BRIEFING NOTE
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UNPACKING 'NET ZERO': KEY FEATURES OF NET ZERO POLICIES AND STRATEGIES

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EXECUTIVE SUMMARY

'Net zero by 2050' has served a powerful political and narrative purpose for climate mitigation, providing a clear unifying objective and direction for decarbonisation efforts.

Whilst the value of this cannot be underestimated, simply applying a net zero CO_2 date in developing decarbonisation strategies and policies 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.

In this paper, we unpack what 'net zero by 2050' means from a scientific perspective. We discuss the significance of associating the 'net-zero' date with an emissions constraint and trajectory, the role of different carbon capture and storage / removal technologies in reaching 'net-zero', and the complexities of carbon offsetting.

What then is required to adequately detail 1.5°C ambition? Ultimately, we find that temperature aligned emissions budgets, modelling timeframes, dealing with uncertainty, and the specification and pricing of negative emissions technologies and natural sinks form the central features of adequate and credible 1.5˚C aligned climate policies and strategies.

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.** 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

The date of net zero is derived from modelling global socio-economic pathways whose cumulative emissions equate to temperature-aligned carbon budgets. Similar to budgets, the date is also a global average (some countries, regions, sectors, and companies will need to achieve net zero earlier and some later).

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

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[1] This paper is an adaptation of a more comprehensive document (Meridian, June 2022), which discussed *'Net Zero'* in the context of the South African power sector, and developed an initial framework to guide the modelling of detailed net zero scenarios for the sector.

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 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 Non-CO_2 emissions is nevertheless critical in achieving the Paris temperature goals.**

Net zero requires CO_2 removal, through Carbon Capture, Utilisation and Storage (CCUS) technologies or natural sinks. There is a difference between CO_2 capture for mitigation (reducing emissions) and capture for removal of emissions once they have been emitted. The technologies of CC(U)S, Direct Air Capture (DACC), Biomass Energy Carbon Capture (BECC) and natural ecosystem storage can remove and store CO_2 emissions from the atmosphere.

Defining 1.5°C aligned emissions trajectories at the sub-global level is subject to significant sources of uncertainty – global carbon budgets themselves, net zero dates, 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 the significant uncertainty around 'net zero' explicitly need to be identified and elaborated.**

In this Briefing note, we unpack the key features of credible 'net zero' policies and strategies, providing a detailed argument for the importance of carbon budgets, trajectories and milestones above net zero dates at the sub-global level.

The note is intended for anyone seeking to understand the features of credible net zero policies and strategies – whether these be for regions, countries, companies, cities or communities.

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, 2022).

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[2].

The notion of 'net zero' is embedded in Article 4.1 of the Paris Agreement. *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[3], and *global net zero by 2050* is necessary to contain temperature rise to 1.5˚C. Not all sectors, emitting activities and parts of the world however 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 the key features of credible 'net zero' policies and strategies, providing a detailed argument for the importance of carbon budgets, trajectories and milestones above net zero dates at the sub-global level. The note is intended for anyone seeking to understand the features of credible net zero policies and strategies – whether these be for regions, countries, companies, cities or communities.

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

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

[3] 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).

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[4] (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[5] 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 GHG emissions 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 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

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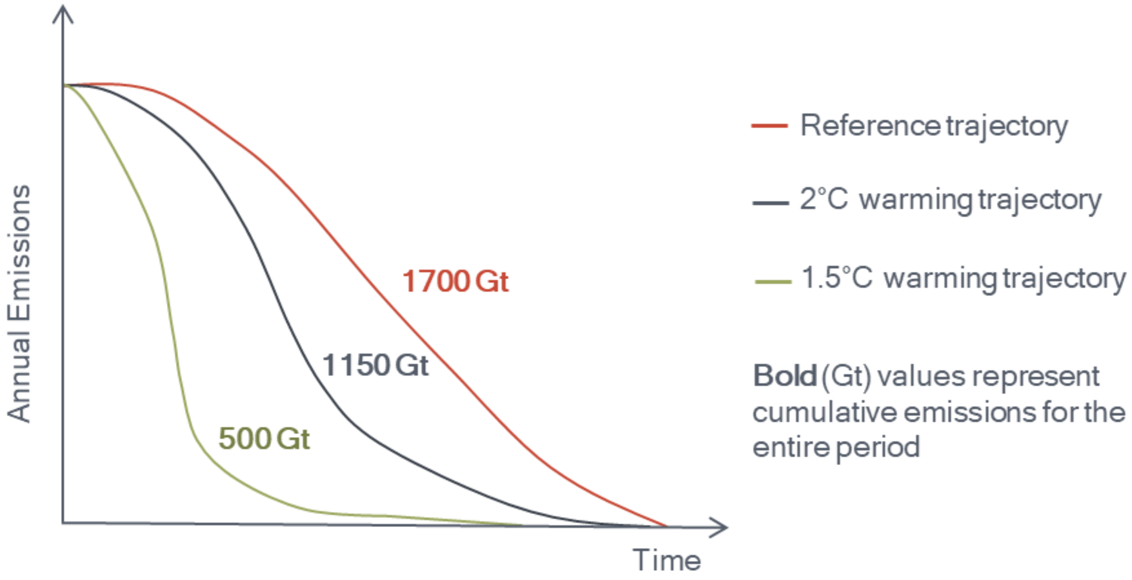
[4] Anthropogenic removals could include increasing biological or geochemical sinks which sequester CO_2, or durably storing CO_2 in geological, terrestrial, or ocean reservoirs, or in products.

