BRIEFING NOTE
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THE MEANING OF 'NET ZERO' FOR SOUTH AFRICA AND ITS POWER SECTOR

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EXECUTIVE SUMMARY

The concept of 'net zero by 2050' has proved a powerful political and narrative focusing device. However, the concept requires careful translation to enable the detailed analysis required for the development of decarbonisation strategies for countries, sectors, cities and companies. In this paper, we unpack what 'net zero' and 'net zero by 2050' mean both at a global and sub-global level, and from there, develop an initial framework to guide the modelling of detailed net zero scenarios for the South African power sector[2].

In 2018, the Special Report on 1.5˚C by the Intergovernmental Panel on Climate Change (IPCC) found that CO_2 emissions reduce to net zero globally around 2050 in socio-economic pathways that limit global warming to 1.5˚C. Thus, the concept of 'net zero by 2050' was born. 1.5˚C is the temperature limit that the Paris Agreement aspires to, and that which the Glasgow Pact reinforces[3]. This means that when we speak of global 'net zero by 2050', we are technically speaking of mitigation ambition aligned with this 1.5˚C temperature goal.

The net zero date of 2050 from the IPCC global assessment has subsequently been extracted and applied to inform net zero targets at 'sub-global' levels e.g. national or sectoral. This has served a powerful political and narrative purpose, providing a clear unifying objective and direction for decarbonisation efforts. The value of this cannot be under-estimated, however we argue in this paper that simply applying a net zero CO_2 date in developing decarbonisation strategies at the sub-global level is insufficient to ensure 1.5°C ambition. It may even mis-represent the underlying science, leaving open the real danger of delaying adequate action.

What then is required to adequately detail 1.5°C ambition at the sub-global level? Ultimately, we find that the introduction of the concept of 'net zero by 2050' has important implications for sub-global decarbonisation strategies, but these are less to do with the actual net zero date and more to do with aspects such as temperature aligned emissions budgets, modelling timeframes, dealing with uncertainty, and the specification and pricing of negative emissions technologies and natural sinks.

From climate science, we learn that global temperature becomes locked in at the point of global net zero carbon emissions. But it is the cumulative carbon emissions to this point - the space below a temporal emissions trajectory - that determines the specific temperature that is locked in. Therefore, a cumulative global carbon 'budget' can be associated with any one temperature goal. The IPCC's Sixth

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[1] Reviewed by Andrew Marquard, Ermi Miao, Luca Lo Re, Sara Moarif and Grové Steyn.

[2] The findings of the subsequent modelling exercise will be detailed in a forthcoming report.

[3] Global socio-economic pathways aligned to a 'well below 2˚C' temperature goal arrive at net zero around 2070

Assessment Report of Working Group 1 suggests the need for a remaining global carbon budget of 500 GtCO_2 for a 50% chance of limiting warming to 1.5°C (Carbon Brief, 2021).

To define sub-global 1.5°C compatible emission trajectories, the global 1.5°C aligned carbon budget then needs to be allocated sub-globally. This allocation is an essentially political task, involving issues of equity and context. Therefore, any attempt to develop sub-global 1.5°C strategies is necessarily situated within a political context. However, science can go a long way to understanding the range in which a fair and adequate sub-global 1.5°C aligned budget lies, and may be useful for revealing cost and other implications of particular net zero dates.

The date of net zero is *derived* from modelling global socio-economic pathways whose cumulative emissions equate to temperature-aligned carbon budgets. The date is also a global average (some countries, regions, sectors, and companies will need to achieve net zero earlier and some later). The date alone is thus less defining of adequate mitigation ambition sub-globally than is the allocation of a 1.5°C aligned budget.

At the global net zero date, any remaining CO_2 emissions need to be balanced with an equivalent volume of removals – where CO_2 is extracted from the atmosphere and permanently stored – in perpetuity. Net zero must be maintained from the net zero date. Any exceedance of a target budget prior to the net zero date will require additional removals over and above those associated with maintaining net zero.

A deeper look at the climate science reveals an added complexity to the 'net zero by 2050' concept; non-CO_2 greenhouse gases such as methane and nitrous oxide, which have an important influence on atmospheric warming, behave differently to CO_2. Non-CO_2 greenhouse gases do not reach net zero in IPCC modelled pathways, and do not need to reach net zero from the perspective of stabilising temperature. However, mitigation of these emissions is nevertheless critical in achieving the Paris temperature goals. In most existing analysis, national-level budgets are expressed as all-greenhouse gas budgets (CO_2-eq), rather than just CO_2, a significant deviation from the global 'net zero', which refers only to CO_2.

Net zero requires CO_2 removal, through Carbon Capture (Utilisation) and Storage (CC(U)S) technologies or natural sinks. However, given the nascence of the net zero concept, a common terminology around storage and removals has not yet been established. A number of aspects therefore require clarification to assist in sub-global net zero analysis. First, is that capture and storage/utilisation can be used to achieve either CO_2 mitigation or removal. Second, there is a distinction between carbon captured at source, and carbon extracted from the atmosphere. Third, geographical location is relevant at different points during the carbon capture and storage / utilisation process, with implications for pricing, and fourth, permanence of the storage type (including utilisation) is critical.

Defining 1.5°C aligned emissions trajectories at the sub-global level is subject to significant sources of uncertainty – global carbon budgets themselves, methods for sub-global budget allocations, the impact of non-CO_2 gases, the size of future natural sinks, the cost and availability of negative emissions technologies. These uncertainties should not be ignored as net zero implications are translated into policy and action. Rather, methods for engaging this uncertainty explicitly need to be identified and elaborated.

Utilising the exploration of the science behind net zero and its application in sub-global analysis presented in the first half of the paper, we develop an initial six-point framework for a net zero analysis of the South African power sector in the second half. This framework may also provide a starting point for developing net zero strategies in other sub-global contexts. A summary of this framework is presented below:

1. *Budget Range*: Net zero power sector modelling for South Africa should be constrained with an appropriate emissions budget range that reflects equity, context and uncertainty considerations, and is associated with particular temperature goals. In the case of 'net zero by 2050', this implies a temperature goal of 1.5˚C, and we identify an associated power sector range of 2–3.1Gt utilising analysis undertaken by the University of Cape Town's Energy System Modelling Group.
2. *Budget timeframes*: Given that 'net zero by 2050' is a global average, it is politically and analytically appropriate to consider applying emissions budgets to timeframes beyond 2050 for the South African power sector, given that the country is classified as developing under the UNFCCC. The actual modelling timeframe chosen will balance the objectives of the particular study with the utility of modelling far into the future.
3. *Enforcing the budget*: No further CO_2 emissions should be allowed beyond the analytical timeframe. This can be achieved by forcing in a net zero date, or by checking modelling results to ensure that any CO_2 emissions left on the system at the modelling end date will reduce to zero within the following year.
4. *Natural sinks:* Given the uncertainty surrounding the size of South Africa's land sink, and that the power sector is characterised by relatively low-cost abatement options compared to the rest of the economy, we assume that no land sink is available to the power sector. This assumption could be relaxed simply by widening the power sector's budget range.
5. *Identifying and pricing removal and storage technologies*: CC(U)S at source in the South African power sector is only potentially feasible for new coal and gas plant, not retrofits, therefore only these options need be considered in a model. CC(U)S at source relies on local storage availability, and should therefore be priced accordingly together with a consideration of the finite storage space available domestically. Carbon capture and storage removal technologies (DACCS and BECCS being the most promising currently) are not geographically dependent. Therefore, these emissions removal efforts can be implemented outside the country and should be considered at a global market-determined price per unit of emissions removed.
6. *Power demand:* Power demand must be uncoupled from historical trends and economic structures, to account for the increased need for electrification of sections of transport, industry and beyond. As economies transition towards net zero, there will be a changing role for power, which needs to be acknowledged beyond a simple demand increase in sectoral models. Non-traditional modelling and analytical approaches will likely be required in order to fully explore these changes.

In terms of actual net zero dates, as long as the aspects identified in the framework above are applied, the actual date when the power system achieves net zero is of political relevance alone. Acknowledging this, contemplating net zero by various dates – keeping the carbon budgets the same in each case – can provide useful information on the relative costs associated with any future political commitments to net zero dates for the power sector.

GLOSSARY

BECCS	Bioenergy with Carbon Capture and Storage
BNEF	Bloomberg New Energy Finance
CCGT	Closed Cycle Gas Turbine
CCU	Carbon Capture and Utilisation
CCUS	Carbon Capture, Utilisation and Storage
CCS	Carbon Capture and Storage
CDR	Carbon Dioxide Removal
CERC	Climate Equity Reference Calculator
COP	Conference of the Parties
CO_2	Carbon Dioxide
DAC	Direct Air Capture
DACCS	Direct Air Carbon Capture and Storage
DFFE	Department of Forestry, Fisheries and the Environment
GHG	Greenhouse Gases
Gt	Gigatonnes
IAM	Integrated Assessment Model
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
IRP	Integrated Resource Plan
Mt	Megatonnes
NDC	Nationally Determined Contributions
NET	Negative Emissions Technologies
NGFS	Network for Greening the Financial System
OCGT	Open Cycle Gas Turbine
RE	Renewable Energy
UNFCCC	United Nations Framework Convention on Climate Change

1 INTRODUCTION

Humanity has a rapidly dwindling window for action to limit global temperature rise and avoid the worst effects of climate change. The United Nations Framework Convention on Climate Change (UNFCCC) is the parent treaty to the 2015 Paris Agreement which commits to containing temperature rise to 'well below 2˚C' and 'pursuing efforts to limit the temperature increase to 1.5˚C'. However, current country pledges across the world are not sufficient to limit warming to below 2°C, let alone 1.5˚C (Climate Action Tracker, 2021).

