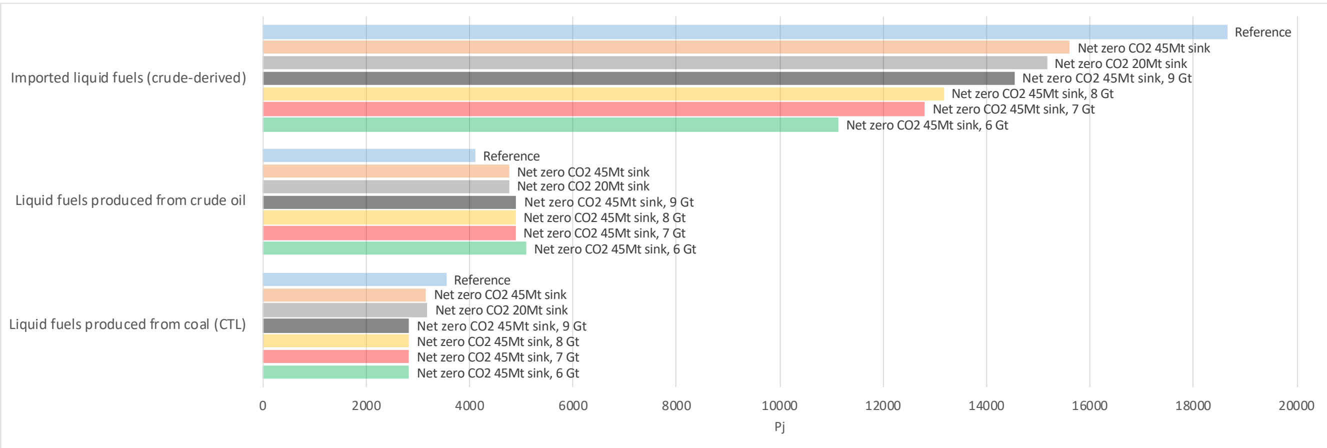

Figure 51 – Cumulative liquid fuels supply (2021-2050) per source, for each modelled case (for diesel, gasoline, HFO and kerosene only, and excluding PetroSA production, which is assumed to cease in 2024).

As a result of a number of factors, including the reduction in demand for liquid fuels, static refinery product slates (including the CTL process), national liquid fuel production from crude oil and coal either shuts down or operates at very low capacity[36] as presented in Figure 50. Current crude oil refineries in the country largely shut down around 2028, and the CTL plant shuts down in 2035. Both these are the earliest dates in the model at which the model has the option to retire them. Liquid fuels demand is thereafter met in all cases via imports. There are some more subtle differences in the supply of liquid fuels between cases which are highlighted by comparing the aggregate quantity of liquid fuels supplied in the period 2021-50 in each case, which is presented in Figure 51. The reference case favours supply from CTL over crude refineries, whereas the introduction of any GHG constraint results in the existing CTL capacity ceasing production in 2035 (at the earliest possible date). The GHG emissions from the CTL process are a similar quantity to those of the transport sector. The most significant impact of the cumulative GHG emissions budget is in the variations in the total quantity of imported liquid fuels. A key weakness of this analysis is that the possibility of a much later transition to low- or zero-carbon transport is not considered.

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36 The continued operation of both crude oil refineries and the CTL plant at a small fraction of their capacity is very likely a modelling artifact.

6.5. Remaining CO_2 emissions in 2050 and the uptake of CCS

Remaining CO_2 emissions in 2050 in the four GHG-constrained cases are presented in Table 4. CO_2 emissions without the land sector are between 60 and 75 Mt; with the use of CCS and factoring in the land sector sink, CO_2 emissions are close to zero or below.

Table 4 – CO_2 emissions in 2050 in the net zero 45 Mt sink cases with 6-9 Gt cumulative GHG emissions budgets

Cumulative GHG emissions budget:	6Gt	7Gt	8Gt	9Gt
Total CO_2 emitted in 2050	58.6 Mt	74.3 Mt	73.9 Mt	75 Mt
Total CO_2 stored in 2050	31.3 Mt	30 Mt	29.7 Mt	28.7 Mt
Net CO_2 emissions in 2050	27.2 Mt	44.3 Mt	44.3 Mt	46.3 Mt
Net CO_2 emission from AFOLU and waste in 2050	-43.8 Mt	-43.8 Mt	-43.8 Mt	-43.8 Mt
Total net CO_2 emissions in 2050	-16.6 Mt	0.4 Mt	0.4 Mt	2.5 Mt

Remaining CO_2 emissions in each case in 2050 is presented in Figure 53, as well as the use of CCS in that year.

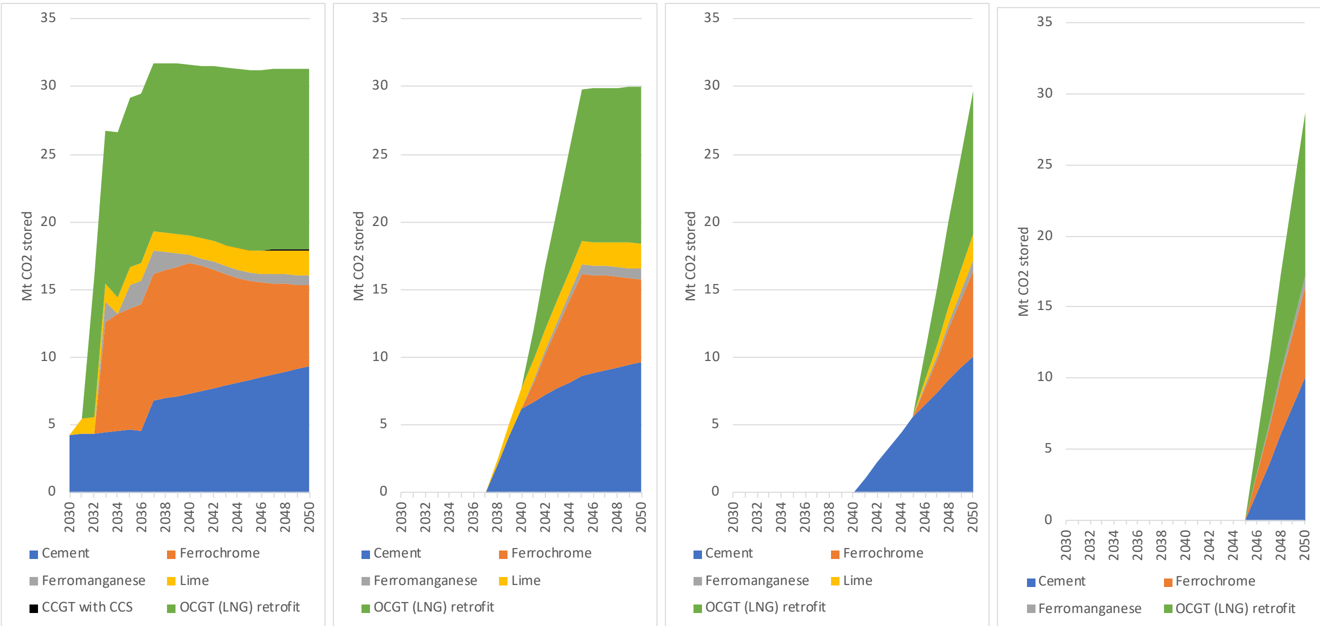

Figure 52 – Use of CCS by sector/technology in the net zero 45 Mt sink cases with GHG budgets of 6-9 Gt (left to right).

Some of the residual CO_2 emissions are a result of a lack of mitigation options – for instance, cement, ferroalloys and lime production. The model allocates CCS capacity to these, and also to the electricity sector, primarily in the form of retrofitting natural-gas-fired OCGT plants. The remaining CO_2 emissions in the electricity sector are from the only remaining coal plant in operation, Kusile, and the use of OCGT plants which have not been retrofitted. Other residual CO_2 emissions remain as a result of either lack of mitigation options or the high cost of mitigation. Some of these respond to a lower GHG budget and reduce or disappear from 9 to 6 Gt. Smaller sources of emissions (for instance, commercial and residential, i.e. buildings) should be considered in more detail in future.

The use of CCS technology in each case is presented in Figure 52. It is assumed that storage of 30 Mt per year is feasible and affordable by 2030 in the 6 Gt case, 2035 in the 7 Gt case, and 2040 in the 8 and 9 Gt case. The key difference between the cases is the extent of the use of CCS over time: in the 9 Gt case, total CO_2 stored over the 2021-50 period is 0.08 Gt, whereas in the 6 Gt case, 0.3 Gt is stored, the magnitude of which is large enough to have an impact on the cumulative GHG constraint. It is not clear whether this amount of CO_2 storage is available in South Africa, given the unfavourable geology. Future work should include a sensitivity analysis without access to CCS, which would probably result in further and earlier decarbonization of the electricity sector.