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

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 Figure 1 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 1.15˚C above pre-industrial levels (World Meteorological Organization, 2022). 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 CO2 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.

Establishing appropriate carbon budgets for individual entities such as countries, regions, companies and cities is an even more significant challenge, with additional levels of uncertainty to contend with.

One of the ways to do this is to divvy 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.

Allocating carbon budgets beyond nation states who are parties to the Convention 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.

It is important therefore 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 yet proved possible at the international policy level[6]. This notwithstanding, analytical endeavors towards sub-national effort allocation remain critical to link climate science with ambition, policies and action.

> 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.

2.2 NET ZERO DATES

Net zero dates (e.g. 'net zero by 2050') have emerged as an *outcome* of the global climate-economic modelling processes discussed above. 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 – 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 can be said to

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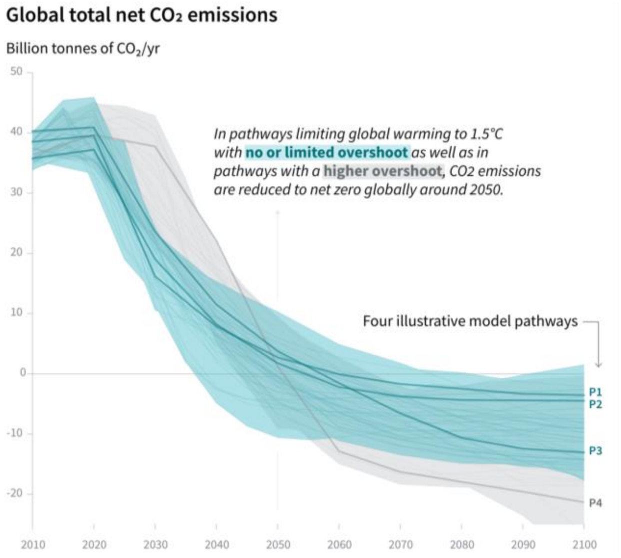
[6] The structure of the Paris Agreement has moved away from *the Kyoto Protocol's* top-down allocation of mitigation effort, to a bottom up framing of what parties are capable of doing. Politics aside, methods for sub-national effort allocation will be important for linking what climate science is finding,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

achieve net zero global CO_2 emissions around 2050.

Limiting global warming to well below 2°C, by way of contrast, results in trajectories that can be said to reach net zero around 2070 (IPCC, 2018, 2021).

The emergence of net zero dates is demonstrated in Figure 2, an output from the IPCC's Special Report on 1.5 degrees. This figure demonstrates both how the net zero date is an output of modelling carbon constrained socio-economic pathways, but also the huge degree of uncertainty that surrounds the net zero date of various 1.5˚ carbon budgets. This compounds the underlying budget uncertainty described in section 2.1.

Figure 2: CO2 emissions in pathways limiting global warming to 1.5 degrees (IPCC, 2018)



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.

In addition to seeing CO_2 emissions declining to net-zero around 2050, many of the modelled 1.5˚C warming pathways are followed by net-negative CO_2 emissions in order to limit total emissions over the 100-year period to each temperature-aligned carbon budget. This is particularly so for the 'grey' warming pathways which contain higher 'overshoot'.

In simple terms, the IPCC scenarios illustrate that even the most ambitious but feasible rates at which society can reduce emissions are 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.

Given the scientific origins of the net zero global date, what can be said about the date at which various sub-global configurations (countries, sectors, regions) should achieve net zero? There is no easy answer here. Analytically there is no basis for *only* imposing a net zero date by 2050 when modelling 1.5˚C at *sub-global* levels. As with carbon budgets, sub-global net zero dates are largely politically determined. 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 ultimately the more 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.

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).

