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Geological Net Zero and the Role of Carbon Capture and Storage

new insights from science for global climate change policy

Abstract

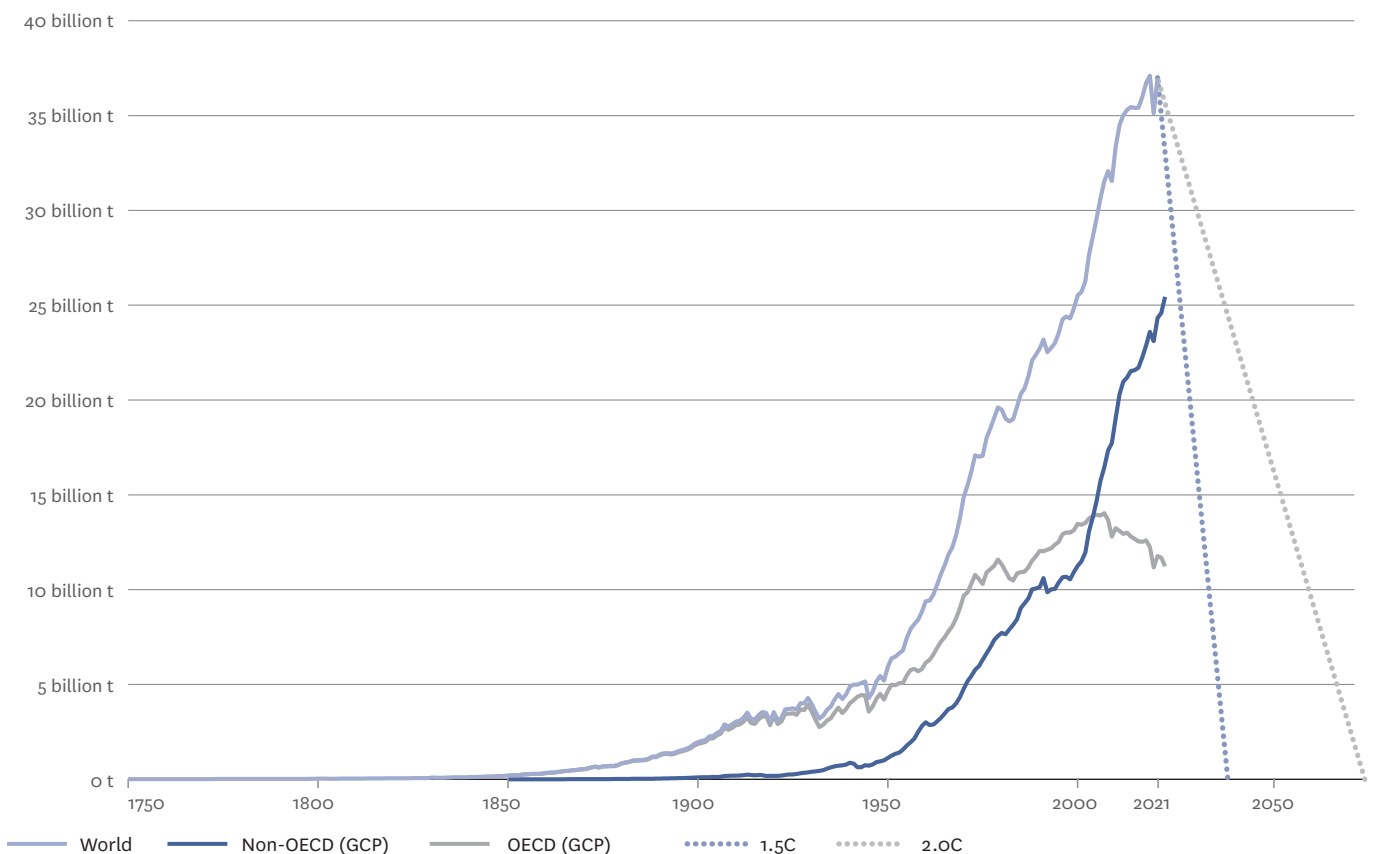
International cooperation on climate change mitigation has been insufficient to put the world on track to meet the Paris Agreement's temperature goal, and some interpretations of 'net zero' do not help because they do not achieve what net zero was intended to achieve: climate stabilisation. Nature's capacity to offset warming is less than is often assumed, so reliance on policies such as tree planting could make the temperature goal even more distant; other approaches, such as bioenergy with carbon capture and storage, risk compromising food production. The recently

developed concept of 'geological net zero' enables a better alignment of policy and temperature outcomes. In this context, judicious use of carbon capture and storage as a backstop technology would avoid over-taxing natural sinks and, given appropriate regulatory design, could become an essential tool in achieving temperature targets.