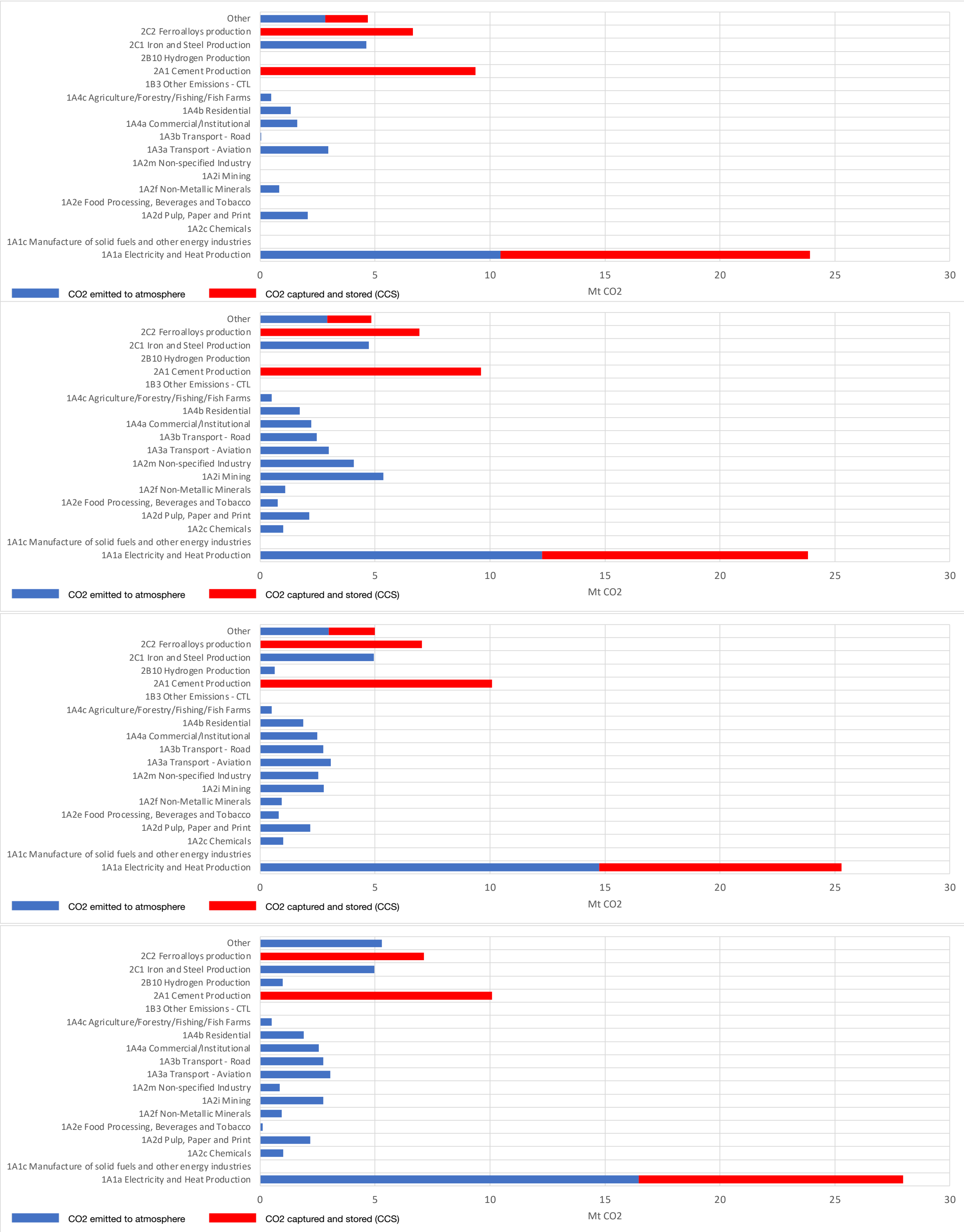

Figure 53 – Remaining CO_2 emissions in 2050 in net zero 45 Mt sink cases with GHG budgets of 6-9 Gt (top to bottom). The overall length of the bars in each category are the CO_2 produced by that sector in 2050; the red section of each bar is the amount of CO_2 which is stored, and the blue section is the amount emitted to atmosphere

6.6. Natural gas and hydrogen utilization

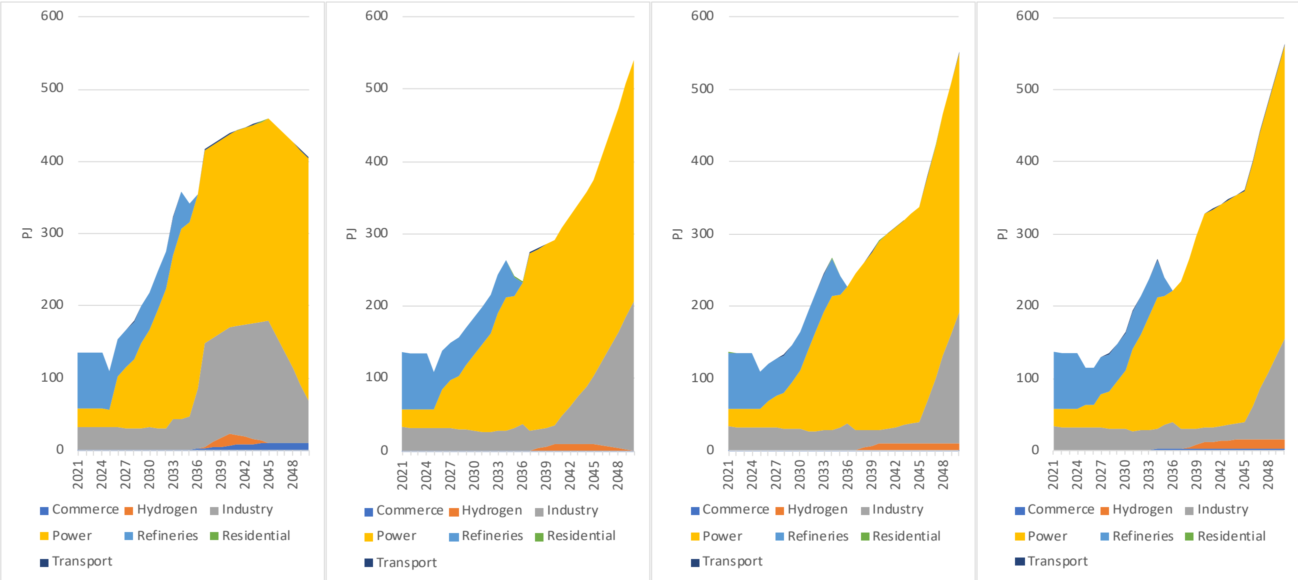

Figure 54 – Natural gas utilization in the net zero 45 Mt sink cases with GHG budgets of 6-9 Gt (left to right). "Hydrogen" = hydrogen manufacture from natural gas.

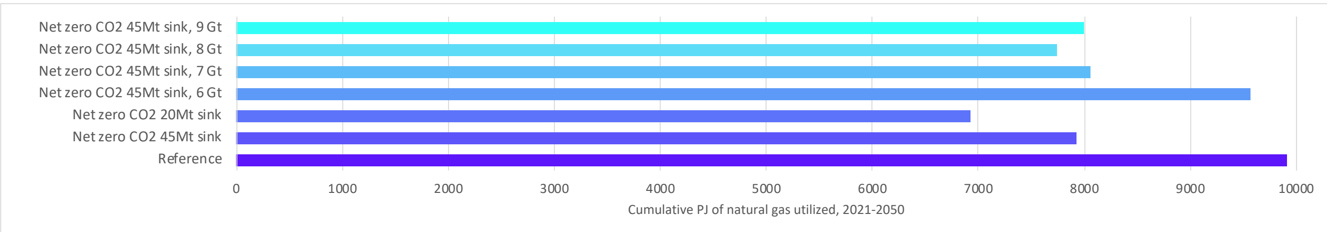

Figure 55 – Cumulative natural gas used in each case, 2021-50

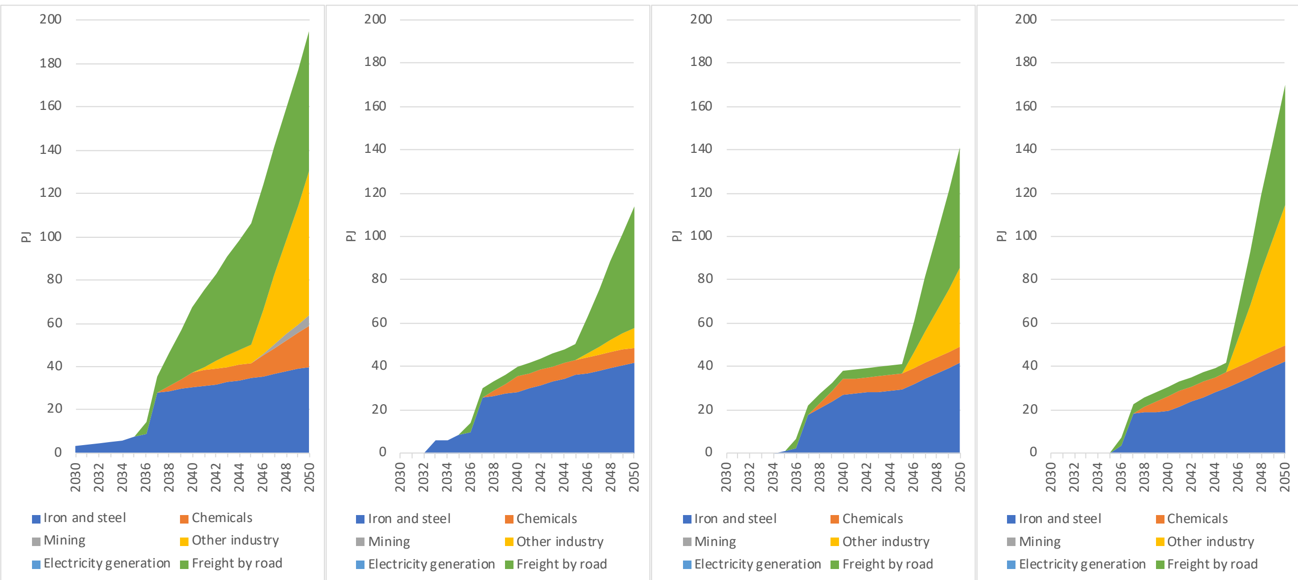

Figure 56 – Hydrogen utilization in the net zero 45 Mt sink cases with GHG budgets of 6-9 Gt (left to right).

There is no hydrogen utilization in the GHG constrained cases for electricity generation. The four predominant uses of hydrogen are for iron reduction, heavy freight transport (road), chemicals (including ammonia) and other thermal applications in industry. Hydrogen use only occurs in the reference case in iron reduction and in the chemical sector from 2036 on, in the unconstrained net zero cases other applications from 2040 on (see Figure 30). In the constrained cases, hydrogen uptake increases until in the 6 Gt case, hydrogen uptake for all uses above begins at scale after 2035, as presented in Figure 56. The possibility of a large green hydrogen export industry is considered in the section below on sensitivity analyses. In this version of the modelling framework, hydrogen is produced from natural gas initially (which results in CO_2 emissions) (see Figure 54), but a relatively small proportion of natural gas is used for this. More sensitivity analyses need to be undertaken on the natural gas price, which will also affect the use (or not) of gas in the electricity sector up to 2050.