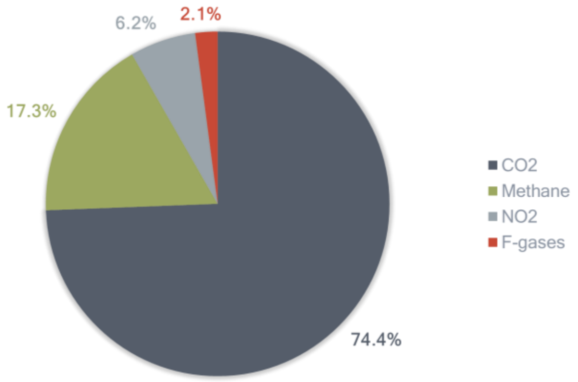
Non-CO_2 GHGs such as methane (CH_4) and Nitrous Oxide (N_2O) have an important influence on warming of the atmosphere, but behave differently to CO_2.

'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).[7]

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

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[7] 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)

[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 $GtCO_2e$

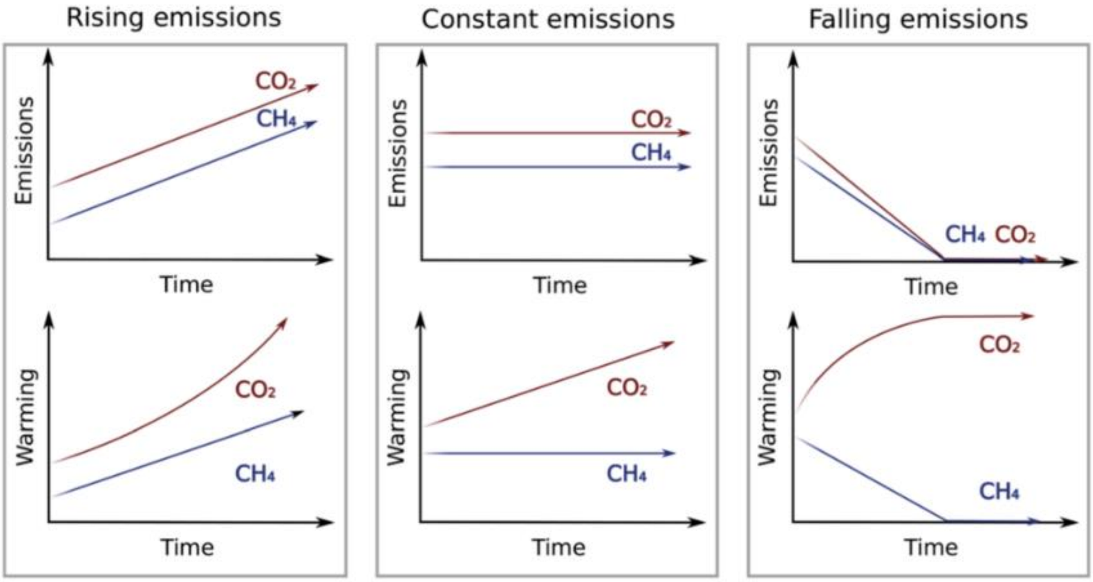
atmosphere for a relatively short timescale (~12yrs) after which it is broken down via natural processes[9] (Cain, 2018). Methane is therefore known as a 'short-lived' climate pollutant (SLCP). The high level differences between how CO_2 and methane influence temperature are demonstrated in Figure 4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

The left panel demonstrates that when emissions over time are rising, CO_2 and methane both cause warming. However, when CO_2 emissions over time 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 over time results 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 over time 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 over time 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 CO2 – could result in the breaching of dangerous 'tipping point' temperature thresholds, which may result in irreversible climate impacts.

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



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[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 rep*ort 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)

Recognising the importance of methane mitigation, over 150 parties have signed the Global Methane Pledge since it was initiated at COP26, with a collective goal of reducing methane emissions by 30% by 2030 to achieve a temperature decrease of 0.2°C (Volcovici, 2022).

There are other GHGs, for example Nitrous Oxide (N_2O) emissions, largely emanating from the agricultural sector but also via natural processes, that 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 higher 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

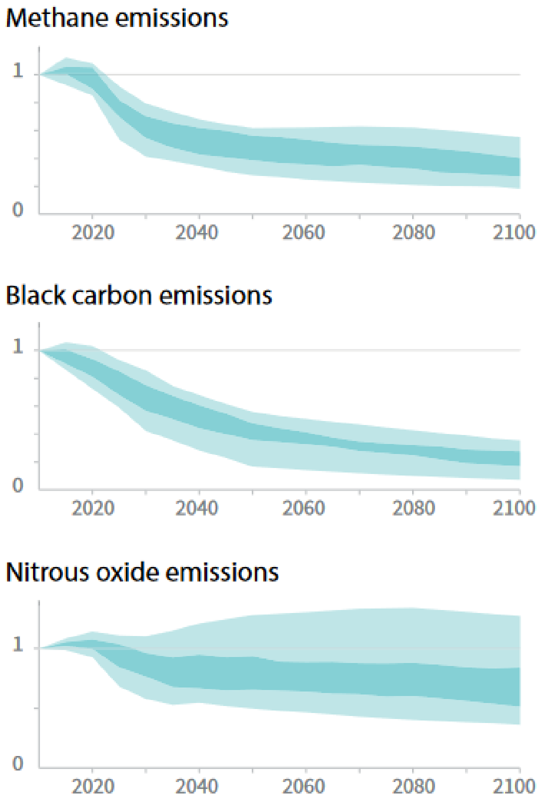
2.3.2 What do non-CO_2 gases mean for carbon budgets?

