Anthropogenic Greenhouse Gas Removals from the Atmosphere

Implications for Sustainable Research Computing

Martin Juckes, 14th April 2026.

1. Summary

The concept of net zero has given individuals, organisations and nation states a shared sense of direction in as we face the confusing and divisive challenge of transforming society into a sustainable pathway (or perhaps transforming ourselves into a sustainable species).

The terms “net zero” and “offset” have entered into social discourse and taken on a life of their own, encumbered by mountain of emotional and societal baggage which often bears little relation to the carefully crafted ideas of their originators.

No matter what economic models we follow, which cultural traditions we favour, how diverse the values we cherish, there is a mathematical certainty that we cannot sustain ourselves and the environment we live in unless we pass through the point at which the net flow of anthropogenic greenhouse gasses into the atmosphere is reduced to zero, and starts to reduce the excess load of these gasses in the atmosphere.

However, there are many complexities in the details which lead to a variety of interpretations about the realisation of net zero.

There are four broad areas of complexity here: the variation of expectations for different stages of the journey to net zero, technical complexity and organizational complexity around measuring and allocating emissions, and ethical complexity about proportionate balancing between immediate and future impacts (how do we ensure fair representation of the views of those who cannot be present), and great complexity about the different offsetting options with their ecosystems of regulatory frameworks.

2. Discussion

a. Where are we on the journey to net zero?

We lack clarity and precision around many of the quantities which we would like to balance in our net zero goal. In order to make progress we may need to accept compromises in the short term which can be discarded at some point when we have made further progress.

But there is concern that accepting too many compromises will undermine rather than enable progress to net zero. How do we define appropriate compromises?

The three-horizons framework, introduced as a conceptual description of our challenge by Curry and Hodgson (2006) and developed into a practice by Sharpe et al. (2016), may help us to communicate clearly on this. In the Curry and Hodgson concept Horizon 1 is the unsustainable mode of operation that we want to leave behind, Horizon 2 is an unstable period of transition characterised "clashes of values in which competing alternative paths to the future are proposed by actors" and Horizon 3 is an ideal future state.

Curry and Hodgson allow that there may be many possible future states, but we now have certainty that we must achieve net zero in or before Horizon 3.

The second horizon could also be referred to as the transition, the journey, or the pathway to net zero. The crucial insight from Curry and Hodgson is to recognise that the clash of values that we encounter is, rather than being a barrier, an intrinsic part of this journey.

The other aspect of our journey is reflected in the escalating climate crisis. The pace of global warming is accelerating, now estimated at 0.27K per decade (Forster et al., 2025), very likely to pass 1.5°C above the IPCC pre-industrial baseline by 2030 or soon after. Perhaps more seriously, the perceived risk associated with temperature thresholds of 1.5°C and 2°C has been raised dramatically as we gain greater understanding of the complex relation between the global mean temperature and the systems that impact on our wellbeing and survival (e.g. McKay et al., 2022).

b. Responsibility: Which Emissions are Our Emissions?

The Greenhouse Gas (GHG) Protocol[1] provides a classification of emissions that has become a de facto standard in reporting and analysis of emissions. The framing set out in the GHG Protocol (2004) standard defines three "scopes" of emissions. For organisations these are:

- Scope 1: Emissions under the organisation's direct control, such as the fossil fuel used in buildings, vehicles and industrial processes.
- Scope 2: Emissions from generation of purchased power, heat, etc.
- Scope 3: Emissions associated with value chain (upstream and downstream), including procurement, business travel, embedded carbon, downstream

[1] The GHG Protocol (https://ghgprotocol.org) is a partnership between the World Resources Institute (WRI) and the World Business Council for Sustainable Development (WBCSD) which sets standards for GHG reporting and accounting.

impact, end of use handling of infrastructure and equipment, the construction of new buildings, and the delivery or power to the site.

There is no doubt that Scope 1 and Scope 2 emissions fall with the responsibility of an organisation, though in the case of Scope 2 responsibility is shared with the provider who, in many cases, sits in a near-monopoly position when it comes to supplying electrical power. Scope 1 emissions are intended to be disjoint in the sense that the Scope 1 emissions of one legal entity are distinct from the Scope 1 emissions of any independent legal entity. It follows that national emissions can be obtained by aggregating Scope 1 emissions of individual legal entities within a nation. Scope 3 emissions, on the other hand, represent an element of responsibility or dependency on emissions which are shared. Scope 3 emissions of any organisation will also sit within the reporting scopes of at least one other organisation, possibly many.