6.7. Investment requirements and economic impacts

Total undiscounted systems costs in SATIM (covering the energy and industry sectors) consist of the annualised capital costs of infrastructure and the fixed and variable costs of operating the infrastructure, which includes supply side and demand side technology, and also the costs of fuel supply. Figure 57 presents the percentage change in total undiscounted system costs for the energy and industry sectors relative to the reference case, which rise to around 6% higher in the most ambitious budget case.

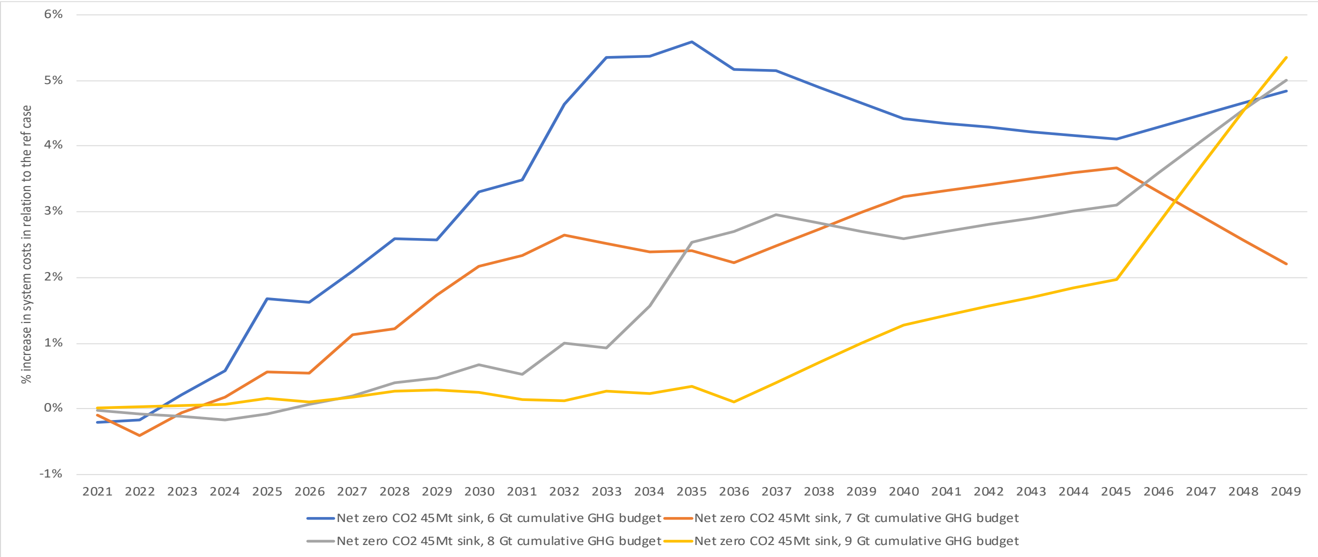

Figure 57 – Percentage increase in total undiscounted system costs (energy and IPPU) relative to the reference case

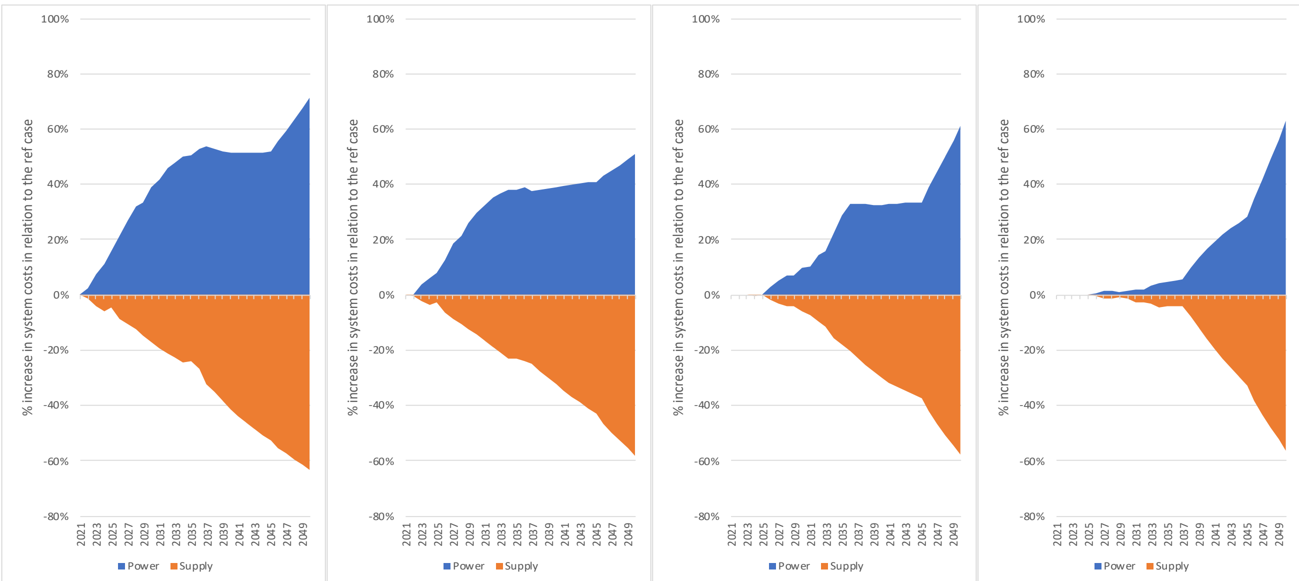

Figure 58 – Percentage undiscounted system cost difference between the reference case and the net zero 45 Mt sink cases with GHG budgets of 6-9 Gt (left to right) for the power sector and the fuel supply sector (which includes the cost of fuels (coal, liquid and nuclear fuels) supplied to the power sector). These two sectors account for an average of 89% of cost differences between cases.

Within the aggregate increase in system costs is a change in the structure of the economics of the power sector, as presented in Figure 59. As above, the imposition of a net zero target results in dramatic increases in the annual investment in the electricity sector in the last five years or so, but this is lower than in the non-GHG-constrained cases due to the earlier investments in decarbonization to meet the cumulative constraint. The relations between the GHG budget and the actual increase in the last five years is somewhat complex and not proportional, since this is a complex interaction between the net zero target and the requirement to reduce GHG emissions over the whole period. Even so, the investment level in the last five years is still very daunting, requiring 3.7% to 6.2% of GVA to be invested in the electricity sector. “Last mile” decarbonization thus requires very high levels of investment, which as presented in Figure 60, results in up to a 10% smaller economy by 2050, again, primarily as a result of the crowding out effect.

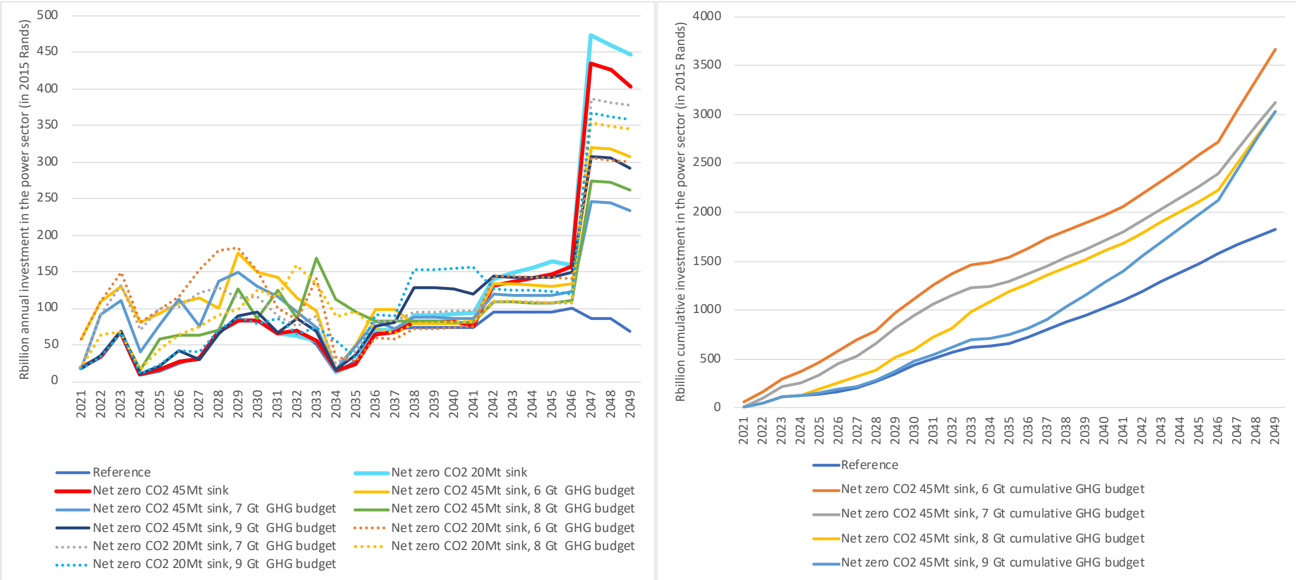

Figure 59 – Annual (left) and cumulative (right) investment requirements in the electricity sector, 2021-49, for the reference and net zero cases with budgets of 6-9 Gt CO_2-eq, and for comparison the non-GHG-constrained 20 and 45 Mt sink cases.