In 2018, the Special Report on 1.5˚C by the Intergovernmental Panel on Climate Change (IPCC) found that CO_2 emissions are reduced to net zero globally around 2050 in socio-economic pathways that limit global warming to 1.5˚C. The phrase 'net zero by 2050' was extracted from this highly complex climate modelling exercise as a simple communication device around ambitious decarbonisation action, with the result that thousands of sub-global 'net zero' targets and pathways by countries, regions, sectors, companies, financial institutions and cities have been, and are being developed.

'Net zero' – the new buzz word – has been used as a communicable device in support of aligning mitigation targets with the Paris Agreement. At face value, 'net-zero' is the state at which a balance is obtained and sustained between anthropogenic CO_2 emissions derived from human activity and anthropogenic CO_2 removal[4]. The notion of 'net zero' is embedded in Article 4.1 of the Paris Agreement, and has become a powerful device in communicating the need for ambitious climate action. *Global net zero* is a pre-requisite, along with deep reductions in non-CO_2 greenhouse gases, to achieving the global temperature goals set out in the Paris Agreement[5], and *global net zero by 2050* is necessary to contain temperature rise to 1.5˚C.

In late 2021, Meridian Economics sought to understand the implications of taking on net zero targets for the South African power sector by building on the set of power sector decarbonisation scenarios developed in our 'A Vital Ambition' project undertaken with the CSIR (Meridian Economics, 2020). The close specification of modelling parameters required when undertaking a modelling exercise demanded that we think through precisely what net zero means at a sub-global, sub-national level. This Briefing Note is the outcome of our thought process. On the way, we have identified some key take-aways associated with the concept of sub-global net zero which we emphasise in the document. We've also made a first attempt at identifying a framework for sub-global, sub-national power sector net zero modelling, focused on the South African power sector.

Ultimately, we find that the introduction of 'net zero by 2050' has important implications for the development of sub-global decarbonisation strategies, but these are less to do with the actual net zero date and more to do with aspects such as the specification of modelling timeframes, emissions budgets, dealing with uncertainty, and the treatment of negative emissions technologies.

Not all sectors, emitting activities and parts of the world will need to achieve net zero CO_2 emissions at the date of 2050. Some will need to arrive there earlier, some can arrive later, as is reflected in the different country's net zero pledges.

The concept of 'net zero by 2050' has political and focusing importance that is critical in the context of a 1.5˚C global ambition. However, we will argue that the most important aspect of this pledge is a 1.5 ˚C aligned budget or emissions trajectory and interim milestones.

In this Briefing note, we unpack what 'net zero' and 'net zero by 2050' mean, discussing its science-based origins, situating the 'net' in the context of current technology options, and considering the role of offset markets in supporting a global net zero ambition in Sections 2-4). In so doing, the Briefing provides a detailed argument for the importance of carbon budgets, trajectories and milestones above net zero dates at the sub-global level.

The second half of the Briefing develops a clear six-point framework within which to conduct detailed quantitative modelling work underpinning pathways to net zero for the South African power sector. When undertaking quantitative modelling exercises the details behind a 'net zero by 2050' target become all-important to ensure the achievement of rigorous and useful results to guide policymaking and action.

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[4] The focus here is on anthropogenic (human induced) emissions, CO_2 flows associated with the natural carbon cycle are not included in this analysis.

[5] The net zero term has often been used synonymously with terms such as 'carbon neutral' and 'climate neutral', creating inconsistency and a lack of clarity around its use. These different terms point towards the different ways in which the emissions sources and sinks are accounted for in a particular context and assist in indicating what is and is not included in the calculation of emissions or the target (Oxford Net Zero, 2021).

2 THE SCIENCE BEHIND 'NET ZERO'

Global assessments undertaken by the IPCC (and others) utilise climate-economic models, known as Integrated Assessment Models (IAMs), which link greenhouse gas (GHG) emissions to impacts on different sectors of the economy. IAMs have become a key guide for international climate policy since the mid-1990s, and are used to project the emissions impact of various global socio-economic development scenarios.

CO_2 is by far the most dominant of the seven anthropogenic Kyoto greenhouse gasses in the atmosphere, and also the most intertwined in our fossil fuelled economies and societies. It is well established that increasing CO_2 concentrations in the atmosphere drive the global warming effect. This is because there is a near-linear relationship between cumulative CO_2 emissions and the global surface temperature rise, i.e. each additional 1000Gt of cumulative CO_2 emissions has been assessed to cause between 0.27°C to 0.63°C increase in global surface temperature – with a best estimate of 0.45°C (IPCC, 2021).

Therefore, in order to stop further warming and stabilise global temperature, it is a requirement for anthropogenic (human induced) emissions to reach and sustain a 'net zero' state – the state at which anthropogenic CO_2 emissions are balanced by anthropogenic CO_2 emissions removals[6] (Reisinger, 2020). Any positive deviation from a net zero state will increase the concentration of CO_2 in the atmosphere, which will cause further warming.

Whilst reaching net zero anthropogenic CO_2 emissions is a requirement to stabilise temperature rise at *any* given level, achieving a *specific* level implies limiting total cumulative CO_2 emissions to a particular amount (IPCC, 2021). There is a stock and a flow element to CO_2 emissions in the atmosphere. CO_2 is described as a 'stock pollutant', one which accumulates in the atmosphere and essentially locks in a certain degree of warming (Frame, Macey & Allen, 2018). The historical emissions *stock* is being added to every year through an additional emissions *flow*, thereby reducing the global emissions space left until a critical point of cumulative emissions (associated with the Paris temperature goals) is breached.

There are other non-CO_2 GHGs, such as methane, which also influence warming and therefore strong and deep reductions in these emissions will also play a role in meeting the Paris temperature goals (IPCC, 2021). However, these gases have different radiative forcing properties[7] to CO_2 (i.e. they influence warming differently) and there is therefore a distinction between achieving net zero *CO_2 emissions* and net zero *GHG emissions*, each with different implications for global warming.

Achieving net zero CO_2 emissions will stabilise global temperatures at a particular degree so long as other non-CO_2 emissions GHG are declining. Net zero GHG emissions will both stabilise global temperature due to the effect of achieving net zero CO_2, and further result in declining temperatures due to the effective cooling resulting from net zero non-CO_2 emissions (these interactions are explained further in section 2.3). We focus in this Brief on 'net zero CO_2 emissions' following the IPCC, but comment at various points on

[6] *Anthropogenic removals could include increasing biological or geochemical sinks which sequester CO_2, or durably storing CO_2 in geological, terrestrial, or ocean reservoirs, or in products.*

[7] *Radiative forcing is the net change in the energy balance of the Earth's atmosphere due to natural or anthropogenic factors of climate change, usually determined over a period of time (Myhre et al., 2018)*

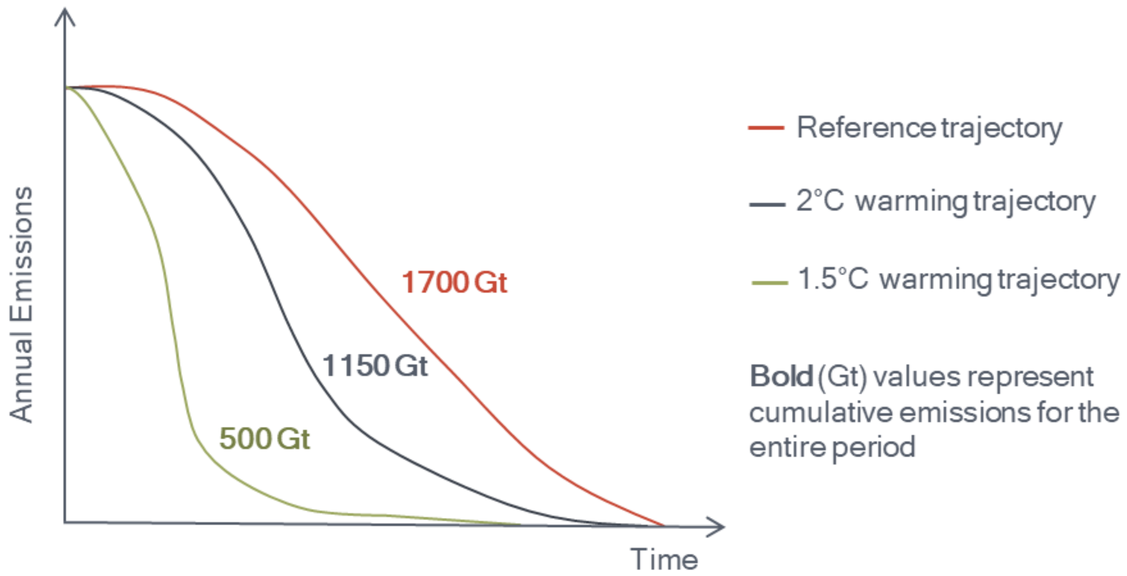
the importance of reductions in other non-CO_2 GHGs.

2.1 CARBON BUDGETS AND MITIGATION TRAJECTORIES

The global CO_2 emissions space left until a particular temperature point is locked in is called a 'carbon budget' by the IPCC. The higher the annual rate of net emissions (flow), the sooner this remaining carbon budget is depleted. Conversely, the sooner the net flow is reduced, the longer the time until a net-zero point is required. Therefore, the pathway or trajectory towards a net zero end-point matters.

A carbon budget is expressed as a number representing the allowable cumulative emissions over a timeframe associated with a particular temperature goal, and can be presented as the area below a temporal emissions trajectory that declines to zero. This is conceptually demonstrated in the figure below.

