The meaning of net zero and how to get it right

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Abstract

The concept of net zero-carbon emissions has emerged from physical climate science. However, it is operationalised through social, political, and economic systems. We identify seven attributes of net zero, which are important to make it a successful framework for climate action. The seven attributes highlight the urgency of emissions reductions, which need to be front-loaded, and coverage of all emissions sources, including currently difficult ones. The attributes emphasise the need for social and environmental integrity. This means carbon dioxide removals should be used cautiously, and the use of carbon offsets should be regulated effectively. Net zero must be aligned with broader sustainable development objectives, which implies an equitable net-zero transition, socio-ecological sustainability and the pursuit of broad economic opportunities.

Main

Climate policy has a new focus: net zero emissions. Historically, climate ambition has either been formulated as a stabilised level of atmospheric concentrations (e.g., in the 1992 UN Framework Convention on Climate Change) or as a percentage emissions reduction target (e.g. in the 1997 Kyoto Protocol). Now climate ambition is increasingly expressed as a specific target date for reaching net zero emissions, typically linked to the peak temperature goals of the Paris Agreement. Almost two thirds of global emissions and a slightly higher share of global Gross Domestic Product are already covered by net-zero targets.[1]

Net zero is intrinsically a scientific concept. If the objective is to keep the rise in global average temperatures within certain limits, physics implies that there is a finite budget of carbon dioxide that is allowed into the atmosphere, alongside other greenhouse gases. Beyond this budget, any further release must be balanced by removal into sinks.

The acceptable temperature rise is a societal choice, but one informed by climate science. Under the Paris Agreement 197 countries have agreed to limit global warming to well below 2°C and make efforts to limit it to 1.5°C. Meeting the 1.5°C goal with 50% probability translates into a remaining carbon budget of 400-800 $GtCO_2$. Staying withing this carbon budget requires CO_2 emissions to peak before 2030 and fall to net zero by around 2050.[2]

However, net zero is much more than a scientific concept or a technically determined target. It is also a frame of reference through which global action against climate change can be (and is increasingly) structured and understood.

Achieving net zero requires operationalisation in varied social, political and economic spheres. There are numerous ethical judgements, social concerns, political interests, fairness dimensions, economic considerations and technology transitions that need to be navigated, and umpteen political, economic, legal and behavioural pitfalls that could derail a successful implementation of net zero.

Getting net zero, the frame of reference, right is therefore essential. This paper recapitulates the scientific logic behind net zero and sets out the attributes we believe are important to turn it into a successful framework for climate action across countries.

The seven attributes complement an emerging set of operational principles and criteria, which have been put forward to govern specific net-zero decisions, such as country-level target setting,[3] the design of institution-level net-zero commitments,[4–6] the management and disclosure of climate risks[7] and the use of carbon offsets.[8]

Net zero as a scientific concept

Net zero is just a number, begging the question "net zero what?" For CO_2, the answer emerged in the late 2000s from understanding what it would take to halt the increase in global average surface temperature due to CO_2 emissions. A series of papers noted the longevity of the impact of fossil carbon emissions[9–11] and the monotonic, near-linear (so far) relationship between cumulative net anthropogenic CO_2 emissions and CO_2-induced surface warming.[12–15] The corollary of this result is that CO2-induced warming halts when net anthropogenic CO_2 emissions halt (i.e. CO_2 emissions reach net zero), with the level of warming determined by cumulative net emissions to that point.

Unless net CO_2 emissions then go below zero, CO_2-induced surface warming is expected to remain elevated at this level for decades to centuries.[16] This occurs because for, and only for, time-intervals of 40-200 years, the rate of atmospheric CO_2 uptake by the deep oceans (acting to reduce warming) occurs at a similar rate to the thermal adjustment of the deep oceans to raised atmospheric CO_2 (acting to increase warming).[11,17]