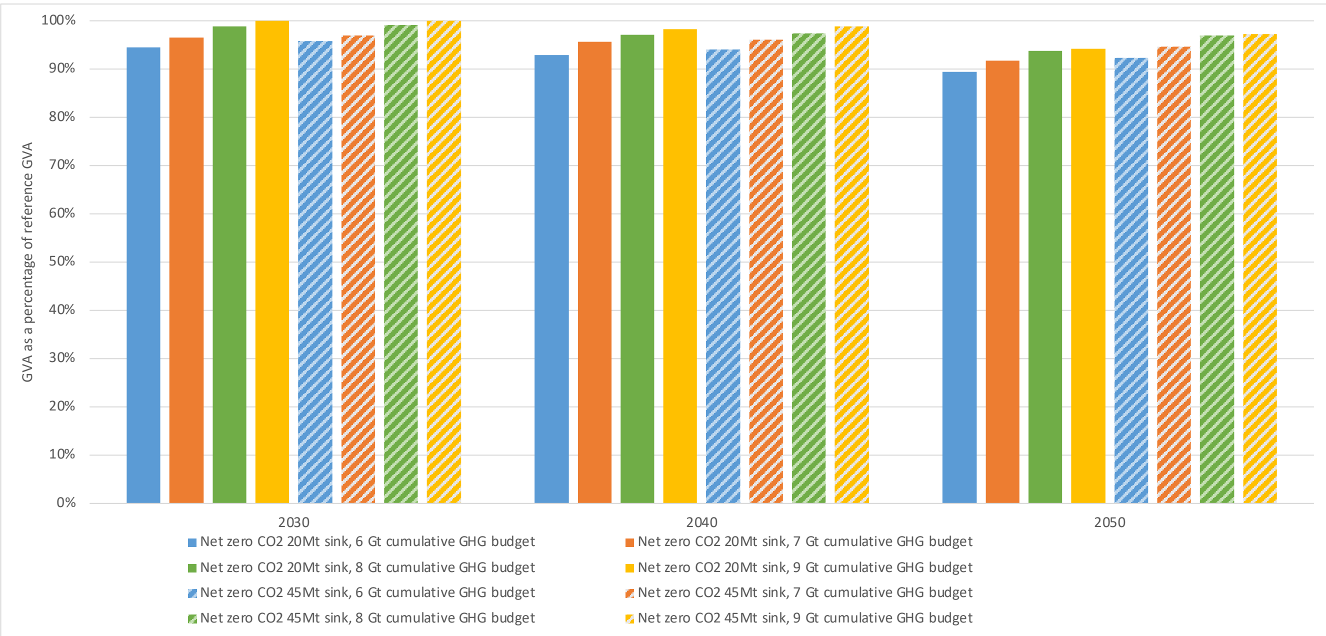

Figure 60 – Gross Value Added (GVA) for each case as a percentage of GVA for the reference case, for the specific year

6.8. Cumulative GHG emissions

Figure 61 presents the cumulative GHG budgets per key emitting sector for the reference case and the GHG-constrained cases. Cumulative GHG emissions per sector give a reasonably good indication of the overall mitigation in that sector, relative to the reference case, and also of the timing of the response, since there are smaller differences in sectors which only respond later. The left hand graph gives a good sense of the absolute magnitude of the reduction, and therefore a clear indication of the sector's importance in meeting national mitigation goals, whereas the right hand graph provides a sense of the relative reductions in each sector, related to the reference case, which indicates the responsiveness of each sector to GHG constraints. There are several interesting conclusions from this: i) GHG emissions in the electricity sector are by far both the most responsive to GHG constraints and have the largest response in absolute terms; ii) in relative terms, there is very little additional response from the liquid fuels sector, since liquid fuels infrastructure mostly retires after 2035 even in the reference case; iii) more response in the rest of the energy sector, and iv) about twice the responsiveness in process emissions.

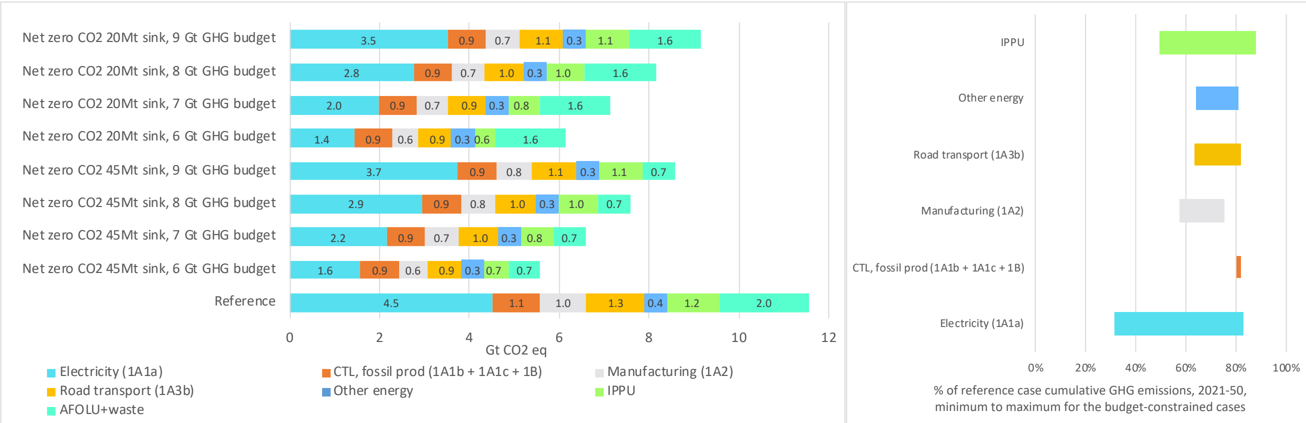

Figure 61 – Cumulative GHG emissions[37] for the reference case and the GHG budget cases, disaggregated by key emitting sectors, 2021-50, in CO_2-eq (left) to give a sense of the scale of reductions in each sector from the reference case. The graph on the right presents the reduction in the cumulative GHG budget of each sector as a percentage of the reference case for that sector, and the range represents the range of this value, and therefore gives a clearer indication (without the absolute magnitude) of how responsive each sector is to more stringent mitigation targets.

[37] There are slight deviations from the target budgets for the cases with cumulative budget constraints (6-9 Gt), as a result of revisions to the land and agriculture policy pathways – 45 Mt sink cases are slightly below their target cumulative budgets and 20 Mt sink cases are slightly above their target cumulative budgets. This does not affect the validity of the results in any way, but should be borne in mind when comparing results with the same cumulative budget and different sink values.

7. Sensitivity to demand-side policies and measures, and to enhanced green hydrogen-based exports

A number of variations were modelled with a) demand-side policies and measures (energy efficiency, and mode-shifting in transport),and b) significantly scaled-up exports of green iron and green hydrogen (in the form of ammonia). These cases are presented below as variations of the net zero 45 Mt sink, 8 Gt cumulative emissions budget case only, to highlight the resulting changes.

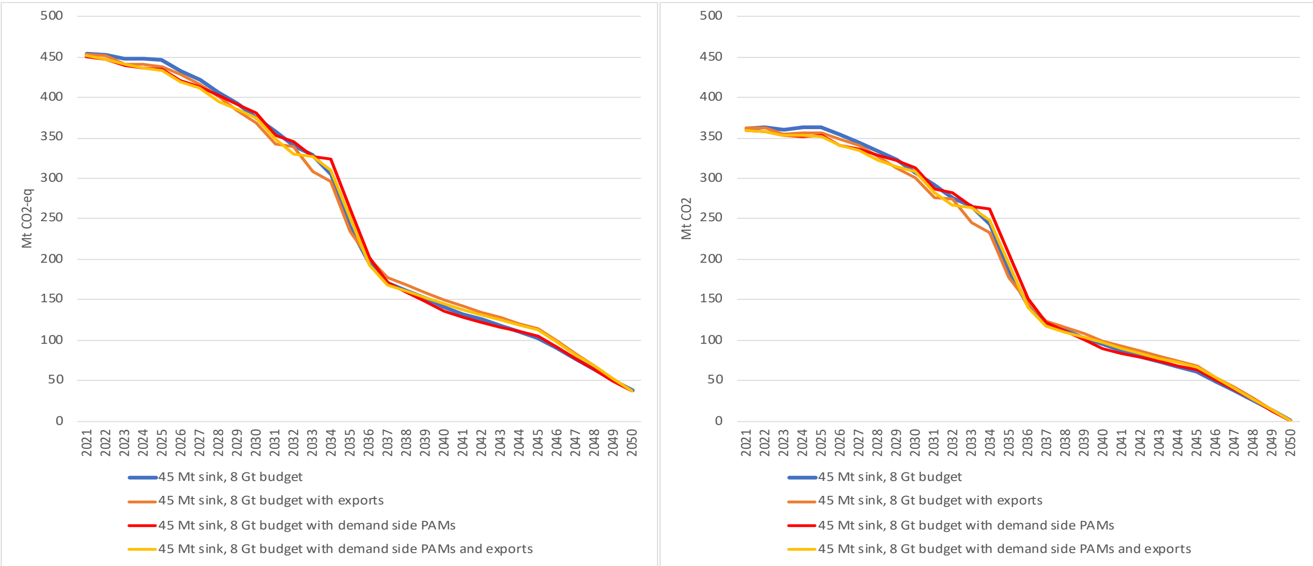

Figure 62 – GHG (left) and CO_2 (right) emissions for the 45 Mt sink, 8 Gt budget with/without demand-side PAMs and exports.

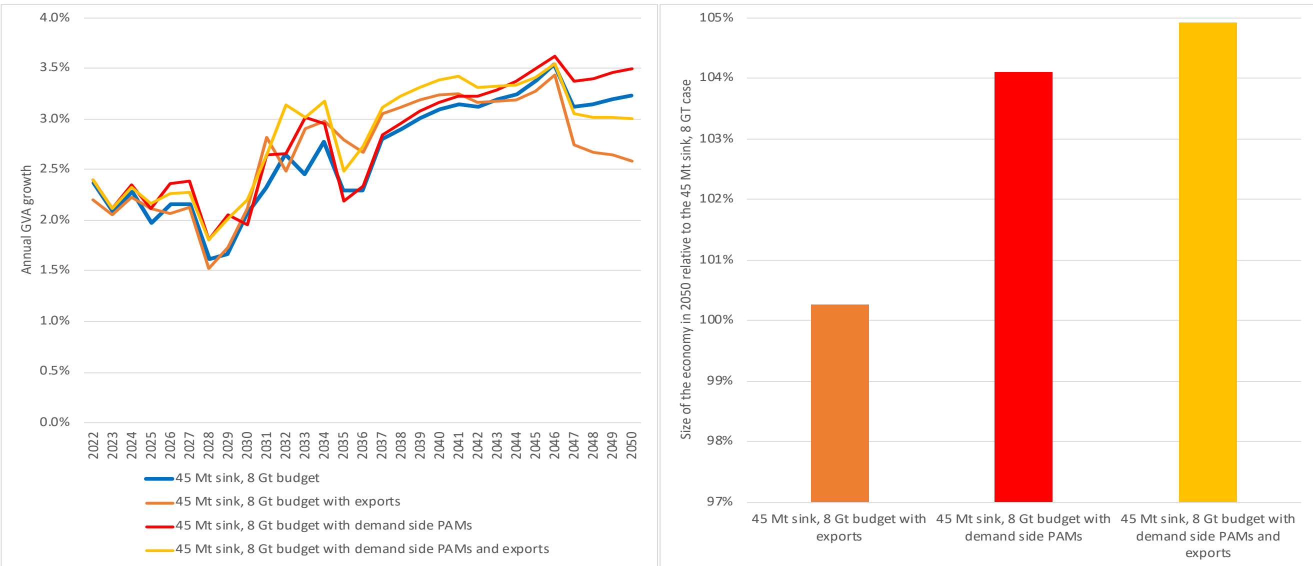

Figure 63 – GVA growth rate (left) of the 45Mt, 8 Gt cases with/without demand-side PAMs and green iron/H2 exports, and the % difference between the GVA in 2050 of the 45 Mt sink, 8 Gt cases with PAMs and/or exports, and the case without PAMs or exports.