Figure 1: Illustration of relationship between emissions trajectories and temperature-aligned carbon budgets



The IPCC 1.5 Special Report introduced the concept of a budget 'overshoot' alongside that of net zero, out of necessity given the likelihood that humanity will exceed the budgets required to lock-in a 1.5˚C temperature rise. An overshoot occurs when a particular temperature related budget is exceeded before net zero is achieved. If an overshoot occurs, corresponding carbon removals will be required in the latter half of the century. Additional carbon removals therefore represent a safety valve if humanity exceeds our global carbon budget on the way to net zero, but relying on these is a high risk strategy given the uncertainties surrounding our ability to remove carbon at scale in the future.

It is now estimated that the earth's temperature is around 1.1˚C above pre-industrial levels (IPCC, 2021). The IPCC's Sixth Assessment Report of Working Group 1, suggests the need for a remaining global carbon budget of 500 $GtCO_2$ (from the year 2020 to the year 2100) for a 50% chance of limiting warming to 1.5°C, and 1150 $GtCO_2$ for a 66% chance of limiting to 2˚C (the latter being widely associated with the Paris target of 'well below 2˚C') (Carbon Brief, 2021).

Despite being conceptually 'simple', it is important to recognise that there are many sources of uncertainty that make it challenging to estimate the remaining global carbon budget (Tokarska & Matthews, 2021).

There are many different factors which may affect the relationship between CO_2 and warming, including non-CO_2 emissions and climate system feedback loops. Some of these are not yet well understood. Matthews et al. (2021) therefore emphasise that while carbon budgets are expressed as a single number, they are actually based on a broader underlying probability distribution of meeting a target. The less CO_2 emitted, the higher the probability of staying within a budget and therefore limiting warming.

The uncertainty around carbon budgets is central to the net zero challenge, and should not be ignored as net zero implications are translated into policy and action. Rather, we need to identify and elaborate methods for engaging this uncertainty productively. We return to this theme in Section 6.1.3.

2.2 NET ZERO DATES

Net zero dates (e.g. 'net zero by 2050') have emerged as an *outcome* of global climate-economic modelling processes mentioned

Figure 2 below shows possible future development scenarios analysed in the IPCC's Sixth Assessment Report, with SSP1-

earlier in this brief. The date(s) emerge as a result of a carbon budget being imposed as a constraint on the modelling of possible global socio-economic developmental pathways over a 100-year timeframe. The IPCC reports on the point at which optimised developmental pathways (trajectories) – when constrained by a specific carbon budget linked to a particular temperature goal (e.g. 1.5 or 2°C) – would reach 'net zero' emissions.

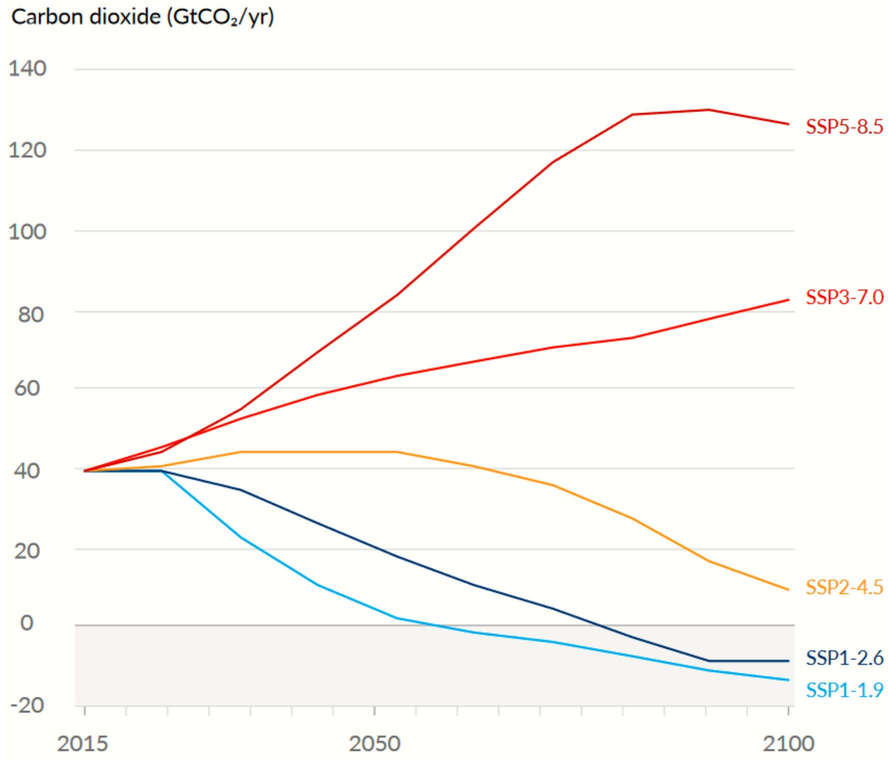
Restricting warming to 1.5°C will therefore require global developmental trajectories constrained by 1.5˚C aligned carbon budgets. These trajectories achieve net zero global CO_2 emissions around 2050. Limiting global warming to well below 2°C result in trajectories that reach net zero around 2070 (IPCC, 2018, 2021).

Plotted on a graph considering CO_2 emissions over time, the area under various global developmental trajectories represents the cumulative carbon emissions that must be considered for compliance against temperature-aligned carbon budgets. below shows possible future development scenarios analysed in the IPCC's Sixth Assessment Report, with SSP1-1.9 adhering to a 1.5 ˚C carbon budget, and SSP1-2.6. complying with a 2 ˚C budget.

1.9 adhering to a 1.5 ˚C carbon budget, and SSP1-2.6. complying with a 2 ˚C budget.

Figure 2: Annual anthropogenic CO_2 emissions across five illustrative IPCC scenarios

The IPCC's Sixth Assessment Report (IPCC, 2021) analyses a set of possible future scenarios using IAMs, with two scenarios being consistent with the Paris goals of limiting warming to 1.5 (SSP1-1.9) and below 2 degrees (SSP1-2.6) by the end of the century.



Importantly, net zero targets are not end states in themselves. Rogelj et al (2021) describe them as 'milestones to meeting net-negative emissions targets further down the road', given the likelihood of us 'overshooting' our temperature target before reaching a net zero point and having to remove additional CO_2 from the atmosphere beyond this point.

The IPCC's scenarios SSP1-1.9 and SSP1-2.6 – consistent with the Paris goals of limiting warming to 1.5˚C and below 2˚C respectively by the end of the century – in addition to seeing CO_2 emissions declining to net-zero around or after 2050 are followed by varying levels of net-negative CO_2 emissions in order to limit total emissions over the 100-year period to each temperature-aligned carbon budget.

In simple terms, the IPCC scenarios illustrate that even the most ambitious but feasible rates at which society can reduce emissions is not fast enough to enable us to 'just' reach net zero and maintain that state – we will still likely need to remove additional carbon from the atmosphere in the second half of the century to limit warming to a set temperature goal. This would therefore assume the use of anthropogenic CO_2 removal approaches in combination with other GHG emissions reductions to 'compensate for earlier emissions as a way to meet long-term climate stabilization goals after a temperature overshoot'.

Further, the modelling of Paris aligned carbon budget constrained trajectories reveal nearer term targets too. This is clearly shown in the IPCC 2018 report, which specifies a 45% reduction of CO_2 emissions by 2030 from 2010 levels to achieve 1.5°C, and for well below 2°C, 25% reduction by 2030.

2.3 NON-CO_2 GREENHOUSE GAS EMISSIONS

Whilst anthropogenic CO_2 emissions must reach net zero (due to the near linear relationship between cumulative CO_2 emissions and warming), it is also imperative that non-CO_2 emissions see deep and sustained reductions to limit temperature rise to that aligned with the Paris goals (IPCC, 2021).

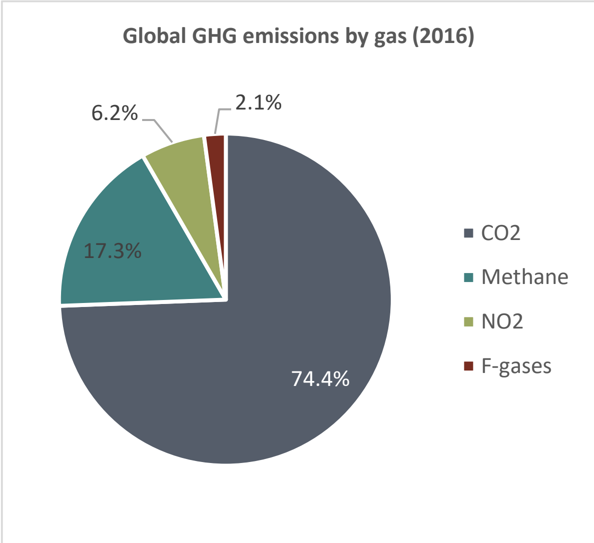
Non-CO_2 GHGs such as methane (CH_4) and Nitrous Oxide (N_2O) have an important influence on warming of the atmosphere, but behave differently to CO_2.

'Global warming potential' (GWP) is a metric that has been designed to normalise the comparison of the impact of different gases on temperature. GWP is a function of two factors: how effective a gas is at trapping heat whilst in the atmosphere, and how long it remains there before breaking down. The larger the GWP value, the higher the impact of the gas on warming over a particular timeframe, relative to CO_2. Non-CO_2 gases can hereby be expressed as "CO_2-equivalents" (CO_2-eq). The GWP100 metric (global warming potential of a gas over a 100-year timeframe) has become the standard metric for reporting national GHG emissions in CO_2-eq to the UNFCCC (UNFCCC, 2015; Lynch et al., 2021).

The relative percentage of CO_2-eq emissions by gas in 2016 at a global level are shown in Figure 3 (Ritchie & Roser, 2020). CO_2 is by far the most dominant, with methane the second largest contributor to global GHG emissions.

Figure 3 Global anthropogenic GHG emissions by gas in 2016

Gases are measured as CO_2-eq emissions using the GWP100 metric.