Keywords climate change science and policy, mitigation, global warming, Paris Agreement, net zero, geological net zero, carbon capture and storage, international cooperation.

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Figure 1: CO₂ emissions and requirements for future net zero CO₂ emissions consistent with the 1.5°C and 2.0°C temperature levels referenced in the Paris Agreement



Source: Ourworldindata. Projections consistent with median TCRE parameters and Canadell et al., 2021

Policy context disconnects

Article 2 of the Paris Agreement sets out the aim of ‘holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels’. Article 4 indicates further that to meet the temperature goal requires ‘a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century’. These are usually taken as giving some sort of specific scientific context around the objective of the United Nations Framework Convention on Climate Change: ‘stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system’.

The article 2 target is not as specific as it could be, since its final expression was a product of negotiations among very diverse interests.¹ The range between 1.5°C and 2°C above pre-industrial levels, put another way, is between people being able to dump 140 and 370 gigatonnes of CO₂ into the atmosphere.²

In a number of places, New Zealand among them, article 2 has been translated into a commitment to keep warming under 1.5°C. The relevant statement of purpose under the Climate Change Response (Zero Carbon) Amendment Act 2019 is to ‘contribute to the global effort under the Paris Agreement to limit the global average temperature increase to 1.5° Celsius above pre-industrial levels’. As two-term climate change minister James Shaw, the architect of much of the domestic institutional structure around climate change governance, put it in his speech to COP 25, the Act ‘enshrines the 1.5°C temperature threshold into primary legislation’ (Shaw, 2019). The prime minister clearly saw this reflecting a wish for New Zealand to be world-leading: ‘I will not allow this country to be a fast follower, because we damage our country, our environment, and our exporters if we allow that to happen’ (Ardern, 2019).

There is no agreed way of deciding how much individual countries should contribute towards this global goal; nor is there agreement that 140GtCO₂ is the collective emissions target. New Zealand

has thus far taken the view that ‘if everyone did what we did, then what would the consequences be?’, resulting in international targets that are entirely independent of domestic capacity to reduce emissions. It is not obvious that other countries reason thus, or indeed what the basis for such an assessment should be. It is also a hiding to nothing. One can brew up in minutes a simple mathematical argument proving that any country that reasons this way awards itself ever-decreasing carbon budgets, even if it meets its own goals, since the global carbon budget, which constrains the domestic budget’s rate of change, is decreasing faster than our original plan expected.

Moreover, as time passes, 1.5°C has become a more and more unrealistic goal. Staying under 1.5°C would require CO₂ emissions to plummet at around 9% per annum, with no rebound, for 25 years. The widespread and unprecedented economic shutdown that accompanied the Covid-19 pandemic knocked about 6% off global emissions, which have now fully bounced back. The fastest sustained national decreases in CO₂ emissions have probably

been achieved, through a combination of circumstance and policy, in the UK, and have amounted to about 3% per annum since 1990. The idea of sustained global emissions reductions at Covid-and-a-half levels for a quarter of a century when the fastest any single country has gone is a third of that is very clearly wishful thinking.

Surveys of IPCC lead authors show that they expect we will have between 2.5°C and 3.5°C of warming, relative to pre-industrial levels, by 2100 (Tollefson, 2021). Ultimately, the rate at which we need to stop emitting fossil carbon into the atmosphere to achieve our collective ambition far exceeds the rate at which we are actually stopping emissions. The emissions reductions that are occurring in the OECD are roughly balanced, for now, by increasing emissions outside that group (Figure 1).

Contrary to what the world needs to do for anything like the Paris aims to be met, fossil fuel development continues apace – even in Europe, as evidenced by Norway’s granting of dozens of new exploration licences in the Arctic. China, India, Iran and many other developing countries continue to expand fossil production and exploration. China and Iran both have higher per capita CO₂ emissions than New Zealand; India’s emissions have doubled since 2007 and, growing at 6% per annum, look set to double again by 2040. India’s Paris pledge (NDC) centres on reducing emissions intensity and increasing the renewable share of energy. India has made no commitment to reduce emissions.