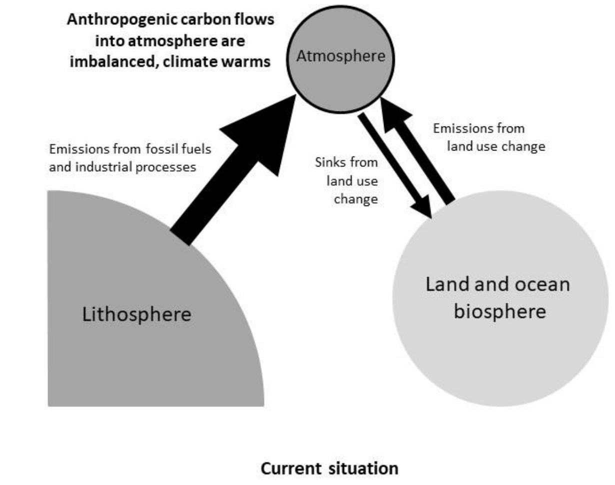
Total anthropogenic warming is a function not only of CO_2, but also of a range of other greenhouse gases and forcings.[18] These have different efficacies and lifetimes of influence on climate, generally shorter-lived than that of CO_2. Non-CO_2 anthropogenic warming is therefore better determined not by cumulative emissions, but by the present day emission rate plus a small correction for the long-term climate response to the average non-CO_2 forcing over a multi-decade to century time-interval.[19] Hence the IPCC statement "reaching and sustaining net-zero global anthropogenic CO_2 emissions and declining net non-CO_2 radiative forcing would halt anthropogenic global warming on multi-decadal timescales."[2]

These observations have an immediate policy implication: it makes little sense to apply the net zero concept on timescales shorter than decades. Achieving net zero though an unsustainable combination of fossil fuel emissions and short-term removals is ultimately pointless. Carbon emissions and removals must balance over multi-decadal timescales (Figure 1).

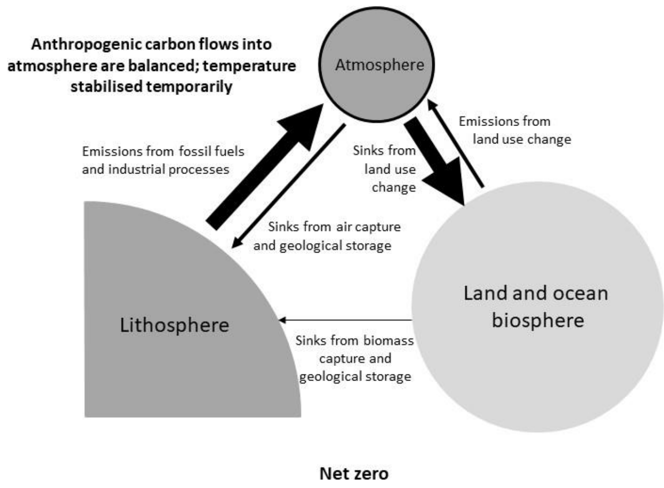
We must also accept that net-zero emissions may still be associated with some further very slow warming or cooling on longer timescales; and that the temperature implications of the net-zero concept when applied to non-CO_2 climate drivers are less clear than they are for CO_2 alone, depending on the specific mix of drivers.[20]

Figure 1: Net zero balance of carbon emissions and removals

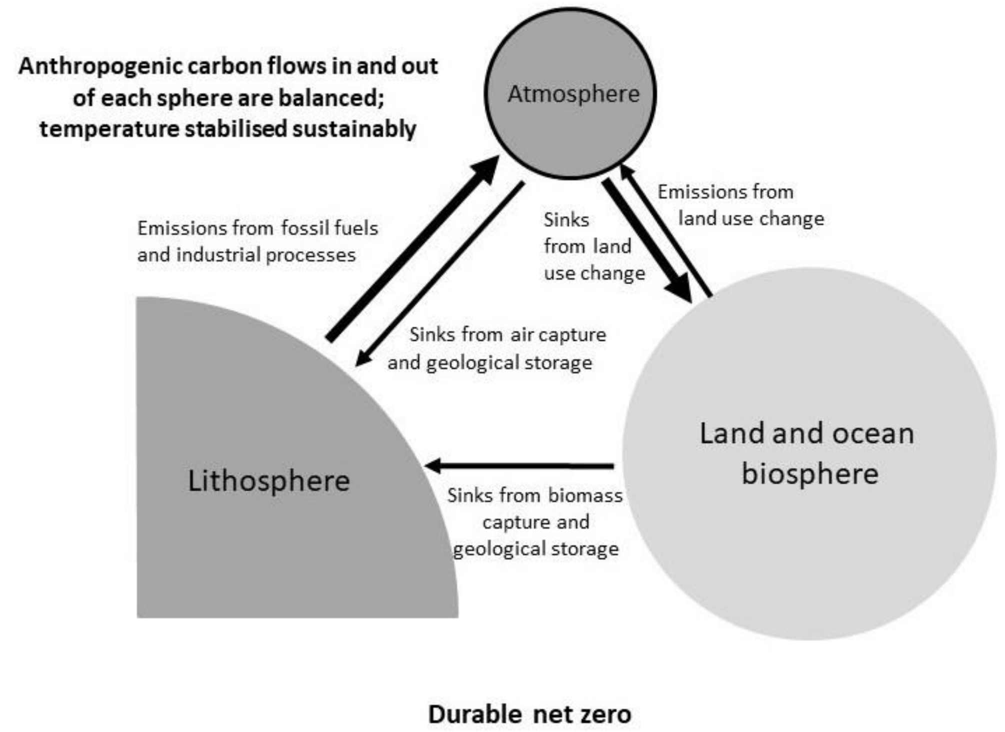
(a)