2.3.1 The role of non-CO_2 GHG emissions in temperature rise

Methane is a potent GHG which has a higher 'radiative forcing' (influence on temperature) than CO_2. Simply put, this means that a pulse of methane emissions will have a larger impact on temperature rise than a nominally equivalent pulse of CO_2 emissions[8].

However, unlike CO_2 which is a stock pollutant that accumulates in the atmosphere, methane is a flow pollutant and only remains in the atmosphere for a relatively short timescale (~12yrs) after which it is broken down via natural processes[9] (Cain, 2018). Methane is therefore known as a 'short-lived' climate pollutant (SLCP). The high level differences between how CO_2 and methane influence temperature are demonstrated in Figure 4 below (Cain, 2018).

[8] *The GWP100 value for methane (CH_4) from the latest IPCC assessment report (AR6) is between 27.2 – 29.8 (dependent on the source of methane, i.e. fossil or non-fossil). This means that methane has a GWP value ~28 times than CO_2, so 1Gt CH_4 equates to ~28 GtCO_2e*

[9] *It is worth noting that the degradation of methane occurs via oxidisation, resulting in CO_2 as a product which continues to have a warming effect in the atmosphere. However the yield of CO_2 from methane oxidisation is still subject to large uncertainty. The IPCC's Sixth Assessment report has included updated GWP values for methane intending to account for the oxidisation of methane to CO_2 to the extent which this is possible (Section 7.6.1.3, IPCC, 2021)*

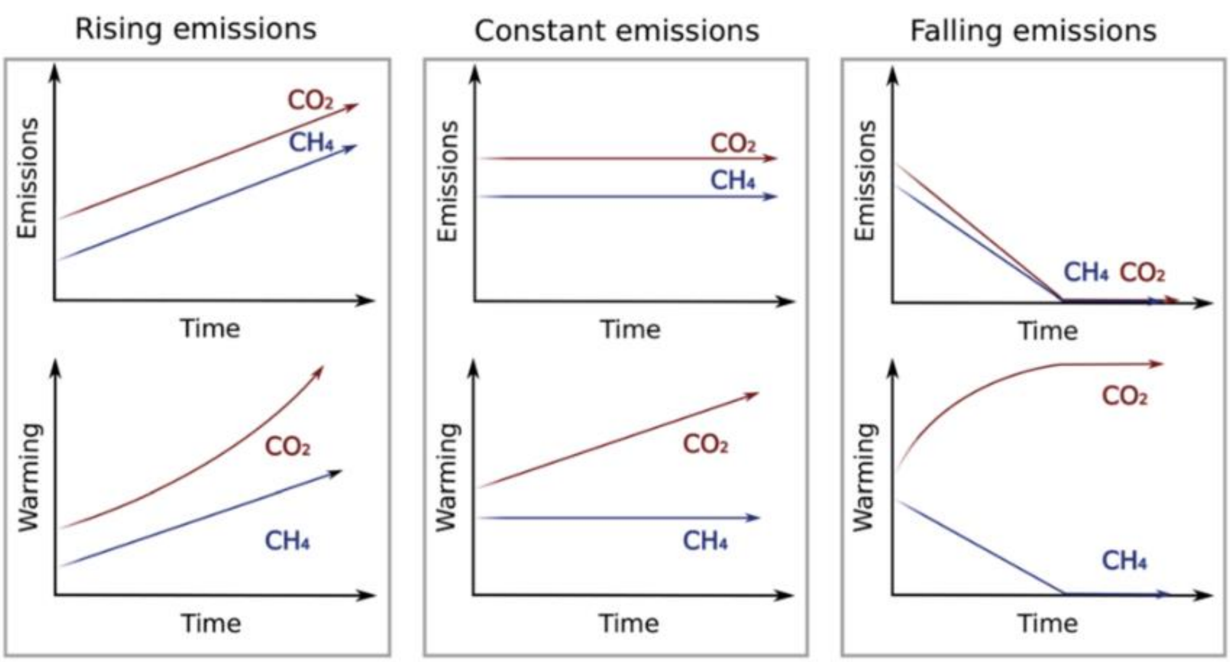
The left panel demonstrates that when emissions are rising, CO_2 and methane both cause warming. However, when CO_2 emissions are held constant, temperature continues to rise as CO_2 continues to accumulate in the atmosphere, and it is the cumulative stock of CO_2 which exerts influence on warming. In contrast, constant methane emissions result in the maintenance of temperatures at an elevated level but cause no further warming. Most markedly, in the right-hand panel, when CO_2 emissions are falling, temperature continues to rise as long as emissions remain above zero (until they reach zero, they continue to add to the stock of CO_2). However, temperature falls in response to falling methane emissions due to the gas's short residency in the atmosphere – once methane is broken down (which takes about a decade) the original temperature response is effectively reversed (Allen et al., 2016).

This renders methane emissions reductions an important climate mitigation tool because immediate action to reduce emissions can bring about significant temperature declines in the short term.

Conversely, the powerful impact of a short-term increase in methane emissions – due to the relatively higher temperature response to methane relative to CO_2 – could result in the breaching of dangerous 'tipping point' temperature thresholds, which may result in irreversible climate impacts.

Recognising the importance of methane mitigation, over 100 parties signed the Global Methane Pledge initiated at COP26, with a collective goal of reducing methane emissions by 30% by 2030 to achieve a temperature decrease of 0.2°C (BBC News, 2021).

Figure 4 Temperature response to different emissions trajectories for CO_2 and methane



Nitrous Oxide (N_2O) emissions, largely emanating from the agricultural sector but also via natural processes, receive less focus than methane and CO_2 in international climate policy circles. Reasons for this include difficulty in monitoring N_2O emissions, as well as lack of mitigation practices and technologies and the cost of such mitigation compared to other GHG sources (Kanter, Ogle & Winiwarter, 2020). N_2O is understood to have a much stronger radiative forcing than CO_2 and has a residency of ~110yrs in the atmosphere before it is broken down. This means its lifespan is longer than methane, but shorter than CO_2 which accumulates in the atmosphere for hundreds of years.

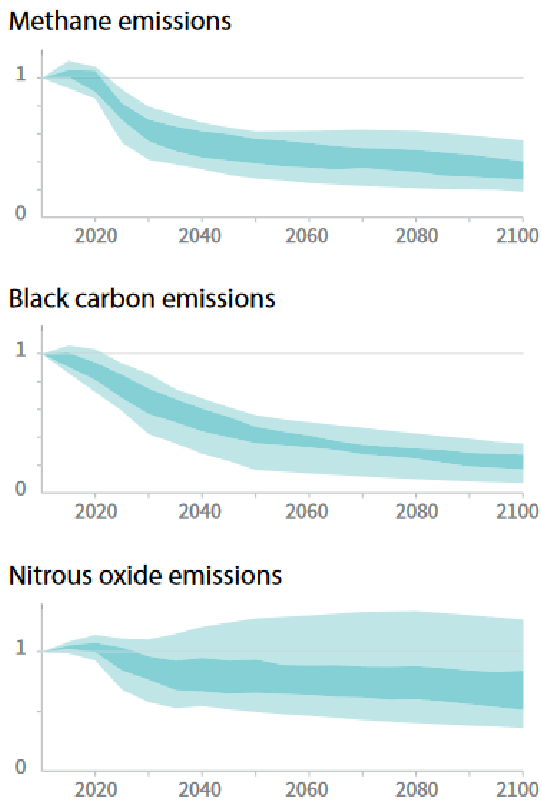
2.3.2 What do non-CO_2 gases mean for carbon budgets?

The IPCC 6th Assessment report states that whilst net zero CO_2 emissions is required for stabilising global temperatures, so too is the need for declining net non-CO_2 emissions (IPCC, 2021).[10]

The IPCC's 1.5°C warming pathways show that immediate declines in non-CO_2 emissions with sustained declines in methane and black carbon in particular are necessary to achieve a particular temperature target (Figure 5). However, it is noteworthy that non-CO_2 emissions do not reach net zero within the next century in pathways that achieve the Paris temperature goals.

Figure 5: Non-CO_2 emissions

Relative to 2010 in pathways limiting global warming to the 1.5°C temperature goal with 'no or limited overshoot' (IPCC, 2018)



The trajectories of these non-CO_2 gases introduce significant uncertainty as to the ultimate size of the global carbon budget. For example, if non-CO_2 radiative forcing were to increase, this could substantially decrease the size of the remaining budget for CO_2 emissions – as less warming would be 'allowable' from the CO_2 stock (Ou et al., 2021). It is estimated that higher or lower reductions in accompanying non-CO_2 emissions could increase or decrease the remaining global carbon budget by at least 220 $GtCO_2$ (~50%) or more (IPCC, 2021).

There is an ongoing debate on whether it is useful to express the emissions mitigation challenge at the global level in the form of one

[10] *"The maximum temperature reached is then determined by cumulative net global anthropogenic CO_2 emissions up to the time of net zero CO_2 emissions (high confidence) and the level of non-CO_2 radiative forcing in the decades prior to the time that maximum temperatures are reached (medium confidence)." (IPCC, 2021)*

budget for all GHGs that incorporates the temperature effect of non-CO_2 forcing in an appropriate manner. It may be that this is only useful if a declining trajectory for non-CO_2 GHGs is assumed. Certainly, an all-GHG budget is theoretically possible, through expressing the warming impact of all GHG in a common metric denominated in CO_2, and hence a CO_2-eq budget. However, there is disagreement in the climate science community around whether and what type of alternative metrics would be appropriate to adequately represent the influence of different gases on warming, with GWP100 being contested by some as too simplistic, resulting in the misrepresentation of the contribution of SLCPs in particular (Allen et al., 2016; Frame, Macey & Allen, 2018; Lynch et al., 2020).