So the world is a long way off course; given the collective goals countries have jointly set, ambition is well out of step with reality. This is a reminder that goals should be set cognisant of capabilities, and calls for new thinking regarding how we can bridge the gap.

Irrespective of how countries reconcile the gap, the first goal for developed countries must surely remain to get to net zero CO₂ emissions as quickly as possible. The two problems with this, unfortunately, are: which net? and which zero? (Allen et al., 2022)

In its original conception, the idea of achieving net zero was part of a strategy ‘to avoid a dangerous total warming commitment’. This strategy had two parts: ‘to limit emission rates of shorter-lived

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agents to avoid dangerous rates of warming and to use the concept of [cumulative warming commitment] to limit cumulative emissions of CO₂ (and other very-long-lived agents)’ (Allen et al., 2009a). Innovatively, New Zealand is acting in accordance with the first part of this strategy by focusing on reducing (but not eliminating) its main shorter-lived agent, methane. The point of net zero, of course, is the second part of the strategy: reducing emissions of long-lived greenhouse gases until any remaining gross emissions are offset by additional carbon sinks. While negotiators could not agree to include the term ‘net zero’ in the Paris Agreement, article 4 as quoted above is consistent with this understanding of the concept.

Recent research, by most of the scientists and researchers behind the initial flurry of ‘net zero’ research papers (Allen et al., 2025), has shown that greenhouse gas accounting systems often treat ‘passive’ uptake of carbon – such as increased forest growth caused by CO₂ fertilisation – to count as a carbon sink in the definition of anthropogenic emissions. Yet the original idea of net zero assumed that these were

part of the natural system – i.e., that they would happen anyway, and that people should not take credit for enhanced plant growth unless they had done something additional towards that growth. Just as the carbon–climate feedback was assumed to be part of the natural system, so the carbon–carbon feedback was assumed to be part of the natural system, too. (See Canadell et al., 2021 for a readable introduction to these feedbacks.)

New thinking – geological net zero

In response to these issues, the ‘geological net zero’ research clarifies the relationship between net zero and limiting warming (Allen et al., 2025). It argues that to ensure the integrity of the carbon accounting behind the idea of an effective net zero, it is imperative to: (a) disaggregate land management categories in emissions reporting and targets to better separate the role of passive uptake; (b) ensure that claimed removals are additional to passive uptake; and (c) acknowledge the need for geological net zero, meaning one tonne of CO₂ permanently restored to the solid earth for every tonne still generated from fossil sources.

This last task promises to be important, since ambitions to halt temperature rise at anything like the levels articulated in article 2 of the Paris Agreement would seem to require active carbon drawdown, in view of the poor prospects of reducing global gross emissions of CO₂ to anywhere near zero by the middle years of the century. Global fossil fuel emissions of CO₂ have remained between 9 and 10GtCO₂ since 2010, drifting upwards slightly over that time.

To bridge the large and persistent gap between ambition and reality, climate researchers usually envisage a very significant role for carbon drawdown. In pathways that see warming restricted to less than 2°C above pre-industrial levels, integrated assessment models already assume a large degree of carbon sequestration, usually in the form of bioenergy with carbon capture and storage (BECCS). From a physical perspective, the obvious place to store carbon originating from geological reservoirs is back in other geological reservoirs. This creates the need to develop a notion of geological net zero,

since the active biosphere's capacity to store carbon is finite and way too small to do the job required.

Accepting the practical reality of the continued reliance on fossil fuels in coming decades leads to the fundamental insight that humans need to get to net zero before they are likely to stop emitting carbon from fossil reservoirs. Capturing CO₂ would seem to be the only way to make this budget balance. This could be done in many ways, and there has been considerable focus in the climate change research literature on bioenergy – growing crops for physical energy, rather than the chemical energy associated with food. These are certainly possibilities worth exploring. However, in a world with a growing population, retiring areas from food production seems a counter-intuitive move. Another alternative is air capture. This could take the form of sophisticated air capture devices, or simpler alternatives such as remineralisation using rocks such as olivine, which are both plentiful and cheap. There are many geological sites around the world where olivine is abundant, including New Zealand; Oman has a particularly large supply. There are already start-up companies, in New Zealand and elsewhere, looking to operationalise this as a mitigation technology and to scale up activity (Wannan, 2023).