There are a range of different approaches to reporting scope 2 emissions. As noted by the GHG Protocol Scope 2 Guidance (2023) each of the different approaches has a different decision-making value. Thus, from a decision-making perspective it is advantageous to have information based on all relevant approaches so as to have maximal information for decision making.

Scope 3 emissions are often difficult to calculate, perhaps with the exception of business travel for which there are reliable and widely available tools. For the UKRI DRI the largest element of Scope 3 is the associated with the embodied carbon in purchased computer hardware.

In many DRI facilities the successful delivery of research depends on the supply of data from instrument systems which have a larger financial and environmental footprint.

Scope 3 emissions are generally considered as being less directly under an organisations control, but there is a clear expectation that due care will be taken when handing public money to external organisations in return for goods and services. Within Scope 3, business travel is increasingly being seen as an exception which needs to be handled on a par with Scope 1 and Scope 2. This decision is supported by a well standardised framework for calculating and reporting business travel footprints based on emissions factors published by the UK Department for Energy Security and Net Zero (DESNZ)[2] and others and which are in turn based on authoritative data issued by the International Energy Agency (IEA). There are ongoing scientific questions about some details of the environmental impact of air travel, but there is transparency and consistency around what is being reported.

[2] https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2025

The issue of clarity impacts on the responsibility discussion because there is a widely understood need to obtain a degree of clarity before committing funds.

For high-performance computing (HPC) systems we do not have the same level of agreement. A range of emissions factors are available, but there are large and usually unquantified uncertainties. For instance, ClimatIQ[3] give a factor of 0.2625 kg/Euro of Carbon Dioxide equivalent (CO_{2e}) emissions for supply chain emissions of office machinery and computers or 0.089 kg/Euro for data processing/hosting and related services (the alternative CEDA[4] database provided by ClimatIQ, however, gives higher, country dependent values, such as 0.47kg / Euro for electronic computer manufacture in Taiwan). For a Dell QCT1255 desktop server the supply chain emissions, estimated at 106kg CO_{2e}, come out close to the lower of these two figures at 0.091 kg/Euro (figures for HPC and datacentre serves are not provided online)[5]. Lövehagen et al. (2023) provide data on manufacturing which imply 0.174 kg/USD for integrated circuit boards[6]. The values appropriate for specialised HPC servers may vary significantly from the figures for the commodity market.

The scope 2 emissions of UK infrastructure benefit from a well-formulated plan for decarbonisation of the national grid which targets clean energy production by 2030[7]. This plan foresees continued strong investment in solar and wind power providing increased capacity at the same time as reducing dependency on gas. Rapid expansion of use of battery storage, a new hydrogen infrastructure (e.g. Riya et al., 2025), investment in maintaining nuclear capacity, a retained gas generation capacity, consumer restraint and consumer flexibility all play a significant role in mitigating well-known weaknesses in the renewable power supply, particularly temporal intermittence and mismatch between areas of plentiful supply and current centres of demand (DESNZ, 2025 and Appendix II).

c. Why are we doing this?

There are two angles to this question. Firstly, we wish to reduce emissions of greenhouse gasses because they are damaging the environment and exposing current

[3] https://www.climatiq.io/ [accessed 23rd February 2026]
[4] CEDA (Comprehensive Environmental Data Archive) https://www.climatiq.io/data/source/watershed [accessed 2nd April 2026]
[5] Based on lifecycle assessment https://www.delltechnologies.com/asset/en-gb/products/desktops-and-all-in-ones/technical-support/dell-pro-tower-qct1255-desktop-report.pdf [accessed 2nd April 2026] and retail price advertised by Dell (£1,162) excluding VAT, https://www.dell.com/en-uk/shop/desktop-computers/dell-pro-tower-desktop/spd/dell-pro-qct1255-desktop/gcto_qct1255_emea [accessed 2nd April 2026].
[6] This is based on data for semiconductor manufacture in 2020. Around 30% of the total is associated with gases released during the production process, 45% with electricity consumed during production, and the remainder is upstream scope 3 (this estimate excludes downstream elements of scope 3).
[7] Clean Power 2030 Action Plan: A new era of clean electricity – main report: https://www.gov.uk/government/publications/clean-power-2030-action-plan/clean-power-2030-action-plan-a-new-era-of-clean-electricity-main-report published April 2025 [accessed 24 Feb. 2026]