Developing an appropriate way to express a global CO_2-eq budget may be significant for understanding estimates for sub-global carbon budgets, national in particular.

In summary then, the science is clear that achieving a particular temperature goal requires adhering to an absolute carbon budget constraint associated with that temperature goal. A net zero point emerges as a result, halting further warming at that date. In 1.5°C and 2°C pathways, the net zero state is followed by varying levels of net-negative CO_2 emissions in order to deal with any temperature overshoot prior to reaching a net zero point, which thereby limits total emissions to a 1.5°C / 2°C aligned carbon budget by 2100.

'Net zero by 2050' has emerged as a useful, communicable device of complex climate science to signal mitigation effort associated with a 1.5°C warming pathway, which achieves net zero CO_2 emissions around 2050 and thereafter, net-negative emissions. However, it is not always interpreted as such, in many cases being viewed as a standalone goal which is abstracted from its original embedment in an absolute, 1.5°C aligned carbon budget.

Non-CO_2 GHGs do not reach net zero in IPCC modelled pathways, and do not need to reach net zero from the perspective of stabilising temperature. There are also large complexities associated with the removal of non-CO_2 emissions, for which there are no natural sinks or proven removal technologies – making the prospect of achieving net zero more difficult than CO_2. That said, deep reductions in non-CO_2 emissions are absolutely necessary and are just as important as achieving net zero CO_2 emissions in adherence to a 1.5°C warming pathway – due to the significant uncertainties related to peak warming and triggering of tipping points etc). It is also worth noting that declining emissions of non-CO_2 GHGs result in a negative temperature forcing (cooling temperatures), which is an important mitigation tool that could be utilised in conjunction to reductions in CO_2. In essence, efforts to mitigate all GHGs are important and one cannot be traded for another.

3 THE 'NET' IN 'NET ZERO': CO_2 REMOVALS AND STORAGE

At the net zero point, any remaining CO_2 emissions need to be balanced with an equivalent volume of removals. Carbon removal refers to the act of extracting CO_2 from the atmosphere and permanently storing it (Allen et al., 2020). Any exceedance of a target budget prior to the net zero date will require additional removals over and above those associated with maintaining net zero by 2100.

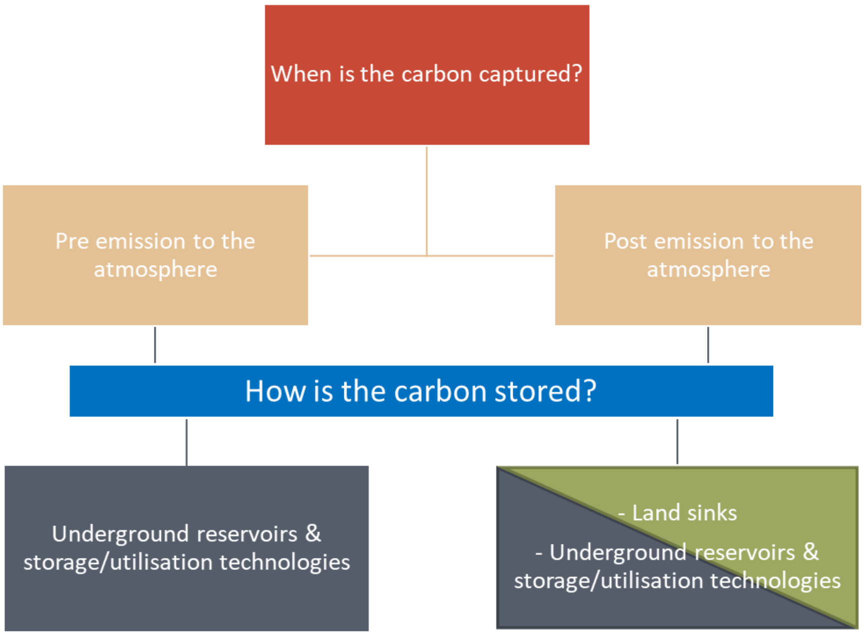
The 'net zero' device has highlighted an inevitability: in addition to finding ways to reduce and avoid the emissions associated with human socio-economic systems, we will have to develop ways to remove CO_2 emissions from the atmosphere after they have been emitted, and store them permanently.

Atmospheric removals are achieved through enhanced ecosystem management, and through the development of 'Direct Air Carbon Capture and Storage' (DACCS) technologies. Storage options vary in terms of their permanence. In general, CO_2 storage associated with natural ecosystems, such as land sinks, have high risk of reversal of the stored carbon back into the atmosphere, making them potentially less permanent. Options involving storage in underground cavities or in a solid form (carbon 'utilisation') have lower risk of reversal (centuries to millennia), although this type of storage is subject to other risks. If the CO_2 stream is utilised in non-solid forms then it is not clear that it ultimately does contribute to either mitigation or removal.

The terminology associated with carbon capture and utilisation/storage is in its infancy, and can cause confusion. Whilst it is beyond the scope of this paper to propose any particular taxonomy or comment on existing terms, we find it important to clarify a couple of aspects relating to carbon capture and storage/ utilisation as pertaining to the transition to net zero socio-economic systems.

Figure 6: Options for carbon capture and storage for net-zero decarbonisation

Adapted by the authors from (Allen et al., 2020)



First, capture and storage / utilisation can be used to achieve either CO_2 mitigation or removal.

Second, there is a distinction between carbon captured at source, and carbon extracted from the atmosphere. CO_2 extracted from the air is typically referred to as 'Direct Air Capture'. It is far cheaper to capture a stream of CO_2 at source than it is to extract CO_2 from the air.

Third, geographical location is relevant at different points during the carbon capture and storage / utilisation process. The site of carbon capture is only constrained if this is pre-emission capture. Natural ecosystem and geographical storage locations are clearly geographically fixed. Utilisation options will vary.

Finally, the permanence of the storage type (including utilisation) is critical.

Figure 6 above sets out a simple way of navigating carbon capture and storage / utilisation options.

The four most common types of carbon capture and utilisation / storage for both mitigation and removal purposes are Carbon Capture (Utilisation) and Storage (CC(U)S) from an emissions source, DACCS, Bio-energy with Carbon Capture and Storage (BECCS) and Natural ecosystem options.

3.1 CCUS

CCUS[11] involves capturing CO_2 released at the source of large fossil fuel / industrial plants, and compressing the CO_2 for transportation and injection into deep underground geological formations where it for permanent storage.

CCUS has been used commercially for the purification of hydrogen and a variety of gasses in industrial settings since the 1930s (Global CCS Institute, 2019). To date, there are 26 CCUS facilities in operation internationally with a capacity to capture and permanently store approximately 40 Mt of CO_2 per year (Global CCS Institute, 2021).

Most planned and active CCUS projects are in industrial sectors, such as chemical, hydrogen and fertiliser production and natural gas processing, where high concentration CO_2 is readily available and can be captured at relatively low cost compared to power plant specific concentrations (Global CCS Institute, 2019). The utilisation of CO_2 captured in various applications, particularly in the production of synthetic fuels and concrete, remains in early stages of development. Although geological storage is likely to do more work to meet net zero targets, carbon utilisation will still play an important role in decades to come (Global CCS Institute, 2019).

Within the global power sector, there are only two small scale coal power plants with CCUS in operation (capturing up to 1 Mt of CO_2 per year), with another seven fossil fuel power plants with CCUS (four coal and three gas) at advanced stages of development. With relatively little experience developing power plants with CCUS facilities at commercial scale, there are significant risks that have driven up the cost of these technologies, with banks not willing to provide debt financing for projects or offer competitive interest rates at this stage (Global CCS Institute, 2019).

3.2 DACCS

DACCS technologies extract CO_2 directly from the atmosphere for permanent storage or use in either food processing or to produce synthetic hydrocarbons.

Unlike fossil fuel / industrial plants retrofitted with CCUS, DACCS plants are not geographically constrained as they can either be situated at the source of the CO_2 emissions, next to an industrial plant that needs CO_2 as a feedstock, or on top of geological storage sites to reduce the need for CO_2 transport (IEA, 2022). This includes storage sites which are located offshore. However, when isolating CO_2 capture specific costs, DACCS is highly energy intensive and expensive compared with other carbon and storage technologies due to low CO_2 concentration in ambient air. The energy

[11] *Also referred to as CCS in literature, as the utilisation aspect remains nascent.*

needs for the DACCS plant will be a significant factor in determining both the plant location and production costs as sources of energy would need to come from renewables to ensure that the system remains carbon negative (IEA, 2020).

As DACCS technologies are yet to be demonstrated at scale, future costs remain unclear.

3.3 BECCS

With BECCS, energy is produced from biomass, and then the resulting CO_2 emissions are captured using CCUS technologies. The production of biomass energy is considered to be renewable energy, so when paired with CCUS technology for its combustion and fermentation processes, negative emissions are achieved (IEA, 2020).

There are industrial scale risks associated with BECCS due to arable land and freshwater being better suited for agriculture and food production, and high risk of further emissions being released through deforestation. According to IPCC (2018), BECCS would demand between 25% to 80% of all the land currently under cultivation to provide the carbon removal consistent with Paris Agreement scenarios.

3.4 NATURAL ECOSYSTEM OPTIONS

Natural sinks play a critical role in decreasing the effects of climate change, involving both mitigation (prevention) and removal (sequestration). Mitigation involves the conservation of existing carbon sinks in soil and vegetation, whilst removal involves enhancing the uptake of carbon in terrestrial reservoirs (Department of Environmental Affairs, 2016). Natural sinks absorb approximately half of the emissions released into the atmosphere each year, slowing down climate change far more effectively than any human technology (Friedlingstein et al., 2019). These sinks could contribute even more towards mitigation and removal efforts if managed and controlled appropriately, however, human endeavour continues to deplete natural sinks, further diminishing their capacity to absorb large portions of emissions. Land use changes dominated by deforestation and degradation of land and soil cause natural ecosystems to become carbon sources.