(b)



(c)



Note: Current anthropogenic carbon flows to and from the atmosphere are not in equilibrium: emissions from fossil fuels, industrial processes and land use change by far exceed the removal of carbon into land use-related sinks (panel a).[18,21] Net zero requires anthropogenic flows to and from the atmosphere to balance on aggregate. This necessitates a radical reduction in fossil fuel-related carbon emissions as well as an increase in geological and biological sinks (panel b). A durable net zero further recognises that biological storage is shorter-lived than geological storage and limited in capacity. A durable net zero state therefore requires that net anthropogenic flows to and from each sphere (not just the atmosphere) equal zero (panel c). Note that natural flows of carbon are not shown in these panels, and involve a small net flow from atmosphere to biosphere when net zero is reached.

There are alternative interpretations of net zero. Sometimes, net zero is used simply to describe emissions trajectories consistent with 1.5°C.[6] While a helpful short-hand, this obscures the fact that halting global warming, at whatever temperature level, requires net zero CO_2 emissions and declining non-CO_2 radiative forcing.

Alternatively, net zero is often understood to mean net zero CO_2-equivalent emissions aggregated using the 100-year Global Warming Potential metric. This cannot be related unambiguously to any temperature outcome but is generally seen as more ambitious, and hence preferable, than "just" halting human-induced global warming.[22] It may, of course, be necessary to aim for a long-term decline in global temperature. If so, the above empirical relationship remains applicable to determine what needs to be net zero to deliver this more ambitious goal. However, as we see it the concept of net zero emerged from our understanding of what it would take to achieve a temperature goal, not vice versa.

The importance of these differences in interpretation should not be overstated: the fact that net zero needs to apply to a state of balance that can be maintained over multiple decades, meeting additional environmental and social criteria, limits the scope for compensation among different climate drivers. It also limits the scope for compensatory exchanges between different carbon pools in the atmosphere, biosphere, oceans and lithosphere.

The adoption of net zero targets

The carbon budgets calculated by scientists apply to the global atmosphere, rather than individual entities. To turn net zero into a useful frame of reference for decision makers, the global carbon constraint needs to be translated into individual decarbonisation pathways for nation states, sub-national entities, companies and other organisations.

Setting such entity-level targets, and defining how they interact, requires judgement. There are many ways in which the remaining carbon budget can be managed. Although there is a considerable literature on this subject,[20,23–26] in practice defining the scope, timing, fairness and relevance of entity-level net zero targets has been left to individual emitters and self-regulated voluntary codes. This leaves open the question of how a diverse set of voluntary pledges adds up to national targets and national targets add up to the global carbon budget.

The Paris Agreement leaves it to its Parties to define their own emissions pathways or nationally determined contributions (NDCs) to global net zero. There is no official yardstick against which the adequacy, ambition or fairness of NDCs is measured. Instead, the Paris Agreement relies on process. Regular stock takes are intended to catalyse ambitious action and ensure that national emissions pathways will gradually converge to a global net zero state consistent with the long-term temperature goals.

More than 120 countries have now pledged to reach net zero in some shape or form around mid-century, consistent with the objectives of the Paris Agreement. They include China, the European Union and the United States, the world's three largest greenhouse gas emitters.