In climate policy circles, carbon capture and storage (CCS) can be a controversial topic. It has often been associated with fossil fuel-company greenwashing, corporate welfare if subsidies are involved, and a licence to keep on polluting. In common with all carbon drawdown technologies, including BECCS and afforestation, it is vulnerable to the charge of creating a moral hazard by promising to sequester CO₂ tomorrow instead of reducing emissions of it today. But these and other pitfalls seen in CCS can be avoided by appropriate policy and regulatory design.

Net zero gains its force – all of it – from being a necessary and sufficient condition for halting warming from fossil carbon sources. But depending on exactly what is counted, and what is not, and how it is counted, there are versions of net zero emissions that fail to halt warming. Geological net zero is a more robust

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concept, which recognises the limitations of the capacity of natural systems to absorb CO₂.

The challenge of international cooperation

The fact that CO₂ emissions have to get to net zero before warming stops makes climate change a 'Hotelling' problem of exhaustible natural resources (Hotelling, 1931): for any level of temperature stabilisation, the atmosphere is an exhaustible sink for emissions (Allen et al., 2009b). If CO₂ emissions are held at net zero, and short-lived climate forcings stabilised, then temperatures stabilise.

The simple economic logic suggests a universal cap on carbon emissions (Smith, 1972; Weitzman, 1974), or at least a universal minimum price on CO₂ emissions (Weitzman, 2014). More sophisticated recommendations acknowledge the difficulties with this idea and suggest bundling side-payments in the form of universal access to basic energy services or electricity (Stiglitz et al., 2017). But the current structure of international climate change politics makes it impossible to set a universal price on carbon emissions. As David Victor has written, the 'reality is that universal treaties are a very bad way to get started on serious emissions controls. Global agreements make it easier for governments to hide behind the lowest common denominator' (Victor, 2011).³

Because people fail to internalise the externalities they cause others, individual actions frequently lead to situations where public goods are under-provided by free markets. Socially optimal provision of public goods usually involves some sort of intervention to coordinate action. In the current era we look first to governments to provide that coordination, often through price mechanisms, but also through regulation and social pressure. In the international arena we lack an entity that can provide credible coordination in this way: neither the United Nations nor any group of countries can set universal prices or regulations to coordinate global action. The present hybrid of soft and hard law in the Paris Agreement is as far as realistically can be achieved towards global governance of climate change action. Paris at least embodies a global consensus. Expecting anything more constraining on governments is utopian in this context and may not even be desirable.⁴ But we are left with problems for the adequate provision of truly global public goods: at least for great powers and other powerful countries, that provision is voluntary.

This does not make the situation hopeless, but it does add complexity. Hirshleifer (1983) describes a range of 'social aggregation functions' which describe different situations in which voluntary collective action provides public goods. The voluntary nature of provision in Hirschleifer's examples are relevant because of the constraints on compulsion outlined above: mitigation is essentially voluntary, because the UN lacks a government's ability to compel.

Hirshleifer sketches out three situations in which contributions may aggregate to meet some threshold of provision for public goods. 'Best shot' public goods are situations in which outcomes are determined by the best single effort – like marksmen hitting a target. Technological breakthroughs such as the development of vaccines provide an example: once the problem is solved once, it is solved for all players, assuming deployment costs are low. 'Weakest link' efforts are where what matters is the performance of the worst player. Hirshleifer gives the example of sea walls on a flat, low-lying circular island, on which people own pizza slice-shaped

segments. If any individual fails to build an adequate sea wall, then everyone gets flooded. Quarantine and defensive fortifications like medieval city walls are examples of public goods that have weakest link properties.

These two types of situations can be summarised like this: a best shot public good is one where if anyone succeeds then everyone succeeds, while a weakest link public good is one where if anyone fails then everyone fails. The third type of social aggregation function discussed by Hirshleifer is the 'aggregate efforts' public good: a situation where the joint efforts of everyone determine the outcome, such as people paying taxes or picking up litter on a beach.

In the international arena, to the extent that national interest rules, contributions to the provision of global public goods are voluntary. Barrett (2010) points out that where provision is voluntary there is a rank-ordering in terms of how difficult it is to provide public goods. From easiest to hardest, the list goes: 'best shot'; 'weakest link'; 'aggregate efforts' (Hirshleifer, 1983).