Natural carbon sink mechanisms include afforestation and reforestation, land restoration and soil carbon sequestration.

Whilst the storage offered by natural sinks is typically short lived due to high risk of carbon reversal, if these sinks are managed appropriately and restoration and protection of natural ecosystems is supported, this storage could be considered as long-term (Allen et al., 2020).

Whilst capture and storage technologies are critical to achieving a net-zero emissions trajectory aligned with limiting global warming to 1.5˚C by balancing out residual / unavoidable emissions and counteracting overshoot, these technologies remain unproven at the scale required, present significant risk and are expensive. The focus should therefore primarily be on immediate avoidance and reduction of emissions together with the development of carbon capture and storage / utilisation technologies and the enhancement of natural ecosystems.

4 THE ROLE OF OFFSETS

From the perspective of achieving global net zero CO_2 emissions, carbon offsetting is a mechanism that assists in allocating mitigation effort following market logics. Basically, carbon offsetting allows resources to flow to the easiest and cheapest mitigation opportunities, to maximise the efficiency of allocation of global mitigation resources. As such, the mechanism is both useful and risky in the context of global net zero requirements. Offsets do not impact the overall ambition of limiting global warming to 1.5˚C nor the size of the budgets and shape of trajectories required to achieve these. Most importantly, offsets should not be used to delay mitigation action on the global critical path to net zero.

Two varieties of offsets can be considered in the context of net zero: first, mitigation offsets for carbon reduction and avoidance on the way to net zero, for the efficient allocation of the global mitigation effort (together with important sustainable development co-benefits); and second, removal offsets which represent CO_2 emissions taken out of the atmosphere. Removal offsets have a role to play both in providing some space on the route to net zero, and in maintaining net zero, matching least cost removal opportunities with the emitting activities that are the most expensive to mitigate.

The carbon offsetting mechanism is contentious and complex, with significant and well known associated risks associated with accounting, permanence, and unintended consequences beyond the mitigation sphere (Allen et al., 2020; Jeudy-Hugo, Lo Re & Falduto, 2021). We don't go into these here, apart from flagging them. Establishing a comprehensive set of rigorous, equitable and credible net zero trajectories, which are the focus of this paper, are a requirement for carbon offsetting to play a useful role in the achievement of global net zero.

5 NET ZERO AT THE SUB-GLOBAL LEVEL

The concept of 'net zero by 2050' has political importance that is critical in the context of a 1.5˚C global ambition, and has been immensely successful at focusing attention at both global and sub-global levels. However, the concept emerged from a global modelling exercise, with the net zero date a global average. How then should it be interpreted when constructing and analysing 1.5˚C aligned mitigation strategies for regions, countries, sectors and companies?

In section 2 we argued that temperature-aligned carbon budgets associated with socio-economic pathways drive net zero dates. Simply extracting a net zero CO_2 date emerging from a global assessment and applying it sub-globally without an accompanying near-term target or budget fundamentally mis-interprets the underlying science.

Analytically there is no basis for only imposing a net zero date by 2050 when modelling 1.5˚C at *sub-global* levels. Rather, imposing an emission constraint on future development pathways at a sub-national level in the form of a 1.5˚C-aligned carbon budget and associated trajectory is the critical task. The sub-global system must achieve net zero by some point, but the driver of this is the budget and trajectory. The date cannot stand alone. Unfortunately then, the words of the politically powerful catch phrase are misleading for detailed target setting in a sub-global context.

Establishing appropriate carbon budgets and trajectories at the sub-global level is a significant challenge, with additional levels of uncertainty to contend with on top of those associated with global net zero and outlined in the Briefing thus far. Linking global 1.5˚C mitigation to a sub-national level requires divvying up a global 1.5˚C aligned carbon budget against certain criteria.

Embedded in the UNFCCC is the principle of 'common but differentiated responsibilities (in terms of contribution to the emissions stock), and respective capabilities' (to reduce emissions flow in the context of the

Sustainable Development Goals) (CBDR-RC). These equity principles are reflected in the level of mitigation effort expected from different parties to the Convention (i.e. nation-states), and is the basis for financial, technical and capacity building support for developing countries. Therefore, the size of carbon budget at a national level (and arguably at any sub-global level considered) should reflect equity criteria. Upfront, it is important to recognise that the allocation of the remaining global 1.5˚C carbon space sub-globally is primarily a political task, and one that has not proved possible at the international policy level [12]. This notwithstanding, analytical endeavors towards sub-national effort allocation remain critical to link climate science with ambition, policies and action.

Allocating carbon budgets beyond nation states that fall under the UNFCCC becomes more complex still. Current criteria for doing this largely involve cost optimization, but could – and arguably should – be expanded to include those pertaining to development considerations, structural economic change, intergenerational justice or other.

In addition to a fair allocation of carbon budgets, the timing of net zero at a sub-global level has an equity aspect to it as well. Certainly, the analytical timeframes for considering net zero dates should extend well beyond 2050 in order to cater for the effects of the global average together with political uncertainty around the 1.5°C temperature goal.

Dealing with non-GHG emissions, removal technology pricing, natural sinks and offsets are further complexities which require translation to any particular sub-global context.

In the remainder of this Briefing Note we develop an initial analytical framework for modelling net zero trajectories for one sub-global system, the South African power sector.

6 TOWARDS A NET ZERO ANALYTICAL FRAMEWORK FOR THE SOUTH AFRICAN POWER SECTOR

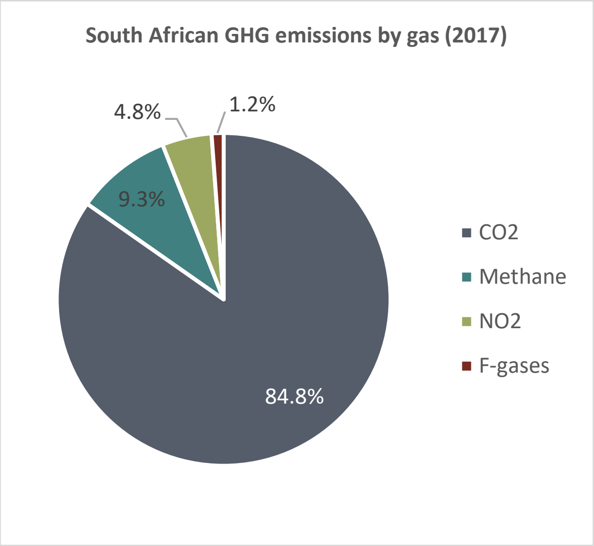
6.1 BUDGETS AND MITIGATION TRAJECTORIES

6.1.1 Towards a South African CO_2-eq budget range

South Africa's GHG profile from the most recent national GHG inventory report compiled using 2017 data (DFFE, 2021), is represented below. Whilst CO_2 dominates overwhelmingly, methane in particular is not insignificant.

Figure 7: South Africa's GHG emissions profile in 2017

All gases are measured in CO_2-eq.



[12] *The structure of the Paris Agreement has moved away from the Kyoto Protocol's top-down allocation of mitigation effort, to a bottom up framing of what parties are capable of doing. Politics aside, methods for sub-national effort allocation will be important for linking what climate science is finding, to the necessary action.*

Two emerging approaches to carbon budget allocation which explicitly deal with equity aspects are those of Carbon Action Tracker (CAT) and Climate Equity Reference Calculator (CERC). These approaches engage with the country-level. A couple of general points on these are useful for the proceeding analysis:

- Each use different methodologies to address equity principles.
- Both consider CO_2-eq budgets – i.e. budgets representing all GHGs, not only CO_2.
- The land sector has been largely excluded from budget allocations, a feature which becomes particularly problematic in the context of achieving net zero.

Based on a combination of CAT and CERC's analysis, the Energy Systems Modelling Research Group (ESRG) of the University of Cape Town (UCT) proposes a 1.5˚C compatible CO_2-eq budget for the whole South African economy as lying between 7 and 8.5Gt[13]. It should be noted, however, that the uncertainties associated with a global carbon budget are compounded at the national level, particularly given the (necessary) inclusion of equity aspects which by their nature evade quantification, and due to the inclusion of non-CO_2 gases.

Ascertaining an appropriate contribution of effort from the electricity sector to a national decarbonization agenda flows from this national carbon budget range, taking into account the sectoral cost of mitigation, together with policy objectives. In South Africa, the power sector both contains the country's least cost mitigation options and is of systemic importance to decarbonization and economic growth. It will therefore be critical to achieving the country's longer term climate goals (Presidential Climate Commission, 2021).

Currently, the only modelling platform that allocates the national budget at a sectoral level in South Africa is the linked SATIMGE model of the ESRG. This model optimises for mitigation cost across the SA energy system, and the outputs include cumulative emissions for each sector over the modelling period.

6.1.2 Deriving a budget range for the South African power sector

In 2021 the ESRG undertook a modelling exercise for the DFFE, modelling 'net zero by 2050' scenarios for the South African economy. To do this, the ESRG allocated various CO_2-eq budgets (a range of 6 – 9 Gt) across the economy under different assumptions around economic growth, hydrogen exports, size of the land carbon sink, energy efficiency, transport and energy policy. The model specifies CO_2 emissions decline to net zero in 2050, whilst non-CO_2 gases are not subject to this constraint (UCT ESRG, 2022)[14].

To reflect more closely a national 1.5˚C range of 7-8.5 Gt, the subset of the 7, 8 and 9 Gt scenarios was considered[15]. South Africa's power sector emissions are dominated by CO_2, with less than 2% made up of methane and N_2O. The associated power sector cumulative CO_2 (only) emissions range that results from analysis of these model runs is 2-

[13] As advised by Andrew Marquard of UCT's ESRG, paper forthcoming.