GHG outcomes are presented in Figure 62. These are very similar as the constraints on GHGs in each case are identical, but there are important differences in the impact on economic growth. Differences in growth rates and the size of the economy in 2050 are presented in Figure 63. The addition of demand-side policies has a positive economic growth impact, whereas the addition of export industries has in this analysis a more complex impact, but results in a larger economy in 2050. The combination of measures results in the highest growth outcome. As specified in the inputs, hydrogen demand increases dramatically in the export cases as presented in Figure 64. The large hydrogen demand in the export cases in Figure 64 is not a significant result since the demand for these cases is specified exogenously. The way in which the demand is met is however significant – via a very large expansion of the grid, as presented in Figure 65, especially in the last ten years. This increase is almost all attributable to demand for hydrogen production.

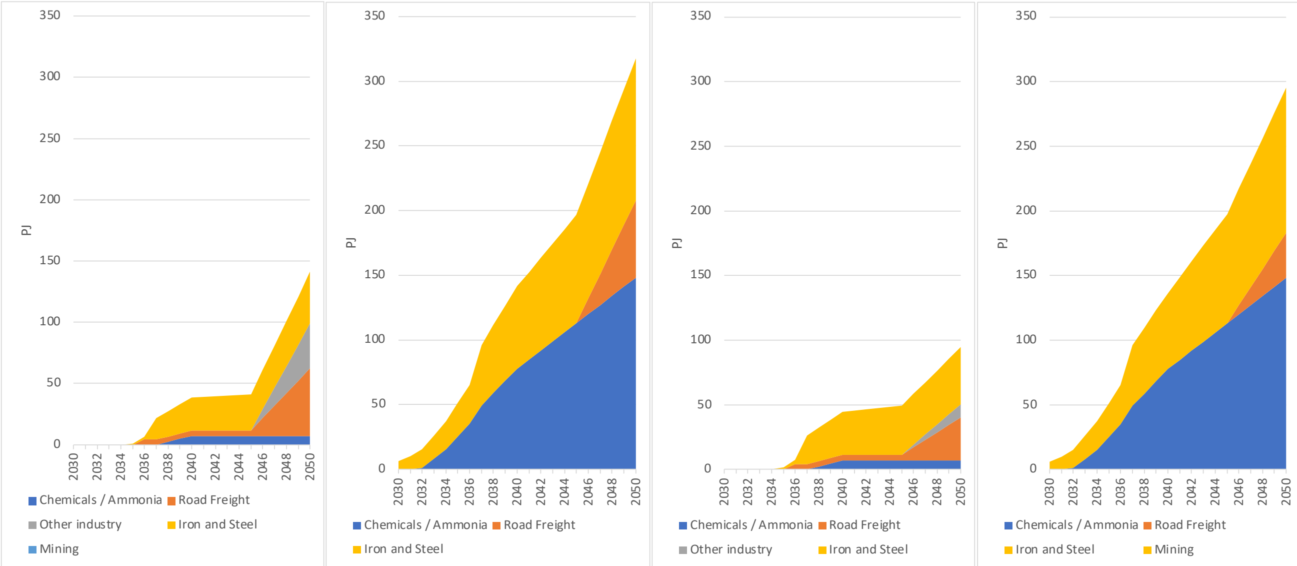

Figure 64 – Hydrogen demand (right), for (left to right) the 45 Mt sink, 8 Gt budget case; the 45 Mt sink, 8 Gt budget with exports case; the 45 Mt sink, 8 Gt budget with demand side PAMs case; and the 45 Mt sink, 8 Gt budget with demand side PAMs and exports. Hydrogen is assumed to be exported in the form of ammonia. This is reflected in the "chemicals/ammonia" category in this figure.

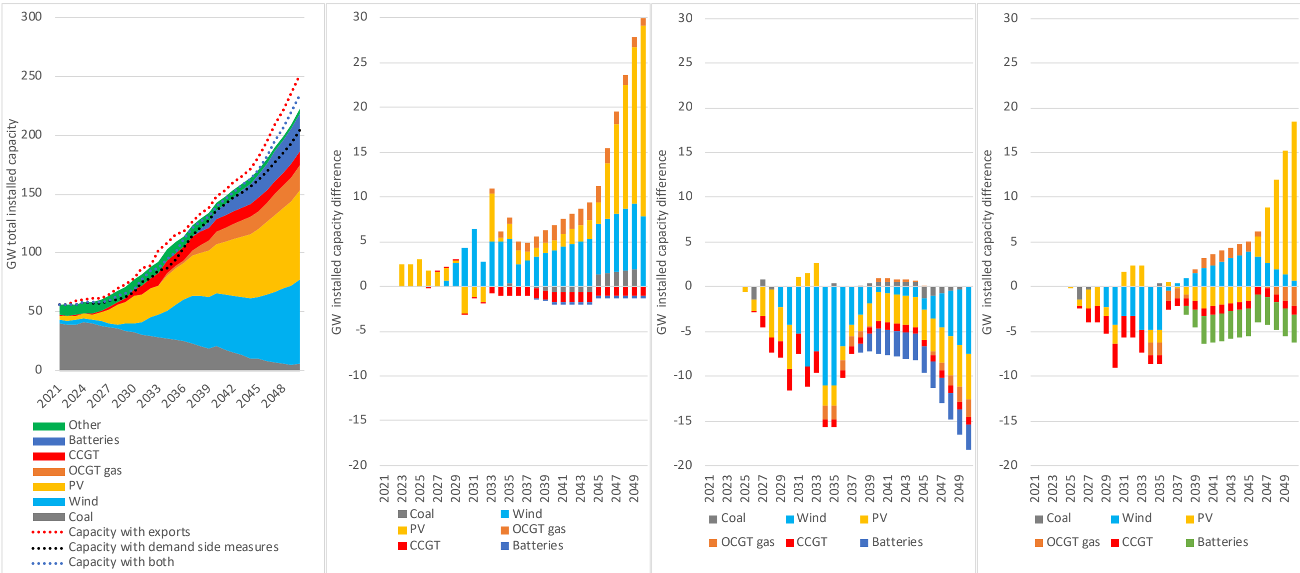

Figure 65 – Total installed capacity for the net zero 45 Mt, 8 Gt case (left) and the difference in total capacity between this case and the 45 Mt, 8 Gt case with exports of green ammonia and green steel, (second from left), the 45 Mt, 8 Gt case with demand-side policies (centre right), and with both (right)

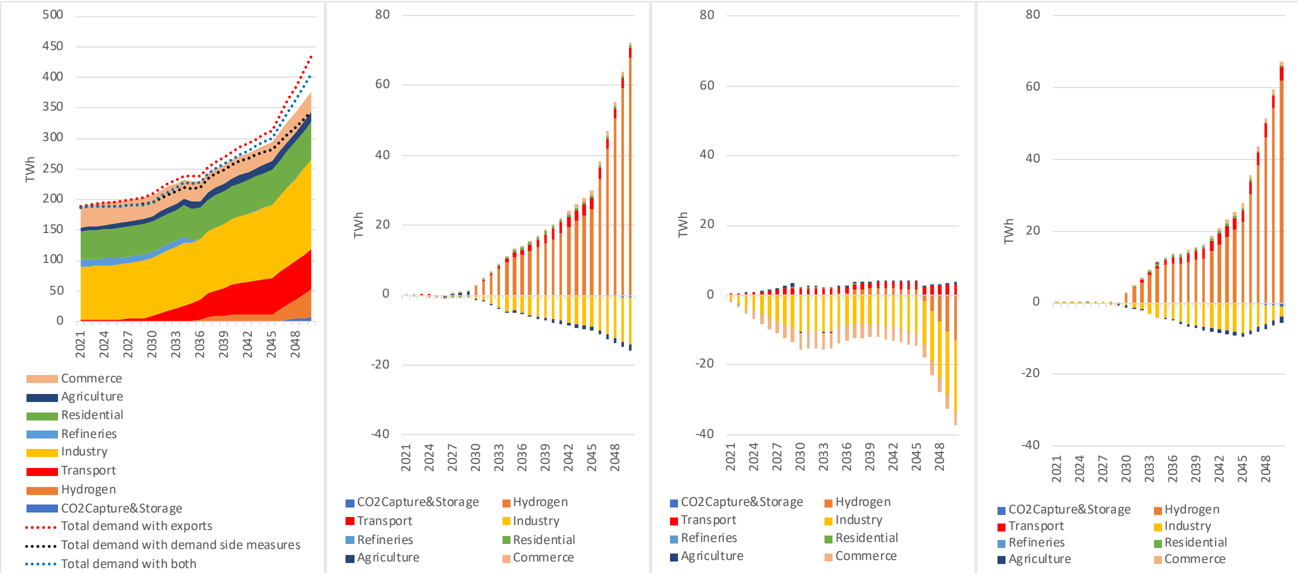

Figure 66 – Electricity demand by sector in the net zero 45 Mt, 8 Gt case (left), and the difference in sectoral electricity demand between this case and the 45 Mt, 8 Gt case with exports of green ammonia and green steel, (second from left), the 45 Mt, 8 Gt case with demand-side policies (centre right), and with both (right)