Things are obviously more complicated than that in the real world, where there is much inequality in capabilities, and social aggregation functions are not so simple. The principle of 'common but differentiated responsibilities and respective capabilities' in the climate treaties reflects the expectation that developed countries will take the lead not only in reducing their own emissions, but also in financing and perhaps pioneering climate-friendly technologies, while also helping assist developing countries with the deployment of these technologies. These have sometimes been modelled as hybrid cases, such as the 'better-shot' and 'weaker link' cases, which include aggregative components as well as a role for a strong or weak primary player (Sandler, 2006).

Climate change is an aggregate efforts public good, which makes it particularly hard to solve, since

global public goods requiring aggregate efforts are particularly susceptible to free riding. Not even the largest and most powerful country can supply [these public goods] unilaterally, and every country's contribution to the overall effort is a perfect substitute for

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every other country's efforts. If one group of countries supplies more of a global public good requiring aggregate efforts, other countries will not have an incentive to step up their efforts. Indeed, they may have an incentive to pare back. (Barrett, 2010, p.101)

However, within some sectors of fossil fuel carbon-emitting industry, the situation may be less of aggregate efforts, and more of a better shot public good, since industry leaders may be rich and powerful enough to play the sort of leadership role that DuPont played in dealing with ozone depletion, albeit in a far more concentrated sector, through the elimination of CFCs (Maxwell and Briscoe, 1998).

CCS as a backstop technology

In an economic sense, CCS would provide a 'backstop technology' that limits the amount of stock pollutant emitted into the atmosphere. As originally conceived, backstop technology is an idealisation that provides 'a substitute process [for

fossil carbon-emitting processes] with infinite resource base' (Nordhaus, 1973). In brief, a technology backstop in this context replaces a depletable resource with a sustainable resource (Heal, 1976). Renewables are, of course, similar in this regard: they provide energy without emitting fossil carbon into the atmosphere, and as the price of renewables comes down, they outcompete fossil-emitting processes in more and more places. The costs associated with developing and deploying renewables are variable, and renewables really ought to be the first port of call for mitigation strategies. But it is unnecessarily constraining, perhaps even naïve, to insist only on renewables as alternatives to fossil-based emissions. Other non-renewable resources, such as nuclear power, and some fossil-based technologies also have constructive roles to play in reducing fossil emissions.

As a backstop, CCS can replace a stock pollution-generating process with a non-polluting process (Löschel and Otto, 2009) and is likely to have particular relevance to hard-to-abate sectors (Paltsev et al., 2021), or where demand is inelastic. Backstop technologies fully substitute for emitting technologies when the price of the backstop technology is less than the price of the emitting technology. In the case of CCS, this would almost certainly involve government intervention in the form of regulation or (more likely) prices, because burning oil is likely to remain cheaper than burning oil and sequestering CO₂. In this case, the CCS technology has to outcompete the combined fossil-emitting price plus the carbon price. In the case of a net zero target, this condition is highly likely to be met at some point, because net zero CO₂ implies no further emissions of CO₂, and this is likely to only happen if the costs of emitting that trillionth tonne are extremely high. In fact, it is often assumed that the price needs to be arbitrarily high for that emission not to occur.

A global carbon price of, say, US\$1,000 is politically implausible, no matter how compelling the economic and environmental rationales for it. The odds of developing countries agreeing to such a price are near zero; the odds of voters in developed countries supporting it in the absence of global agreement just as low. This is where

CCS backstops show great promise, because, first, if effective, they cap carbon emissions at a lower price than would be available without the backstop. The price is obtained from the actual cost of sequestering a tonne of CO₂ from the atmosphere, rather than set politically. They also have the potential to transform important public goods dimensions of the problem.