[14] The results of this exercise remain unpublished at the time of writing. Meridian has therefore used the data tableau dated 17 March 2022 in our analysis. The authors are grateful for the assistance of, and conversations with Andrew Marquard and Bruno Merven from the ESRG to enable many of the insights in this section. All errors in interpretation lie with the authors.

[15] The analysis was based on a total of 34 scenarios between 7-9 Gt from the UCT ESRG modelling.

3.1 Gt[16]. This cumulative emissions range, an output of the economy-wide modelling, can be argued as representing an appropriate 1.5˚C CO_2 budget range for the power sector if South Africa is to achieve a 1.5˚C aligned net zero economy. This range could then be introduced as an exogenous input to a sectoral power system modelling platform.

6.1.3 Budget range uncertainty

There are many sources of uncertainty inherent in determining appropriate budget constraints at a sub-global and sub-national level. These uncertainties stem from the underlying science, the long-term nature of the issue, the need to incorporate aspects not amenable to modelling (such as equity criteria and political consideration) and, as will continue to be demonstrated in the remainder of this section, the use of the outputs of one type of modelling environment as input to another, different modelling environment.

Having this extent of uncertainty surrounding the key modelling parameter (and more importantly, driver of mitigation effort) is far from ideal. However, the use of budgets appears be the only method currently available to reduce a highly complex set of issues into one or a range of numbers tractable to models. This state of affairs should give pause for thought, first to modellers regarding how models are most usefully engaged to provide insight in the face of such complexity and uncertainty, and then to the users of modelling outputs. What other, complementary forms of knowledge are required to take decisions on mitigation action?

In our investigation here, we have incorporated three ways of managing the budget uncertainty into our approach. The first is to engage a wide range of 1.5˚C compatible budgets for the South African power sector, as opposed to just one. The second, is to only consider potential complexities up until a point. The deep detail of atmospheric science hints that our method may need expanding in the way we consider non-CO_2 gasses, as does the deep detail of different modelling frameworks, and how these might nudge the resulting power sector budgets slightly up or down. But there is a point at which the uncertainty is so great that it is no longer useful to engage.

The third approach is to triangulate modelled South African power sector trajectories against findings from other, less disaggregated analyses, bearing in mind the granularity of the particular study considered, together with the criteria used for budget allocation.

One example of this is the net zero analysis by the International Energy Agency (IEA) which explored what it would take to achieve net zero emissions in the global energy system by 2050[17].

The IEA analysis offers a level of sub-global disaggregation, in that it provides clear milestones on the route to net zero for a developed and emerging market category respectively. For emerging markets:

1. By 2020 no new unabated coal plants are approved for development.
2. By 2040 all unabated coal and oil power plants are phased out.

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[16] Meridian calculation: linear interpolation based on this subset was used to provide a power sector emissions value for 8.5Gt

[17] A cumulative emissions budget aligned to the target of keeping temperature rise below 1.5ºC was employed, and the emissions pathway undertaken for the IEA net zero scenario maps to Pathway 2 'P2' of the IPCC's Special Report on 1.5ºC (IPCC, 2018), with a carbon budget of 500 Gt CO_2 and 'limited acceptance' for negative emissions technologies

However, it is not clear from the available information how the IEA analysis accounts for the UNFCCC principles of equity. In addition, 'emerging' versus 'developed' are clearly not homogenous categories, meaning that local starting points and contexts will not be well represented in the modelling. Nevertheless, these two points can be used to triangulate the results of the South African power sector scenarios constrained by the 2 - 3.1Gt budget range.

As the net zero space becomes increasingly populated with studies aimed at different scales and using different methods we will get additional information on appropriate net zero and 1.5˚C aligned sub-global trajectories. The task of understanding and unpacking what net zero means sub-globally is in its infancy, with climate and social sciences developing rapidly as resources are increasingly flowing to elaborate the mitigation challenge in various contexts.

6.2 MODELLING TIMEFRAMES

From the discussion thus far, we have argued that net zero scenarios at a sub-global level do not necessarily imply that a particular sub-global entity's emissions must necessarily be net zero by 2050. Rather, the priority is appropriately described CO_2 budgets that are aligned with 1.5˚C level of ambition and take equity and contextual considerations into account.

As argued by Winkler et al (2021), there is a risk that the call for global emissions to reach net zero by 2050 becomes seamlessly translated into a call for each country to announce net zero by 2050 targets, without a consideration of equity at the sub-global level (and without due emphasis on accompanying budgets).

However, modelling 1.5˚C compatible budgets requires specifying a modelling timeframe (i.e. how many years does the model take into account?). As a developing country, it is likely that South Africa can achieve net zero after the global average of 2050. Other emerging economies such as China and India have announced net zero dates of 2060 and 2070, respectively. Therefore, a modelling timeframe beyond 2050 would seem appropriate, but balanced by the challenges of long-term modelling: the longer the timeframe, the longer the run times and computing power required for the model to solve. In addition, uncertainty escalates as one models further out into the future.

Therefore, in order to balance modelling tractability with political plausibility, a modelling timeframe to, for example, 2060 for the South African power system may be appropriate.

A related challenge is that of ensuring that there are no significant CO_2 emissions remaining after the modelling timeframe. This can be achieved in three ways. The first is to impose a net zero date in addition the budget as part of the modelling parameters to strengthen the condition of the budget being absolute. Whilst rebounds from a net zero date are always possible, the only way to account for this is to extend the modelling timeframe with the net zero condition being held constant after the imposed net zero date.

The second is to check that carbon emissions naturally come off by 2060, and the third is to ensure that anything that is left in 2060 is so small so as to be within the modelling noise.

The ESRG modelling timeframe from which the power sector CO_2 budgets are derived is from 2021 to 2050. In order to satisfy ourselves that the economy-wide budgets employed were treated as absolute, we only considered ESRG scenarios that additionally require that net zero is achieved by 2050[18].

6.3 CO_2 REMOVALS AND STORAGE

Because CO_2 removals become an option in net zero modelling, removal technologies that extract CO_2 from the atmosphere and store it permanently would need to be made available to the power system model in addition to traditional mitigation technologies and those that capture and store carbon. The intention of this section is to highlight which carbon capture, storage and removal technologies could usefully be made available to a power system model, and how.

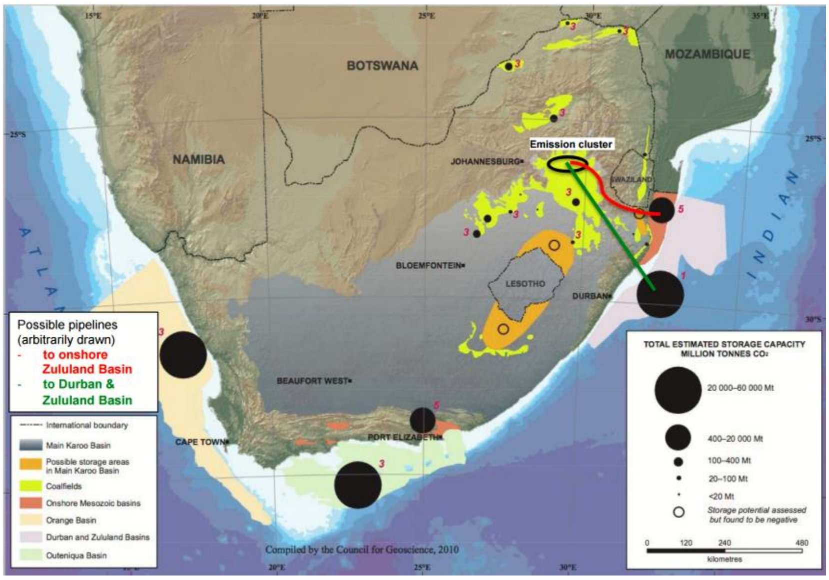
We begin by considering the costing of storage associate with the capture of emissions at source. Carbon capture and storage / utilisation for mitigation in the power sector, such as coal / gas with CCUS, are physically associated with existing or new South African power plants, meaning that the storage component remains within the country and must be costed accordingly.

According to the Atlas on Geological Storage of Carbon Dioxide in South Africa (Cloete, 2010), there is 150 Gt of theoretical storage capacity available to South Africa, of which 98% is offshore (this occurs in a combined capacity located in Outeniqua basin (South), Orange Basin (West) and the Zululand Basin (East), as seen in Figure 8. The remaining 2% onshore is split between the Algoa and Zululand Basins along the southern and eastern coastlines, respectively (Surridge et al., 2019).

A pilot carbon storage project is planned to be carried out on the Zululand Basin that monitors the injection and storage of small quantities of CO_2 (10,000 – 50,000 tonnes) over a period of two years (Surridge et al., 2019). Although there is significantly more offshore storage, the associated costs would most likely be more expensive than onshore storage, as captured CO_2 would need to be transported from power plant sites (mainly situated in the Mpumalanga region inland) to geological injection sites offshore at significantly high costs.

[18] *The cumulative emissions of the power sector from ESRG scenarios with identical budget constraints were smaller when a 2050 net zero constraint was imposed versus those where it wasn't (see (Marquard et al., 2021)*

Figure 8: Potential Storage Capacity in South African on and offshore basins (Cloete, 2010; Viebahn, Vallentin & Höller, 2015)



In terms of retrofitting the existing South African coal fleet with CCUS, according to Viebahn, Vallentin and Höller (2015), only Kusile is worth considering for retrofitting, as it was designed to be "capture-ready" in 2008, whereas the other new large power plant Medupi was not. The costing behind the retrofitting existing plants within SA in comparison with building a new coal plant with CCUS is relatively unknown.