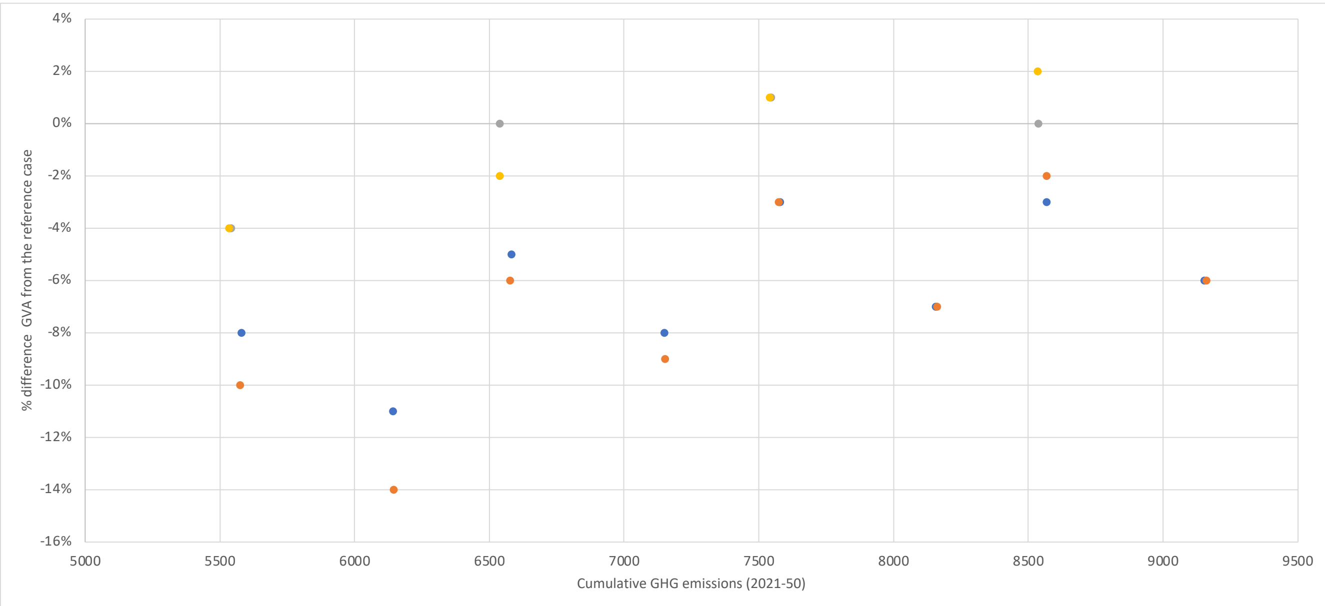

Figure 67 – % difference in the size of the economy in relation to the reference case, plotted against cumulative GHG emissions (2021-50)

Figure 67 correlates cumulative GHG emissions with differences in the size of the economy in 2050 from the reference case, and cumulative GHG emissions. While most cases have a net negative impact on the size of the economy due to the crowding-out effect, the addition of demand-side measures and an export industry in green iron and ammonia results in a larger economy in 2050, even with a large GHG emissions constraint.

8. Conclusion

This initial analysis was intended to map the net zero challenge, as a prelude to a more detailed, scenario-based study, and to identify key challenges, limitations and options which need to be analysed more thoroughly. At the same time, it examined the consequences of limiting GHG emissions to a cumulative budget over the 2021-2050 period.

8.1. Initial results

The Paris Agreement does provide guidance in its Article 4 on GHG emissions being reduced to a point at which sources match sinks "in the second half of the century". The IPCC's Special Report on 1.5 degrees further quantified this, as did the IPCC's 6th Assessment Report (Working Group 3), and both put forward specific global emissions goals to be met for CO_2 – to reduce CO_2 emissions by 45% from current levels by 2030, and to reduce CO_2 emissions to net zero around 2050 – in order to keep "1.5 alive", i.e. to achieve the global goal of limiting temperature increase to 1.5 degrees. This found policy expression in the Glasgow Climate Pact (decisions under the COP, CMA and CMP), in which a) the mitigation "gap" to 2030 was found to be a great source of concern, and b) in which long-term strategies as outlined in Article 4 were directly linked to the science of the 1.5 degree report.

As discussed above, in terms of the architecture of the Paris Agreement, this confirms that all countries including developing countries will be required to reach net zero CO_2 emissions "by or around mid-century", "taking into account different national circumstances". All major economies, including major developing economies, and all members of BASIC, now have net zero targets, although some of them are later than mid-century. There is likely to be increasing international pressure on all countries to develop more ambitious targets over the next three decades, both through the multilateral climate process and via unilateral measures such as the EU's Carbon Border Adjustment Mechanism. In addition there will be other drivers for decarbonization, including economic competitiveness, as the economics of low-carbon technologies continue to improve.

The implications for South Africa are i) that the country requires a long-term strategy to reach net zero CO_2 emissions "by or around mid-century", and ii) medium term emissions reductions are as important, and are currently the focus of a work programme in addition to the GST, under the UNFCCC and its Paris Agreement. This element of mitigation is well represented by a GHG budget to 2050, which provides some flexibility in limiting long-term cumulative GHG emissions, which is illustrated in Figure 6; the range of outcomes between policy scenarios for waste and AFOLU is very significant over the period 2021-50, and provides more or less space for the energy sector to transition.

In terms of allocating South Africa's "fair share", in accordance with the Paris Agreement and South African national climate policy, as assessed above, the literature on fair shares in 2030 is extensive if in some instances dated, but the literature on fair shares to 2050 is much more limited. Comparisons have been made with assessed "fair shares" in 2030 and a range of long-term budgets, and an important conclusion is that cost-optimal GHG emissions reduction pathways to net zero CO_2 in 2050 for South Africa tend to be less ambitious in the short term and more ambitious in the long term, by comparison to the few available long-term pathways available for comparison at the moment. Apart from the sensitivity to discount rates, which was not tested in this analysis, this is also a reflection of the profile of South Africa's existing high-carbon assets. This will be further discussed below.

Baseline GHG emissions for South Africa, defined here as a modelled least-cost GHG emissions pathway with no additional policies, reduce GHG emissions from around 470 Mt CO_2-eq in 2021 to around 330 Mt in 2050, mostly as a result of the decline of CO_2 emissions, which decline from above 350 Mt CO_2 to 240 Mt CO_2. Much of this decline is in the electricity sector, in which coal plants are replaced with low or zero carbon electricity technologies as the coal plants retire. Without intervention, while coal use declines in the electricity sector, it grows in the manufacturing sector (still being a cheaper source of thermal energy to 2050). A slow transition begins in the transport sector but is incomplete by 2050. With only a constraint of net zero CO_2 emissions in 2050, CO_2 emissions depart from their least-cost trajectory only after 2035; much additional mitigation depends on additional assumptions concerning policies and measures implemented in the AFOLU sector, which in the absence of other policies and measures, determine whether the country will meet its 2030 NDC target or not. In addition, overall GHG emissions decline to a range of 40-70 Mt CO_2-eq. The source of the CO_2 reductions after 2035 is mainly the energy sector. As presented in Figure 27, the key remaining CO_2 emissions in the reference case are in the electricity sector (remaining coal plants), road transport and manufacturing. With the CO_2 constraint, only a very small fraction of electricity is produced from coal, and remaining emissions result from the use of natural gas. CCS is deployed in the electricity sector and in the cement and ferroalloys sector, and remaining CO_2 emissions are offset by the land sink. There is a large difference as a result in the uptake of natural gas for power generation between the reference and net zero cases, and between the 45 and 20 Mt sink cases. Hydrogen use is very limited in the reference case but expands considerably from 2040 in the net zero cases. The cost and economic impacts of this deviation in CO_2 emissions towards 2050 are noticeable (relative to the reference case) from 2040 on, and result in a dramatically increased investment requirement for the power sector, which expands dramatically from 2040 to reduce emissions from electricity generation and in other sectors; this results in an unrealistic acceleration of investment in new generation plant in Figure 18, which reaches over 40 GW a year in the 2045-50 period. The same is true for the rest of the CO_2 emitting sector, in which very rapid transitions take place to meet the 2050 goal. This also impact the size of the economy in 2050, which is 3% smaller in the 45Mt case and 6% smaller in the 20Mt case. This is as a result of the crowding out effect of the massive increase in investment in the last 5-10 years of the modelled period, which results in between 6% and 7% of GVA being invested in the electricity sector in 2049, as opposed to 1% in the reference case.

In reality, this massively upscaled programme of last-minute investment would probably not be possible, for logistical, institutional and economic reasons, and requires careful analysis with a range of other policy priorities in mind; in addition, delayed action will probably result in South Africa's economy becoming uncompetitive internationally, as the economics of the energy transition unfold. This is therefore also an argument for earlier mitigation action, which would phase the investment requirements over a long time period; there is thus some confluence between long-term GHG pathways and the medium-term requirements of South Africa's GHG mitigation targets (in terms of a "fair contribution"). The other possibility is shifting the net zero goal outwards. This also runs into the problem of fairness, without earlier mitigation, but options could be explored that consider using the same GHG budget over a longer period, which would in turn require earlier mitigation to free up the relevant GHG emissions space.