and future generations to risks of economic and physical harms, including lethal risks. Secondly, we believe that continued provision of well-resourced research infrastructure will play critical role in enabling society to tackle climate change and other pressing societal challenges. That is, simply cutting investment in research infrastructure would do more harm than good, so we must find a way to build and operate the infrastructure sustainably.

On the need for research infrastructure there is surprisingly little empirical evidence. A study in China (Qiao et al., 2016), looking at the impact of a relatively rapid build-up in research infrastructure, placed research infrastructure at the centre of the knowledge triangle of research, education and innovation, and identified four main areas of benefits:

1. Directly advancing science.
2. Building capability in the scientific community and enhancing education.
3. A focus for individual networking, creating collaborations.
4. A focus for clustering of activities and interaction with industry.

The second of these ties in with the Humboldtian view of academic research as delivering value through an educational role. There is also a move to using cost-benefit-analysis, often with a narrow focus on the near-term financial benefits to society (e.g. Gilead, 2014).

To a certain degree these uncertainties about the fundamental justification of research investment are moot in the context of UKRI Digital Research Infrastructure because we have a generous spending commitment from a government which believes in the value of digital capability, yet the lack of clarity does undermine quantitative resource planning needed to optimise sustainability.

The driving justification for seeking deep cuts in our environmental footprint also needs to be clarified. There is a broad agreement on the need to achieve net zero, but there remain differing views on timing and acceptable costs in terms of perceived financial and performance costs of measures taken to reduce carbon footprints.

Although there has been much talk of a “climate crisis”, it is largely treated as an external and abstract crisis. Organisations which have acknowledged the climate crisis are not generally going into a crisis response comparable to the reaction to COVID.

An assessment of risk by Trust et al (2025) identify some of the new systemic and existential risks (that is, risks that threaten us with extinction) that face us and draw attention to the importance of addressing issues such as agency, justice and responsibility alongside the technical challenges.

d. What are the offsetting options?

The definition of net zero given by the UK Natural History museum puts it clearly:

"A person, company or country is carbon neutral if they balance the carbon dioxide they release into the atmosphere through their everyday activities with the amount they absorb or remove from the atmosphere"

With this aim of net zero in mind, people, organisations and countries have been seeking ways of achieving a balance between their estimated emissions (discussed above) and the carbon removals from the atmosphere that they can claim. Here we interpret the term "carbon offsetting" to include all activities which are intended to balance carbon dioxide releases. There are subtle variations in the definitions of offsetting given by different organisations, discussed in Appendix III below, particularly with regard to the critical distinction between intended and achieved outcomes. The gap between these two has created a chasm through which billions of dollars of well-intentioned investments have disappeared.

The concept of offsetting entered legal statutes through a 1977 amendment to the US Clean Air Act which allowed companies to pay for pollution reduction elsewhere rather than reducing their own emissions. Lane (2012) traces origins further back to the Marketable Emissions Permit trading concept developed by a student, Thomas Crocker, in 1966. It has been argued, as in a blog article by Tim Challies (2007), that the underlying concept dates back much further, to the papal indulgences sold to European Christians in the 16th century to secure forgiveness of sins. Lane (2012) argues that the underlying premise that offsetting benefits the economy through greater efficiency is false.

Net zero entered the discussion relatively recently in SR15: "To stabilize global temperature at any level, 'net' CO2 emissions would need to be reduced to zero".