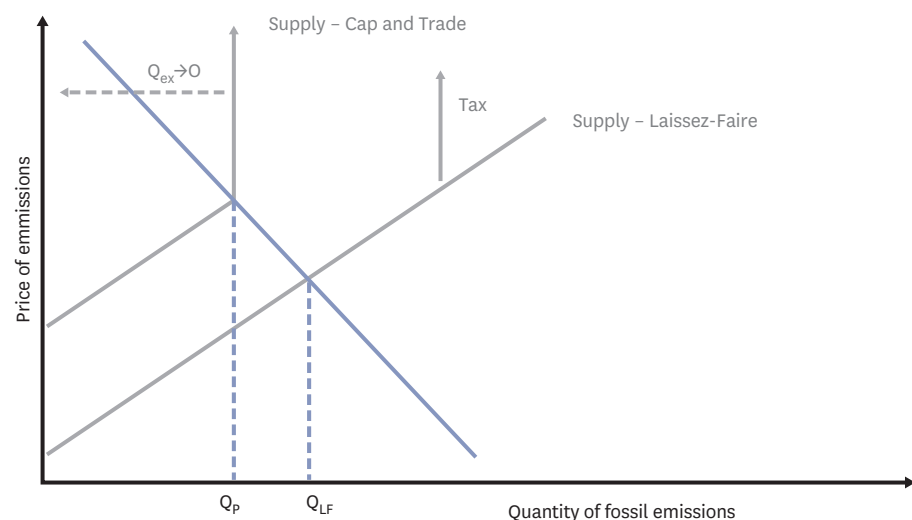
Creating widespread CCS capability and incentivising it through policy transforms the aggregate efforts emissions reductions problem into a better shot problem of CCS development and deployment. An example is how new technologies transformed the ozone destruction problem from an aggregate efforts CFC emissions reductions problem into a better shot technology development and deployment problem. In the case of CCS, providers can, in expensive cases, provide a cheaper alternative for the non-accumulation of CO₂ concentrations than emissions reductions. Physically, there is a clear plausible pathway through which the sequestration of an increasing fraction of fossil fuel emissions can be matched to climate targets (Allen et al., 2009b). Whether this is scalable at the rate required to meet current warming aspirations is a vital question, and one over which reasonable minds may disagree. Nonetheless, CCS is increasingly being seen as an essential part of any mix of policies that keep us anywhere in the ballpark of limiting warming to 2°C or less (IEA, 2025; IPCC, 2024).

This approach has two main advantages over the universal tax: it does not require an arbitrarily high price on the trillionth and first unit; and it does not require full participation. These are important advantages. The first point matters in two ways: first, by limiting the ceiling on the price of carbon (as long as the cost of sequestering tonnes that should not enter the atmosphere is less than the cost of not emitting those tonnes, then sequestration will be the cheaper option); and second, by consequently limiting the political pressure to renege on the policy: if CCS in effect caps the price on carbon, then it caps the pressure to renege.

The second point matters because agreements that turn on universal participation are likely to be limited in

Figure 2: Illustrative supply (Gray) and demand (blue) curves for quantities of emissions.

A no policy or laissez-faire approach leads to some quantity of emissions, Q_{LF} , while adding a tax increases prices and reduces the quantity of emissions (Q_P). The distinctive thing about Hotelling problems, such as fossil carbon emissions and climate change, is that in the long run emissions must fall to zero, i.e. $Q_{ex}P \rightarrow 0$ at whatever price is required. As shown, elimination of the remaining emissions (Q_{ex}) implies very high prices, if price is the only instrument.



effectiveness. ‘Under the rules of international law, countries are free to participate in treaties or not as they please, and while there is a customary obligation for countries to comply, there is no world executive that can enforce compliance’ (Barrett, 2010). The hybrid legal form of the Paris Agreement is a recognition of this fact. Targets pledged under the agreement are non-binding, a necessary condition to achieve its almost universal participation.

CCS also faces limitations, especially around cost, efficiency and scalability. CCS can be deployed either as a point source at the well-head, ‘factory-side’ post-combustion technology, or as a way of capturing CO₂ from the atmosphere (‘direct air capture’, or DAC). Point source capture and re-injection is mature technology more commonly known for its ability to enhance field production (and is commonly referred to ‘enhanced oil recovery’ or EOR). Factory-side or post-combustion technology has been developed, but is itself energy-intensive – around 30–40% of the energy produced by oil plants using CCS has to go to drive the CCS processes, which decreases the amount of energy available for the energy’s primary purpose. Requiring widespread factory-side CCS would add significantly to the costs of energy provision where such requirements are in place. Additionally, the technologies that underpin the use of CCS post combustion are nowhere near mature enough to be deployed at the scale required

to solve climate change within the next few decades. Furthermore, this technology is just as prone to political and implementation problems as any other environmental policy. Only 15% of carbon capture capacity in the EU planned for 2020 was installed, due to economic declines, political opposition and inadequate investment. As with nuclear power, there is a tendency for some environmental voices to object to CCS and other effective climate mitigation technologies, which is somewhat at odds with the characterisation of climate change as an emergency and an existential threat.