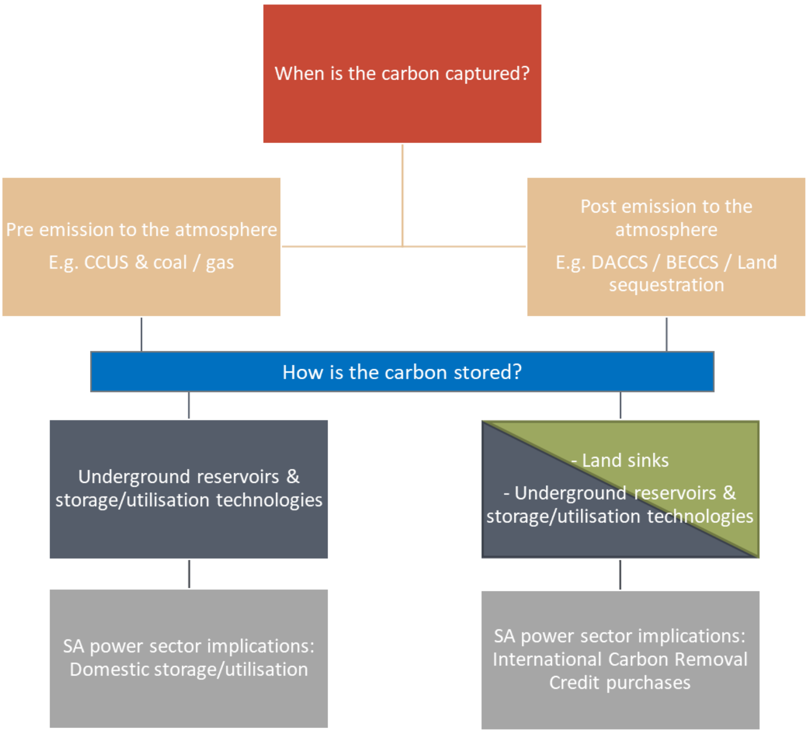
In the context of gas, incorporating CCUS facilities is only feasible and economical with larger closed cycle gas turbine (CCGT) plants with higher capacity factors. In South Africa, we currently only have open cycle gas turbine (OCGT) plants for peaking power. Therefore, it is most likely that CCUS would only be feasible for new coal and gas plants, and hence only these options could be made available to the model.

Technologies that primarily deliver CO_2 removal for the purposes of the South African power system achieving net zero (as opposed to power generation), such as BECCS and DACCS, need not be physically tied to the South African power system, but will in theory be built wherever internationally it is cost optimal to do so. This means that the South African power system model need only be presented with a global average cost per tonne of CO_2 removed. This would most likely in future to be represented by a tradeable offset (e.g. Carbon Removal Credit). Land use offsets are already traded in this way and theoretically could equally be available to the South African power sector for purchase.

Tradeable permits are a market-based approach that would ensure that an equivalent amount of carbon is removed from the atmosphere and stored permanently to compensate for the equivalent amount of emissions (Rickels et al., 2021). Currently the cost of removal technologies remain significantly higher than land management and forestry techniques, due to the lack of commercial viability, and would need addition remuneration to participate in the existing offset market (Rickels et al., 2021).

A net zero technology taxonomy as it applies to the power sector is elaborated in Figure 9 below.

Figure 9: Taxonomy of net zero technologies for the power sector



In terms of natural ecosystem removal options, we make the assumption that the South African power system cannot rely on there being natural ecosystem removal options available to it. This is for two reasons. The first is the extent of the uncertainty around the size of any future potential land sink. According to the AFOLU Baseline Steering Committee report (Department of Environmental Affairs, 2016), it is estimated the land sink will increase and stabilize from 2014 figures of 21 Mt $C0_2$ to 31 Mt $C0_2$ in 2030. This increase mainly results from a predicted increase in forest land.

However, current national AFOLU inventory data does not take into account any degraded lands in this calculation (Department of Environmental Affairs, 2016). The carbon lost from degraded woodlands, soil thicket losses and degraded grasslands is significant. Open grasslands and savannas across the country, which are natural carbon sinks, have increasingly shifted to bush encroached land as a symptom of continued land degradation. Other examples of changes include the continued conversion of natural vegetation to agricultural crops and forest plantation, accelerated urbanisation and changes due to overgrazing (Department of Environmental Affairs, 2016).

In addition, there is no coherence in terms of policy around land sinks, with land sink impacts driven by other policy objectives (such as clearing bush for agricultural purposes, managing wildfire risks, replanting with different types of vegetation), often in competing directions. The lack of an overarching strategy for managing South Africa's land use sink makes it very difficult to predict its size with any accuracy going forward[19]. The generation of land use offset credits for the international voluntary or

[19] *Dr Tony Knowles, Cirrus Group, expert opinion January 2022.*

compliance carbon markets adds further complexity to predicating a land use sink. How much of this sink will be under contract to international purchasers, and therefore required to be reduced from South Africa's own 2050 carbon inventory?

The second reason for assuming that there is no land sink available to the power sector is that the sector is well recognised as having the least cost mitigation options within the economy. If South Africa does have a land sink, we would assume this space would be optimally allocated to the hard-to-abate sectors in industry[20].

Were it deemed preferable to make a land sink available to the power sector, this could be achieved by simply increasing the sector's carbon budget range.

6.4 ELECTRICITY DEMAND AND SECTOR INTEGRATION

Electrification of transport and industry will play a critical role in realising 1.5 ˚C aligned decarbonisation. In net zero scenarios, demand for zero carbon electricity increases between two and threefold (Bataille, 2020; IEA, 2021), requiring that demand profiles aligned with this type of increase are factored in to net zero power sector scenarios.

However, the link between green electricity and net zero economies is not as straightforward as just a substantial increase in demand. Largely driven by the need to decarbonise, the power sector itself is in period of disruptive change – from centralised supply systems of the twentieth century to decentralised, digitalised twenty-first century systems that are fundamentally integrated into the rest of the economy.

Power storage solutions will span sectors (e.g. electric vehicle fleet batteries), and peaking requirements in the power system will need to be met by greener fuels such as green hydrogen which is produced via renewable energy, thereby increasing the requirement for renewable energy capacity in the system.

This in turn suggests that traditional power sector models, which generally only represent supply-side dynamics, will not be sufficient to represent the future complexity of power systems – modifications and adaptations will be necessary to meet our analytical needs.

6.5 THE NET ZERO DATE

This paper has argued that the actual net zero date is secondary to the carbon budget in indicating 1.5˚C alignment at a sub-global level. As long as an adequate, equitable and absolute carbon budget is applied, the actual date when the system achieves net zero is of political relevance alone[21].

Acknowledging this, forcing in net zero dates at various points – keeping the carbon budgets the same in each case – would provide useful information on the relative costs associated with political commitments to net zero at particular points in time.

7 SIX-POINTS FOR ANALYSING NET ZERO IN THE SA POWER SECTOR

This Briefing Note started by introducing the concept of net zero by 2050, discussing its science-based origins, situating the 'net' in the context of current technology options, and considering the role of offset markets in supporting a global net zero ambition.

[20] This assumption is challenged, however, by the ESRG modelling outputs. This model assumes a sink of between 20 and 45 Mt, and does allocate removal space to the power sector

[21] We have suggested that forcing the net zero date at the end of the modelling timeframe (i.e. 2060) is useful to strengthen the absolute carbon budget assumption

It then shifted to a sub-global view: First, to argue for the importance of carbon budgets, trajectories and milestones above net zero dates at the sub-global level. Whilst the 'net zero by 2050' phrase is powerful politically, it can be argued as misleading for the development of 1.5˚C sub-global decarbonisation strategies. Second, to develop an analytical frame for net zero modelling of the South African power sector. This framework is summarised here in six points:

1. *Budget Range*: Net zero power sector modelling for South Africa should be constrained with an appropriate emissions budget range that reflects equity, context and uncertainty considerations, and is associated with particular temperature goals. In the case of 'net zero by 2050', this implies a temperature goal of 1.5˚C, and we identify an associated power sector budget range of 2-3,1Gt, utilising analysis undertaken by the University of Cape Town's Energy System Modelling Group.
2. *Budget timeframes*: Given that 'net zero by 2050' is a global average, it is politically and analytically appropriate to consider applying emissions budgets to timeframes beyond 2050 for the South African power sector given that the country is classified as developing under the UNFCCC. The actual modelling timeframe chosen will balance the objectives of the study with the utility of modelling far into the future.
3. *Enforcing the budget*: No further CO_2 emissions should be allowed beyond the analytical timeframe. This can be achieved by forcing in a net zero date, or by checking modelling results to ensure that any CO_2 emissions left on the system at the modelling end date will reduce to zero within the following year.
4. *Natural sinks:* Given the uncertainty surrounding the size of South Africa's land sink, and that the power sector is characterised by relatively low-cost abatement options compared to the rest of the economy, we assume that no land sink is available to the power sector. This assumption could be relaxed just by widening the power sector's budget range.
5. *Identifying and pricing removal and storage technologies*: CC(U)S at source in the South African power sector is only potentially feasible for new coal and gas plant, not retrofits, therefore only these options need be made available to a model. CC(U)S at source relies on local storage availability, and should therefore be priced accordingly together with a consideration of the finite storage space available domestically. Carbon capture and storage removal technologies (DACCS and BECCS being the most promising currently) are not geographically dependent. Therefore, these emissions removal efforts can be implemented outside the country and should be considered as a global market determined price per unit of emissions removed.
6. *Power demand:* Power demand must be uncoupled from historical trends and economic structures, to account for the increased need for electrification of sections of transport, industry and beyond. As economies transition towards net zero, there will be a changing role for power, which needs to be acknowledged beyond a simple demand increase in sectoral models. Different modelling and analytical approaches will likely be required in order to fully explore these changes.

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