Statutory requirements for offsetting have led to a rapidly expanding global market in carbon credits, valued at USD 900 billion in 2025[8]. The majority of this volume is associated with compliance credits issued by regulatory authorities and traded within managed markets. Voluntary carbon credits, which work outside the emissions trading regulatory framework also have a rapidly growing market volume, though somewhat smaller at USD 4 billion in 2024[9]. There are, however, many concerns about the validity of the products being traded in this global market, as shown in a recent study by Probst et al. (2024) which estimated that fewer than one in six credits in the voluntary market actually related to real emissions reductions. The situation in the UN Reducing Emissions from Deforestation and Forest Degradation in Developing Countries (REDD+)

[8] https://www.precedenceresearch.com/carbon-credit-market [accessed 9 February 2025]

[9] https://www.grandviewresearch.com/industry-analysis/voluntary-carbon-credit-market-report

framework[10], which accounts for about one third of the voluntary market[11], appears to be even worse. It has been estimated that only 7% of expected offsets in REDD+ projects through to 2020 would actually deliver (West et al., 2023).

This could be seen as a glass-half-full situation, though some may argue that the 7% success rate of REDD+ offsets is far below half and not significantly different from zero. Others, however, may feel that the 7% figure fails to represent the huge range of procedural and organisational challenges that have been overcome. We need a different metaphor which is able to express the differing perspectives without suggesting that we have the luxury of quantification of our level of success. Perhaps we are like Odysseus steering between Scylla and Charybdis, except that we have to steer between the complacency of treating offsetting as a solution and the fatalism of believing that it is worthless.

A wide range of organisations and academic teams have worked on guidance and standards aimed at improving the offsetting market. Helppi et al. (2023) provide an insightful review of offsetting guidelines and identify five key criteria listed in Box 1 (with slight re-phrasing). Items 1 and 3-5 could all be considered as subsidiary to item 2, the requirement that the offsetting approach is compatible with and contributes to the goals of the Paris Agreement and broader goals of ensuring a sustainable and liveable future.

Box 1: Five key criteria for effective offsetting
1. **Justified**: the corporate sustainability should provide clear justification for use of offsetting rather than greater reductions in emissions. Offsetting cannot be seen as equivalent to emissions reductions. 2. **On Target**: the offsetting strategy should contribute towards the international ambitions for a stable climate and towards the targets set in the Paris Agreement. **3.** **Effective**: purchased credits should be linked to measurable reductions in emissions or removals from the atmosphere. 4. **High Quality**: there should be a shift towards use of removals over time. 5. **Transparent**: The amounts and the types of carbon credits should be clearly communicated in public documents.
Notes: In these criteria, “reductions” refers to reductions in greenhouse gas emissions outside an organisation which an organisation “buys”, “removals” refers to processes which actually take greenhouse gasses out of the atmosphere. The second item has been broadened relative to Helppi et al. (2023), who stated it in terms of the Paris goals. The broader aim here because the Paris Agreement imposes obligations of conduct rather than outcomes (Rajamani et al, 2018) and it is the outcomes that concern us here. The vagueness in the Paris Agreement is typical of

[10] https://unfccc.int/topics/land-use/workstreams/redd/what-is-redd
[11] https://abatable.com/blog/the-voluntary-carbon-market-in-2024/ [accessed 6th March 2026]

modern environmental agreements and represents what could be called, a maximum achievable compromise (e.g. Kassab and Zaki, 2025).

The offsetting options are, if anything, more varied and confusing, but there are also emerging areas of consensus. “Offsetting” is a broad concept which attracts strong feelings despite being poorly defined. It refers in general to actions taken to compensate for emissions in line with net zero goals.

Here are a few more specific terms:

- **Reduction** versus **removal** offsets: reduction offsets refer to reductions in emissions outside an organisations value chain; removal offsets involve actual (or intended) removal of greenhouse gases from the atmosphere into storage.
- **Certification of process** versus **certification of outcomes**. Many offsetting schemes now claim certification, but this is generally a certification of a process and does not provide any guarantee of meeting intended outcomes. Certification of a process is clearly useful, but net zero is about outcomes. Certification of outcomes is very rare. An intermediate option would combine certification of process with demonstration of a track record of positive outcomes.
- **Carbon credits**. A carbon credit is a tradeable certificate representing, nominally, a certain level of carbon removal or reduced emissions. In many cases the reduction in emissions is measured against an artificial baseline. These are most widely used in statutory carbon markets in which certain organisations have legally binding objectives.
- **Statutory** and **Voluntary Carbon Markets**: The statutory carbon markets have been introduced to force reductions in a range of key industrial sectors, and they operate at a national or regional scale (e.g. within the European Union). Voluntary markets provide an independent mechanism outside the statutory framework.
- The term “**carbon contribution**” has been introduced in an attempt to separate the discussion of removing carbon from the atmosphere or reducing emissions from the claims about balancing an organisational carbon budget (Kreibich et al., 2024).