The cases in which a GHG emissions budget has been imposed (from 9-6 Gt CO_2-eq over the period 2021-50, with different options for the land sink) are more relevant from a long-term pathways perspective. As before, the electricity sector is the key site of variability. The shift away from coal-fired electricity occurs more and more rapidly with smaller GHG budgets; whereas in the 9 Gt case the transition only really starts to occur around 2030, in the 6 Gt case, the transition is almost complete by 2033. As presented in Figure 61, the magnitude of CO_2 reduction is by far the greatest in the electricity sector, and the path dependencies in this sector, including technical constraints, technology costs and availability, and the imperative to include just transition and industrial policy goals in the transition, will to a large extent determine the long-term mitigation goal which South Africa is able to achieve. Other sectors also depend on the rapid decarbonization in the electricity sector, as presented in Figure 41. This does not in any way detract from the massive effort required to shift to low-emissions technologies in other sectors; in more ambitious cases, these transitions begin much earlier.

8.2. Key questions for further work

Further work will be required in the following areas:

- Mitigation policies and measures in the land and agriculture sectors;
- The costs and benefits of achieving net zero CO_2 emissions later than 2050, with the same cumulative GHG emissions budget;
- The crowding out effect, which drives a large proportion of the model's economic response – further work is required to explore response measures;
- Model sensitivities to the discount rate, to lower and higher prices for fossil fuels;
- Understanding the impact and requirements of green industrial policy, and other relevant policies, on the design of long-term pathways, including limitations on annual investment in new capacity;

In addition to this, while this complex analysis maps out the quantitative terrain for net zero pathways, it does not directly address some key policy questions regarding the multiple transitions which will take place over the next 30 years or so. As asserted in the introduction, this is initial work in this critical area.

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10. Annex

10.1. Detailed table of modelled cases

Table 5 – Cases modelled with parameters

Number	Description	Growth rate	Net zero goal specified for CO2?	Carbon sink in 2050 (Mt)	GHG constraint (2021-2050)	Demand side policies included?	New export industries included?
1	reference economic growth, no cumulative GHG emissions constraint, no net zero goal, carbon sink of -12Mt CO2 in 2050, no demand-side policies included, no green export industries included	reference	no	-12	none	no	no
2	reference economic growth, 6 cumulative GHG emissions constraint, 2050 net zero goal, carbon sink of -20Mt CO2 in 2050, no demand-side policies included, no green export industries included	reference	yes	-20	6	no	no
3	reference economic growth, 6 cumulative GHG emissions constraint, 2050 net zero goal, carbon sink of -20Mt CO2 in 2050, no demand-side policies included, new green export industries included	reference	yes	-20	6	no	yes
4	reference economic growth, 7 cumulative GHG emissions constraint, 2050 net zero goal, carbon sink of -20Mt CO2 in 2050, no demand-side policies included, no green export industries included	reference	yes	-20	7	no	no
5	reference economic growth, 7 cumulative GHG emissions constraint, 2050 net zero goal, carbon sink of -20Mt CO2 in 2050, no demand-side policies included, new green export industries included	reference	yes	-20	7	no	yes
6	reference economic growth, 8 cumulative GHG emissions constraint, 2050 net zero goal, carbon sink of -20Mt CO2 in 2050, no demand-side policies included, no green export industries included	reference	yes	-20	8	no	no
7	reference economic growth, 8 cumulative GHG emissions constraint, 2050 net zero goal, carbon sink of -20Mt CO2 in 2050, no demand-side policies included, new green export industries included	reference	yes	-20	8	no	yes
8	reference economic growth, 9 cumulative GHG emissions constraint, 2050 net zero goal, carbon sink of -20Mt CO2 in 2050, no demand-side policies included, no green export industries included	reference	yes	-20	9	no	no

Number	Description	Growth rate	Net zero goal specified for CO2?	Carbon sink in 2050 (Mt)	GHG constraint (2021-2050)	Demand side policies included?	New export industries included?
9	reference economic growth, 9 cumulative GHG emissions constraint, 2050 net zero goal, carbon sink of -20Mt CO2 in 2050, no demand-side policies included, new green export industries included	reference	yes	-20	9	no	yes
10	reference economic growth, no cumulative GHG emissions constraint, 2050 net zero goal, carbon sink of -20Mt CO2 in 2050, no demand-side policies included, no green export industries included	reference	yes	-20	none	no	no
11	reference economic growth, no cumulative GHG emissions constraint, 2050 net zero goal, carbon sink of -20Mt CO2 in 2050, no demand-side policies included, new green export industries included	reference	yes	-20	none	no	yes
12	reference economic growth, 6 cumulative GHG emissions constraint, 2050 net zero goal, carbon sink of -45Mt CO2 in 2050, no demand-side policies included, no green export industries included	reference	yes	-45	6	no	no
13	reference economic growth, 6 cumulative GHG emissions constraint, 2050 net zero goal, carbon sink of -45Mt CO2 in 2050, no demand-side policies included, new green export industries included	reference	yes	-45	6	no	yes
14	reference economic growth, 7 cumulative GHG emissions constraint, 2050 net zero goal, carbon sink of -45Mt CO2 in 2050, no demand-side policies included, no green export industries included	reference	yes	-45	7	no	no
15	reference economic growth, 7 cumulative GHG emissions constraint, 2050 net zero goal, carbon sink of -45Mt CO2 in 2050, no demand-side policies included, new green export industries included	reference	yes	-45	7	no	yes
16	reference economic growth, 8 cumulative GHG emissions constraint, 2050 net zero goal, carbon sink of -45Mt CO2 in 2050, no demand-side policies included, no green export industries included	reference	yes	-45	8	no	no
17	reference economic growth, 8 cumulative GHG emissions constraint, 2050 net zero goal, carbon sink of -45Mt CO2 in 2050, no demand-side policies included, new green export industries included	reference	yes	-45	8	no	yes
18	reference economic growth, 9 cumulative GHG emissions constraint, 2050 net zero goal, carbon sink of -45Mt CO2 in 2050, no demand-side policies included, no green export industries included	reference	yes	-45	9	no	no

Number	Description	Growth rate	Net zero goal specified for CO2?	Carbon sink in 2050 (Mt)	GHG constraint (2021-2050)	Demand side policies included?	New export industries included?
19	reference economic growth, 9 cumulative GHG emissions constraint, 2050 net zero goal, carbon sink of -45Mt CO2 in 2050, no demand-side policies included, new green export industries included	reference	yes	-45	9	no	yes
20	reference economic growth, 6 cumulative GHG emissions constraint, 2050 net zero goal, carbon sink of -45Mt CO2 in 2050, demand-side policies included, no green export industries included	reference	yes	-45	6	yes	no
21	reference economic growth, 6 cumulative GHG emissions constraint, 2050 net zero goal, carbon sink of -45Mt CO2 in 2050, demand-side policies included, new green export industries included	reference	yes	-45	6	yes	yes
22	reference economic growth, 7 cumulative GHG emissions constraint, 2050 net zero goal, carbon sink of -45Mt CO2 in 2050, demand-side policies included, no green export industries included	reference	yes	-45	7	yes	no
23	reference economic growth, 7 cumulative GHG emissions constraint, 2050 net zero goal, carbon sink of -45Mt CO2 in 2050, demand-side policies included, new green export industries included	reference	yes	-45	7	yes	yes
24	reference economic growth, 8 cumulative GHG emissions constraint, 2050 net zero goal, carbon sink of -45Mt CO2 in 2050, demand-side policies included, no green export industries included	reference	yes	-45	8	yes	no
25	reference economic growth, 8 cumulative GHG emissions constraint, 2050 net zero goal, carbon sink of -45Mt CO2 in 2050, demand-side policies included, new green export industries included	reference	yes	-45	8	yes	yes
26	reference economic growth, 9 cumulative GHG emissions constraint, 2050 net zero goal, carbon sink of -45Mt CO2 in 2050, demand-side policies included, no green export industries included	reference	yes	-45	9	yes	no
27	reference economic growth, 9 cumulative GHG emissions constraint, 2050 net zero goal, carbon sink of -45Mt CO2 in 2050, demand-side policies included, new green export industries included	reference	yes	-45	9	yes	yes
28	reference economic growth, no cumulative GHG emissions constraint, 2050 net zero goal, carbon sink of -45Mt CO2 in 2050, demand-side policies included, no green export industries included	reference	yes	-45	none	yes	no

Number	Description	Growth rate	Net zero goal specified for CO2?	Carbon sink in 2050 (Mt)	GHG constraint (2021-2050)	Demand side policies included?	New export industries included?
29	reference economic growth, no cumulative GHG emissions constraint, 2050 net zero goal, carbon sink of -45Mt CO2 in 2050, demand-side policies included, new green export industries included	reference	yes	-45	none	yes	yes
30	reference economic growth, no cumulative GHG emissions constraint, 2050 net zero goal, carbon sink of -45Mt CO2 in 2050, no demand-side policies included, no green export industries included	reference	yes	-45	none	no	no
31	reference economic growth, no cumulative GHG emissions constraint, 2050 net zero goal, carbon sink of -45Mt CO2 in 2050, no demand-side policies included, new green export industries included	reference	yes	-45	none	no	yes
32	reference economic growth, no cumulative GHG emissions constraint, no net zero goal, carbon sink of -12Mt CO2 in 2050, demand-side policies included, no green export industries included	reference	no	-12	none	yes	no
33	high economic growth, no cumulative GHG emissions constraint, no net zero goal, carbon sink of -13Mt CO2 in 2050, no demand-side policies included, no green export industries included	high	no	-13	none	no	no
34	high economic growth, 6 cumulative GHG emissions constraint, 2050 net zero goal, carbon sink of -21Mt CO2 in 2050, no demand-side policies included, no green export industries included	high	yes	-21	6	no	no
35	high economic growth, 6 cumulative GHG emissions constraint, 2050 net zero goal, carbon sink of -20Mt CO2 in 2050, no demand-side policies included, new green export industries included	high	yes	-20	6	no	yes
36	high economic growth, 7 cumulative GHG emissions constraint, 2050 net zero goal, carbon sink of -21Mt CO2 in 2050, no demand-side policies included, no green export industries included	high	yes	-21	7	no	no
37	high economic growth, 7 cumulative GHG emissions constraint, 2050 net zero goal, carbon sink of -21Mt CO2 in 2050, no demand-side policies included, new green export industries included	high	yes	-21	7	no	yes
38	high economic growth, 8 cumulative GHG emissions constraint, 2050 net zero goal, carbon sink of -21Mt CO2 in 2050, no demand-side policies included, no green export industries included	high	yes	-21	8	no	no