Individual organisations are effectively accounted for in the carbon targets of the countries in which they operate, but many have made their own individual net zero pledges. In doing so, they are guided by voluntary schemes like Cities Race to Zero, the Net Zero Asset Owners Alliance, and the Science-based Target Initiative, which encourage entities to bring down their emissions as fast as reasonably practicable and many of which are partners of the UN's Race to Zero campaign,.[4] Progress is measured and assessed by frameworks like CDP and the Transition Pathway Initiative.[27,28]

At the time of writing, over 100 regional governments, 800 cities and 1,500 companies had adopted organisational net-zero targets, often considerably earlier than mid-century.[1] One in five corporates in the Forbes Global 2,000 list have set a voluntary net zero target.

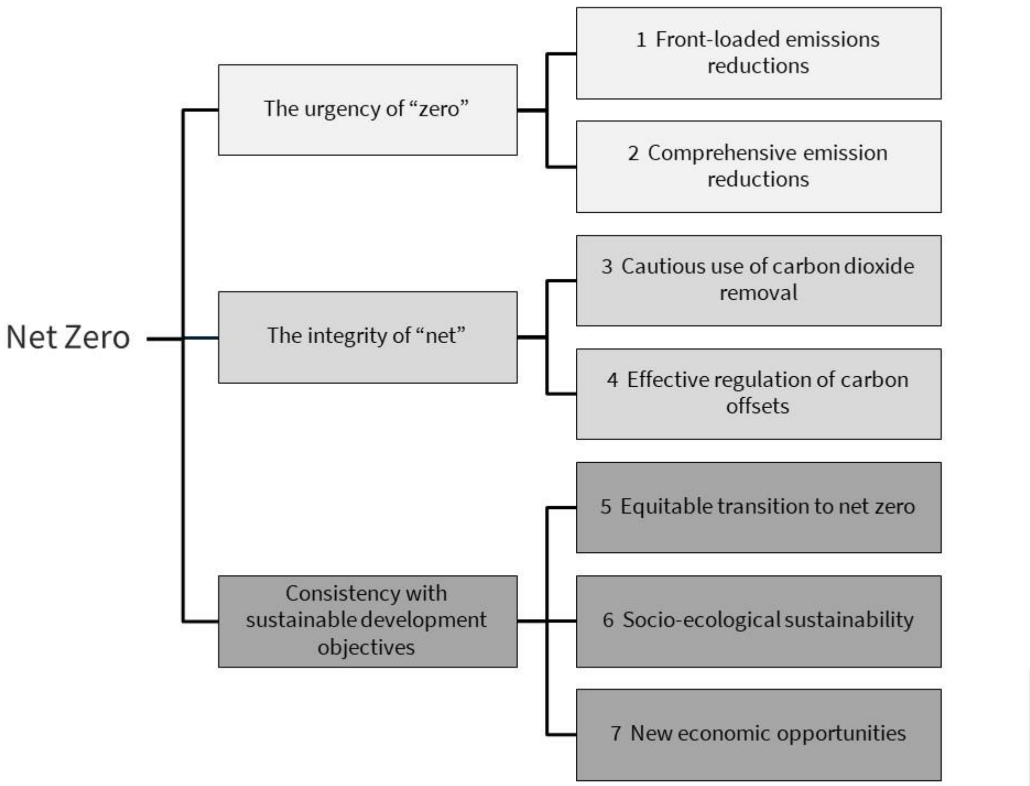
Attributes of a credible net zero

The readiness with which a growing number of countries, sub-national entities and individual organisations have made net zero pledges speaks to the unifying and galvanising power of the net zero narrative. These pledges should be encouraged. However, there is concern that these often-voluntary commitments allow too much discretion in the design of net zero pathways and may therefore not be consistent with global net zero, or with ambitious climate action more generally.[29]

Governance, accountability and reporting mechanisms are currently inadequate. Long-term ambition is often not backed up by sufficient near-term action. Many entities have not yet set out detailed plans to achieve them, and are opaque about the role of carbon offsets in place of cutting their own emissions. [1] The environmental and social integrity of some of these offsets is questionable. As a result, some advocates have accused these pledges of amounting to little more than "greenwashing". [29,30]

These concerns do not negate the scientific logic of global net zero. However, they demonstrate the need for clear guardrails to ensure the robustness of net zero as a framework for climate action. Below, we set out seven attributes, which we believe a successful net zero framework must have (Figure 2).