In December 2024 the New Zealand government announced the development of an enabling regime for carbon capture utilisation and storage (CCUS) through the emissions trading scheme (ETS), to ‘allow New Zealand’s industries to access CCUS technology on a level playing field with other reduction and removal tools’ (Ministry for the Environment, 2024). The most likely immediate opportunity is seen as the establishment of sequestration facilities at existing gas fields, though the New Zealand government was premature in counting on 2.7 million tonnes being sequestered in the Kapuni gas field (Gibson, 2025).

Factory-side CCS is yet to fully mature, and DAC is in its infancy. DAC capacity would need to increase something in the order of 10,000 times to meet our 2030 target on the path to net zero. The quantity,

source and costs of the required energy are big issues (Ozkan, 2025). In order for it to be efficient, DAC will require abundant renewable energy. While the price is decreasing, it still costs at least US\$130–300 per tonne/CO₂ sequestered, often more (Babiker et al., 2023). This is towards the top end of the consistent prices on carbon we have seen today, globally. On the positive side, we have seen those prices fall in some jurisdictions. The prices would need to halve for the technology to begin to play an important role in meeting temperature aspirations.

To show how CCS as backstop policy could work, let's start from the fact that olivine rock remineralises atmospheric CO₂. Suppose that the price of sequestering 1 tonne of CO₂ is currently \$1,000, and this declines by \$5/year. The most obvious way to place a price on CO₂ mineralised is via the ETS. The curves in Figure 2 show the price of emissions (vertical axis) versus the quantity of emissions (horizontal axis). The demand curve rises very steeply towards the axis; but the axis is exactly where the quantity of emissions needs to go; yet this is just the zone in which political pressure on prices is likely to be unbearable. In these situations, a backstop technology makes perfect sense. Backstop technologies are technologies which are expensive, but which become economically viable at some price level.

While it is unequivocal that CO₂ emissions reductions must remain the cornerstone and sine qua non of climate mitigation, it is hard to imagine how some form of geological CCS will not play a backstop role. This seems all the more certain given the gulf, detailed above,

between the aspirations of articles 2 and 4 of the Paris Agreement and the reality of carbon pricing and climate policy, globally. The alternatives to geological CCS would seem to be the following:

- wildly over-shooting the Paris Agreement temperature targets;
- solar radiation management;
- large future investments in BECCS, potentially replacing food production with growing crops for bioenergy;
- massive afforestation, tying up valuable agricultural land, perhaps forever.

None of these is attractive. At the very least, it will be useful for governments and private actors to have CCS in the policy and accounting toolkits – as recently acknowledged by the IPCC and the International Energy Agency (IEA, 2025; IPCC, 2024) – and ensure that the appropriate regulatory environment is in place to enable it to operate effectively as and when it is required.

Conclusion

Geological net zero is a third major insight from science for climate change policy since the beginning of international climate change negotiations in the 1990s. The first (Allen et al., 2009a) was the realisation that global temperatures are dependent on cumulative emissions of long-lived gases. The second was the related fact that the customary metric selected to measure warming relative to CO₂, GWP 100, was inaccurate for assessing the temperature impacts of emissions of short-lived gases, notably methane (Allen et al., 2018; Cain et al., 2019). This was not a new point, scientifically (Wigley, 1998; Shine, 2009),

but the reframing of climate targets around cumulative emissions gave the point renewed salience.

The first insight is now reflected in the language of the Paris Agreement and in the concept of net zero. The second has been slower to be assimilated by the policy community, but is gaining more attention as it is recognised as a solution to the misalignment of the measurement of emissions and their actual warming of the atmosphere (Allen et al., 2022). None of these contributions from science is new atmospheric physics, but all three apply the physics to provide important insights and information for policymakers.

Recognition of the need for geological net zero together with the slow phase-out prospect of fossil fuels is likely to give CCS an increasingly important role towards mid-century. This applies first to getting the relevant sort of emissions to net zero so that global temperature stabilises, and subsequently to compensating for overshoot of temperature goals through net negative emissions, where there are fewer options. There is thus a strong case for research and development on CCS technologies, for creating the policy and regulatory frameworks for their use, and for promoting international cooperation in this field.

1 For an explanation of how the Paris target emerged through the negotiations, see Stern, 2024.

2 Using median estimates of the transient response to cumulative emissions, following Canadell et al., 2021.

3 Victor presents a simple summary of the problems facing current diplomatic efforts to address climate change.

4 Most traditions in international relations treat the idea of global government as unattractive. Hedley Bull observes that 'the advocate for world government makes the tacit assumption that it is his own moral and political preferences that will be embodied in it' (Bull, 2012).

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