Number	Description	Growth rate	Net zero goal specified for CO2?	Carbon sink in 2050 (Mt)	GHG constraint (2021-2050)	Demand side policies included?	New export industries included?
39	high economic growth, 8 cumulative GHG emissions constraint, 2050 net zero goal, carbon sink of -21Mt CO2 in 2050, no demand-side policies included, new green export industries included	high	yes	-21	8	no	yes
40	high economic growth, 9 cumulative GHG emissions constraint, 2050 net zero goal, carbon sink of -21Mt CO2 in 2050, no demand-side policies included, no green export industries included	high	yes	-21	9	no	no
41	high economic growth, 9 cumulative GHG emissions constraint, 2050 net zero goal, carbon sink of -21Mt CO2 in 2050, no demand-side policies included, new green export industries included	high	yes	-21	9	no	yes
42	high economic growth, no cumulative GHG emissions constraint, 2050 net zero goal, carbon sink of -21Mt CO2 in 2050, no demand-side policies included, no green export industries included	high	yes	-21	none	no	no
43	high economic growth, no cumulative GHG emissions constraint, 2050 net zero goal, carbon sink of -21Mt CO2 in 2050, no demand-side policies included, new green export industries included	high	yes	-21	none	no	yes
44	high economic growth, 6 cumulative GHG emissions constraint, 2050 net zero goal, carbon sink of -45Mt CO2 in 2050, no demand-side policies included, no green export industries included	high	yes	-45	6	no	no
45	high economic growth, 6 cumulative GHG emissions constraint, 2050 net zero goal, carbon sink of -45Mt CO2 in 2050, no demand-side policies included, new green export industries included	high	yes	-45	6	no	yes
46	high economic growth, 7 cumulative GHG emissions constraint, 2050 net zero goal, carbon sink of -45Mt CO2 in 2050, no demand-side policies included, no green export industries included	high	yes	-45	7	no	no
47	high economic growth, 7 cumulative GHG emissions constraint, 2050 net zero goal, carbon sink of -45Mt CO2 in 2050, no demand-side policies included, new green export industries included	high	yes	-45	7	no	yes
48	high economic growth, 8 cumulative GHG emissions constraint, 2050 net zero goal, carbon sink of -45Mt CO2 in 2050, no demand-side policies included, no green export industries included	high	yes	-45	8	no	no

Number	Description	Growth rate	Net zero goal specified for CO2?	Carbon sink in 2050 (Mt)	GHG constraint (2021-2050)	Demand side policies included?	New export industries included?
49	high economic growth, 8 cumulative GHG emissions constraint, 2050 net zero goal, carbon sink of -45Mt CO2 in 2050, no demand-side policies included, new green export industries included	high	yes	-45	8	no	yes
50	high economic growth, 9 cumulative GHG emissions constraint, 2050 net zero goal, carbon sink of -45Mt CO2 in 2050, no demand-side policies included, no green export industries included	high	yes	-45	9	no	no
51	high economic growth, 9 cumulative GHG emissions constraint, 2050 net zero goal, carbon sink of -45Mt CO2 in 2050, no demand-side policies included, new green export industries included	high	yes	-45	9	no	yes
52	high economic growth, 6 cumulative GHG emissions constraint, 2050 net zero goal, carbon sink of -45Mt CO2 in 2050, demand-side policies included, no green export industries included	high	yes	-45	6	yes	no
53	high economic growth, 6 cumulative GHG emissions constraint, 2050 net zero goal, carbon sink of -45Mt CO2 in 2050, demand-side policies included, new green export industries included	high	yes	-45	6	yes	yes
54	high economic growth, 7 cumulative GHG emissions constraint, 2050 net zero goal, carbon sink of -45Mt CO2 in 2050, demand-side policies included, no green export industries included	high	yes	-45	7	yes	no
55	high economic growth, 7 cumulative GHG emissions constraint, 2050 net zero goal, carbon sink of -45Mt CO2 in 2050, demand-side policies included, new green export industries included	high	yes	-45	7	yes	yes
56	high economic growth, 8 cumulative GHG emissions constraint, 2050 net zero goal, carbon sink of -45Mt CO2 in 2050, demand-side policies included, no green export industries included	high	yes	-45	8	yes	no
57	high economic growth, 8 cumulative GHG emissions constraint, 2050 net zero goal, carbon sink of -45Mt CO2 in 2050, demand-side policies included, new green export industries included	high	yes	-45	8	yes	yes
58	high economic growth, 9 cumulative GHG emissions constraint, 2050 net zero goal, carbon sink of -45Mt CO2 in 2050, demand-side policies included, no green export industries included	high	yes	-45	9	yes	no

Number	Description	Growth rate	Net zero goal specified for CO2?	Carbon sink in 2050 (Mt)	GHG constraint (2021-2050)	Demand side policies included?	New export industries included?
59	high economic growth, 9 cumulative GHG emissions constraint, 2050 net zero goal, carbon sink of -45Mt CO2 in 2050, demand-side policies included, new green export industries included	high	yes	-45	9	yes	yes
60	high economic growth, no cumulative GHG emissions constraint, 2050 net zero goal, carbon sink of -45Mt CO2 in 2050, demand-side policies included, no green export industries included	high	yes	-45	none	yes	no
61	high economic growth, no cumulative GHG emissions constraint, 2050 net zero goal, carbon sink of -45Mt CO2 in 2050, demand-side policies included, new green export industries included	high	yes	-45	none	yes	yes
62	high economic growth, no cumulative GHG emissions constraint, 2050 net zero goal, carbon sink of -45Mt CO2 in 2050, no demand-side policies included, no green export industries included	high	yes	-45	none	no	no
63	high economic growth, no cumulative GHG emissions constraint, 2050 net zero goal, carbon sink of -45Mt CO2 in 2050, no demand-side policies included, new green export industries included	high	yes	-45	none	no	yes
64	high economic growth, no cumulative GHG emissions constraint, no net zero goal, carbon sink of -12Mt CO2 in 2050, demand-side policies included, no green export industries included	high	no	-12	none	yes	no

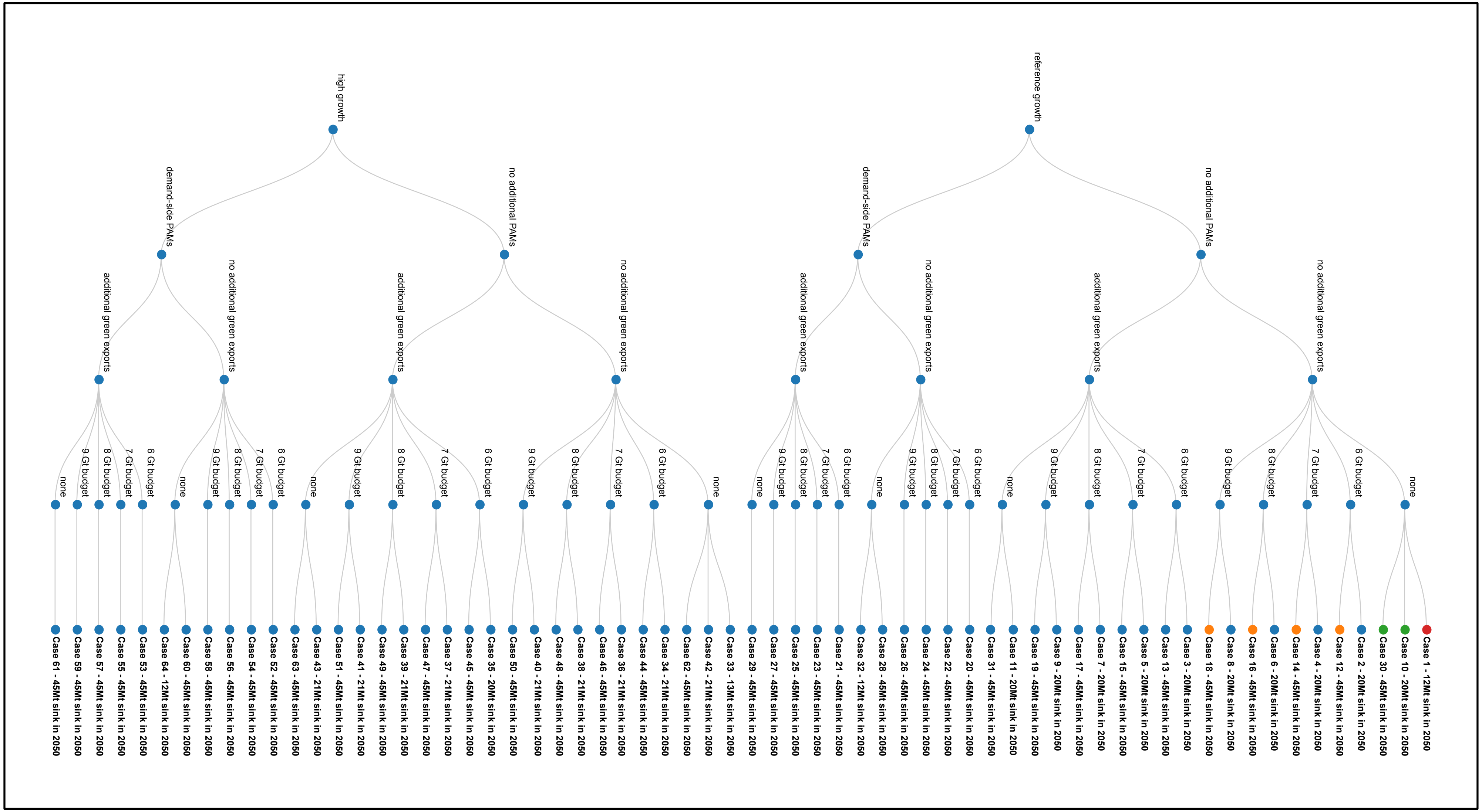

Figure 68 – Dendrogram of the cases modelled and contained in Table 5. Numbers of cases correspond to numbers in the first column of Table 5. Non blue cases are those analysed in detail above.