Allen et al. (2025) emphasize the importance of longevity of removals: extraction of carbon, in the form of fossil fuels, from deep geological storage needs to be balanced by sequestration of carbon into equally long-lived reservoirs.

Extracting carbon dioxide from the atmosphere and sequestering it in secure geological storage remains the ideal solution, provided that it can be powered by renewable energy. This approach is being pioneered by Climeworks[12] who now offer technology-

[12] https://climeworks.com/

based removals of carbon-dioxide from the atmosphere into deep storage at £400 per tonne [site accessed 4th March 2026]. It is worth noting that the capital investment in Climeworks has surpassed USD 1 billion and there are reservations about the ability of the technology to scale up[13].

Cambridge University have taken such an approach by investing in a carbon credit scheme with augmented academic oversight to provide them with confidence that they are having a meaningful impact (Malan et al., 2024). A recent review across the UK research and innovation sector, published by the Wellcome Trust, found that 11% of signatories to the Concordat for the Environmental Sustainability of Research and Innovation Practice are engaged in some form of offsetting, 33% are not offsetting but are exploring future options[14].

3. Conclusions

There are a few points where there appears to be agreement:

- Removing of carbon from the atmosphere and storing it in secure geological storage which will keep it out of the atmosphere for millennial time scales is essential for achieving a meaningful global net zero target.
    - Removal from the atmosphere can be achieved via the biosphere or via direct mechanical systems powered by renewable energy. For the former there are limits on the volume that can be achieved and concerns about whether there is any real additional carbon, for the latter there is not yet a mature and scalable technology.
- Preservation of the biosphere is vital and can also deliver carbon budget benefits. The capacity of the biosphere is, however, very limited. If we rely on biosphere for carbon removals we will need to reduce total emissions to a very low percentage of current values.

There also appear to be some emerging realities:

- The carbon removals market is growing rapidly and could surpass the volume of the fossil fuel market in the next decade.
- The certification framework for carbon credits provides an important enabling mechanism, but the principal of *caveat emptor* applies, and customers need to take great care to ensure that products the products that they buy match their

[13] https://www.theguardian.com/environment/2025/may/17/swiss-firm-that-captures-carbon-from-air-to-cut-workforce-by-more-than-10

[14] **Concordat: https://wellcome.org/about-us/positions-and-statements/environmental-sustainability-concordat ; Review: https://cms.wellcome.org/sites/default/files/2026-01/Environmental%20Sustainability%20Concordat%20-%20Landscaping%20Report%20-%202026.pdf**

expectations. The certification process provides customers with a rich source of data.

- Decarbonisation of the UK power supply continues to progress at a good pace, but there will be pressure to respond to demands for flexibility and restraint.
- Calculation of the carbon footprint of procured DRI infrastructure remains beset by uncertainty, but the level of uncertainty need not prevent progress on planning for net zero.

Appendix I: Some varying definitions of Net Zero

Term	Description/Source
Atmospheric Net Zero (NZa)	"Net zero refers to a state in which the greenhouse gases going into the atmosphere are balanced by removal out of the atmosphere."
	Oxford Net Zero Institute web site: https://netzeroclimate.org/what-is-net-zero-2
Geological Net Zero	"one tonne of CO_2 permanently restored to the solid Earth for every tonne still generated from fossil sources"
	Allen et al. (2025)
UN Net Zero	Put simply, net zero means cutting carbon emissions to a small amount of residual emissions that can be absorbed and durably stored by nature and other carbon dioxide removal measures, leaving zero in the atmosphere
	https://www.un.org/en/climatechange/net-zero-coalition
Emissions Net Zero	"A person, company or country is carbon neutral if they balance the carbon dioxide they release into the atmosphere through their everyday activities with the amount they absorb or remove from the atmosphere."
	Natural History Museum web site: https://www.nhm.ac.uk/discover/quick-questions/what-do-carbon-neutral-and-net-zero-mean.html

Appendix II: What is happening to UK, European and Global Power Supply?