Figure 2: Attributes of net zero as a frame of reference



Attribute 1 - Front-loaded emissions reductions

There are many different pathways to bring down greenhouse gas emissions. The Intergovernmental Panel on Climate Change (IPCC) has identified over 200 scenarios that are consistent with either 1.5°C or 2°C. [2] However, there are sound scientific and economic reasons to bring forward emissions reductions as much as possible.

Global temperature change is determined by cumulative emissions, that is, total of emissions over time, and not isolated emissions at a particular point in time (see above). How quickly emissions are reduced therefore matters. Scientists have demonstrated that every year's delay before initiating emission reductions decreases the remaining time available to reach net zero emissions while keeping below 1.5°C by approximately two years.[31,32]

Front-loading emission reductions also preserves optionality. In particular, it maintains the option to further tighten remaining carbon budgets in light of new scientific findings, for example if carbon cycle feedbacks (e.g. more rapid thaw of permafrost) begin to add to anthropogenic emissions.[33,34]

Economic model calculations have shown that front-loading climate action, paired with long-term planning over several years, is the most cost-effective way to reach a given temperature target.[35–38] Earlier action helps (or would have helped) to overcome the inertia in economic systems[39,40] and allows learning and scale effects to unfold, bringing down technology costs .[41,42] It maximises the growth potential of clean innovation and reduces the risk of investing in stranded assets, particularly in growing economies.[43–45]

To encourage early emission reductions, governance experts recommend the combination of long-term net zero commitments – which set the direction of travel – with short-term interim targets, which define emissions pathways over decision-relevant time horizons. The two sets of targets are complementary and mitigate the well-known risk of time inconsistency in long-term political commitments. [46] Both at the corporate and country level they should be anchored in robust and enforceable legal frameworks (i.e., contracts, legislation or enforceable regulation).[47,48]

Attribute 2 - A comprehensive approach to emissions reductions

A critical facet of net zero is the comprehensive emissions abatement that it implies. Under partial emissions targets it was possible to subsume difficult emissions sources under the residual emissions that would remain. Net zero removes this option (except for the possibility of carbon removal, see point 3 below). It means tackling all emissions.

The traditional focus of emissions reduction strategies has been energy, and the scale-up of clean energy remains at the core of decarbonisation.[49] However, important tipping points have been reached. The fall in renewable energy costs has been so steep that the transition to zero-carbon electricity now seems hard to stop.[50] The automotive industry appears to be at a similar tipping point, although the uptake of zero-emissions vehicles is still low.[51]

In most other sectors the transition to zero carbon is still uncertain. Without diverting attention from finishing the job in the most advanced sectors, net zero is about extending the focus to "harder-to-treat" sectors, like heavy industry, buildings, food and agriculture, aviation and mining. In most of them, zero-carbon solutions exist, but they are still costly and not yet as established as incumbent technologies and infrastructures.[52]

Tackling all emissions requires an equally comprehensive approach to the involvement of stakeholders. There are signs that supportive coalitions on net zero are starting to emerge. Climate change is increasingly reaching community groups, city administrations, board rooms, regulatory agencies, central banks, international financial institutions and the courts.[53,54] In some countries the climate debate has been energised by an increased role for participatory democracy in the form of citizens' assemblies and juries.[55] This broad-based societal support will be essential for a successful net zero, and requires that the concept is operationalized in ways that increase its public legitimacy.

Attribute 3 - Cautious use of carbon dioxide removal

In principle, net zero can be achieved through different levels of residual emissions and different forms of compensating removals. In reality, there is a strong case for a net zero carbon balance that combines a very low level of residual emissions with low levels of multi-decadal removals.