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 1.5ºC 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).

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[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)

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

Finally, 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 sum, 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

Carbon removal refers to the act of extracting CO_2 from the atmosphere and permanently storing it (Allen et al., 2020). At the net zero point, any remaining CO_2 emissions need to be balanced with an equivalent volume of removals. In addition, any exceedance of a target budget prior to the net zero date (overshooting) 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 CO2 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 higher 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. For example, 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 can cause confusion. Here we clarify a couple of aspects relating to carbon capture and storage/ utilisation as pertaining to the transition to net zero socio-economic systems:

First, capture and storage / utilisation can be used to achieve either CO_2 mitigation or removal, depending on the circumstances of its use, **only the extraction of CO_2 from the atmosphere counts as removal.**

Second, there is a distinction between carbon captured at source, and carbon extracted from the atmosphere. CO_2 extracted from the air by human technology 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 clearly constrained to the emitting source if this is pre-emission capture. Natural ecosystem and geographical storage locations are clearly geographically fixed. The geographical relevance of utilisation options will vary.

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

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

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

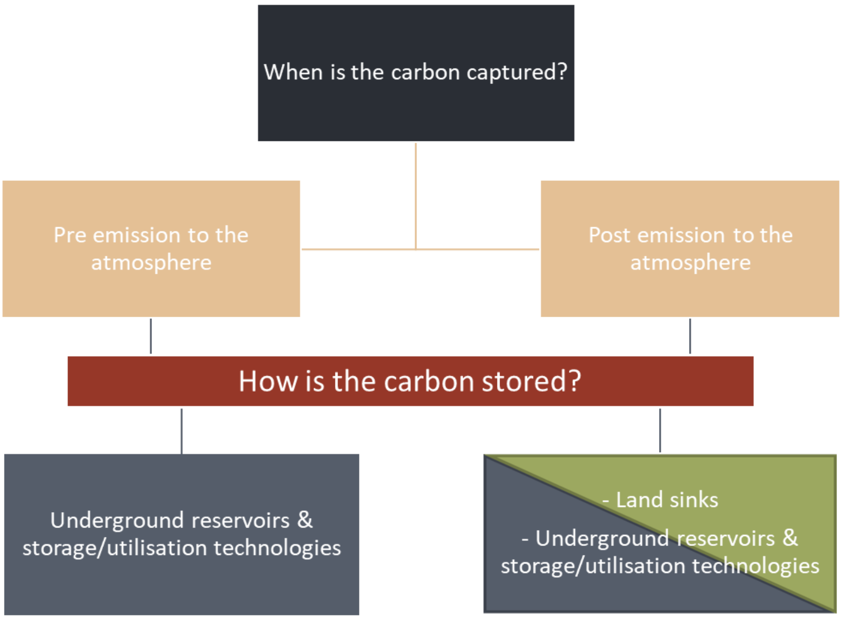

Figure 6 above sets out a simple way of navigating carbon capture and storage / utilisation options.

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.

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 for permanent storage.

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

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 CO2 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 CO2 is readily available and can be captured at relatively low cost compared to power plant specific concentrations (Global CCS Institute, 2019). The utilisation of CO2 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 CO2 per year), with another seven fossil fuel power plants with CCUS (four coal and three gas) at advanced stages of development.

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 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).

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

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 risks associated with industrial scale 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.

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. Critically though, 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.

Carbon offsetting mechanisms are 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 rigorous, equitable and credible net zero trajectories for countries, regions, companies, cities and communities are a necessary requirement for carbon offsetting to play a useful role in the achievement of global net zero.

5 CONCLUSION

This paper has unpacked what 'net zero by 2050' means from a scientific perspective in order to inform the development of adequate and credible 1.5˚C aligned climate policies and strategies for entities such as regions, cities, sectors and companies. We discussed the significance of associating the 'net-zero' date with an emissions constraint and trajectory, the role of different carbon capture and storage / removal technologies in reaching 'net-zero', and the complexities of carbon offsetting.

Ultimately, we find that temperature aligned emissions budgets, modelling timeframes, and the specification and pricing of negative emissions technologies and natural sinks form the central features of adequate and credible 1.5˚C aligned climate policies and strategies.

Perhaps most importantly however, adequate and credible 1.5°C aligned climate policies and strategies are subject to significant sources of uncertainty – global carbon budgets themselves, net zero dates, 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 the significant uncertainty around 'net zero' explicitly need to be identified and elaborated.

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