We are primarily interested in what is happening to the UK power supply, particularly with regard to variations in price by region and in time, stability of supply, and expected can provide insight into likely longer-term trends.

The UK "Clean Power 2030 Action Plan" (DESNZ, 2025) sets out the expectations for green power supply in the UK. This foresees nationally averaged carbon intensity of generation falling from 171 g of CO_2e emissions per kWh in 2023 to 50 g/kWh in 2030, with an additional target of matching 2030 net power consumption with net renewable generation. The renewable generation target will be met through expansion of wind and solar power generation. Additional sources such as tidal power could be important in the longer term. The approach to implementation is described in more detail by NESO 2025.

The intermittency of renewable power generation will be managed through a combination of battery storage (23-27GW capacity), long-duration energy storage (4-6GW), hydrogen infrastructure for storage and other uses, and 10-12 GW of consumer-led flexibility. Of these, the battery storage represents the most mature technology with grid scale systems already in place in many countries. Lithium-ion remains the dominant technology and is uniquely placed to provide infrastructure at scale.[15]

Nuclear power will continue to be a significant contributor, but no significant expansion is expected on the 2030 timescale.

At the European level we see a similar pattern of expanding solar and wind power (e.g. the Hamburg agreement for 300GW of offshore wind capacity in the North Sea by 2050[16]) backed a range of storage, transport, and flexibility plans.

Internationally, nations with high potential for solar power generation, such as Spain (Urbasos and Escribano, 2024) and Morocco, are looking the potential for developing hydrogen export markets to support moves away from gas dependency.

[15] Lithium-ion batteries have a global market volume of close to USD200 billion; potential complementary technologies include flow batteries (providing scalable static storage) and aluminium-air batteries (providing high-energy-density single-use batteries with potential for efficient recycling) currently enjoy healthy growth with a market volume around 100 times smaller.

[16] https://www.gov.uk/government/news/uk-and-europe-sign-historic-pact-to-drive-clean-energy-future

Appendix III: What is offsetting?

There appears to be a common understanding of what offsetting means, but the definitions offered by different organisations have subtle but important variation. The definition offered by the Oxford Dictionary is perhaps the most accurate as it identifies offsetting as an action with an intent to remove carbon dioxide from the atmosphere. The Cambridge Dictionary and GHG Protocol both imply that offsets are actual removals of carbon from the atmosphere. This might be an ambition but does not align with current usage.

	Table III.1: A sample of published definitions of carbon offsetting or carbon offsets.
	Carbon Offsetting [intent] {Oxford Dictionary} : "The action or process of compensating for carbon dioxide emissions which result from industrial or other human activity, by participating in schemes designed to effect equivalent reductions of carbon dioxide in the atmosphere." https://www.oed.com/dictionary/carbon-offsetting_n?tab=meaning_and_use#1210690260
	Carbon Offsetting [transaction] {Cambridge Dictionary} "the act of paying for things to be done, for example planting trees, that reduce the amount of carbon dioxide in the environment, as a way of trying to reduce the damage caused by activities that produce carbon dioxide" https://dictionary.cambridge.org/dictionary/english/carbon-offsetting
	GHG Protocol: "Offsets are discrete GHG reductions used to compensate for (i.e., offset) GHG emissions elsewhere, for example to meet a voluntary or mandatory GHG target or cap." GHG Protocol (2004)
	University of the Built Environment: "Carbon offsetting is the process of compensating for emissions by taking part in activities that reduce the equivalent amount of carbon dioxide in the atmosphere. It's usually performed by organisations, governments or even individuals who are unable to reduce or address their own greenhouse gases." https://www.ube.ac.uk/whats-happening/articles/carbon-offsetting-pros-and-cons/

Glossary

Carbon Dioxide Equivalent is a metric used to standardise the measurement of greenhouse gas emissions. It represents the amount of carbon dioxide which, over a reference time period, on the basis of generally accepted modelling assumptions, provides an estimate of the amount of carbon dioxide which would give the same aggregate radiative forcing as the quantity of greenhouse gas being described.

CO_{2e} – see Carbon Dioxide Equivalent.

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