Carbon dioxide removal will likely be constrained by cost considerations, geopolitical factors as well as by biological, geological, technological and institutional limitations on our ability to remove carbon from the atmosphere and store it durably and safely. There are also concerns about moral hazard risks arising from an over-reliance on carbon removal strategies, which may enable business as usual rather than the drastically scaling back of fossil fuel use.[29]

There are other unresolved issues. In the case of biological storage through large scale plantations, often using exotic tree species, there are concerns about trade-offs with other ecosystem services and the permanence of the carbon store given the vulnerability of these approaches to hazards such as weather fluctuations, fire and pathogens. Conversely, nature-based solutions - biodiversity based protection, restoration and sustainable management of native ecosystems – involve fewer trade-offs and are more resilient (see point 6 below). An additional concern is that climate change itself might already be destabilising some terrestrial carbon reservoirs.[56] While this arguably strengthens the case for nature-based solutions to mitigate climate risks, it also raises questions about relying on them too heavily.

In the case of geological storage, the risk of physical reversal is thought to be extremely low, but questions remain about the appropriate rate of injection and the geo-mechanical response of the reservoir.[57] The public understanding and acceptability of subsurface geological storage is also still evolving. More nascent removal options such as soil carbon sequestration, ocean alkalinization and mineralisation need further development to ascertain their safety and effectiveness. [58]

Prioritising emission reductions does not equate to "reduction only", nor does it mean delaying the ramp up of carbon dioxide removal. Most modelled pathways to meet the Paris Agreement involve a significant scaling up of removals.[2] Given that many important technologies are still in their infancy much investment is and will be needed to ensure there are enough removal options for residual emissions. We need to make progress as fast as realistically possible on both emission reductions and removals.

The regulatory frameworks that will govern the deployment of removals at scale are yet to be developed. Appropriate policy signals will be required to ensure the right balance between emissions and removals and the environmental integrity of any removal solutions that are being deployed. These rules are part of broader legal and governance frameworks on the capture, transport and storage of CO_2, which ensure clear accountabilities, transparent reporting, prudent risk management and transparency about the environmental characteristics of different removal options. This is essential not just environmentally, but also to maintain public support and a social and political license for carbon removal technologies. [59]

Attribute 4 - Effective regulation of carbon offsets

The need for social and environmental integrity in carbon dioxide removal is linked to the integrity, and appropriate regulation, of carbon offsets. Prior experience with carbon offset markets, such as the Clean Development Mechanism or the current voluntary carbon market, suggests that the environmental integrity of carbon offsets will be problematic, unless quality standards are upgraded and scrupulously enforced.[60–62]

Because very few organisations and not even all countries will be able to achieve the balance between residual emissions and removal into sinks themselves, there is a need for systems that can deliver a global balance between sources and sinks.

Such arrangements could take many forms.[63,64] Some governments may opt to procure carbon offsets centrally, through regular purchases to balance their national carbon account. Another structure is a private market for carbon offsets. The increased ambition embodied in net zero pledges is already driving up demand for offsets,[65] renewing concerns over their effectiveness.

Social and environmental concern about carbon credits centres around the credibility of their purported carbon benefit, including the risk of non-additionality, the poor monitoring of emissions avoidance, reduction or removal, and the presence of unwanted side-effects (see point 6 below). Because net zero requires the physical balancing of residual emissions with removals, any entity using carbon credits to deliver net zero would need to purchase exclusively carbon *removal* credits.[8] This poses immediate technical challenges, as the infrastructures for robust monitoring, reporting and verification of removed carbon are yet to be developed.

A key issue is the longevity of storage, which depends on both social and physical factors. As shown above, net zero demands multi-decadal storage (see "net zero as a scientific concept"). Geological storage should be possible for millennia but the timescales associated with biological carbon storage in, for example, afforestation projects, range from less than a decade to over a century depending on governance and ownership.[66] and biophysical factors. Scientific understandings of the sequestration potential of different carbon sinks are constantly evolving, which introduces a degree of inherent indeterminacy in any offset scheme.

Despite appearances to the contrary, with a number of standards in place, and a large range of independent verification agencies, the current carbon offset market and its attendant governance mechanisms do not sufficiently address these concerns. Badly conceived schemes have been accused of issuing credits for the preservation of forests that were not under threat[67,68] or, in the case of commercial plantations, only offer short term high-risk carbon storage with negative outcomes for biodiversity and local communities. The scaled-up use of carbon offsets will have to be accompanied by a radical enhancement of their quality, and scaled up regulatory scrutiny.

Attribute 5 - An equitable transition to net zero

Fairness is an essential aspect of climate action. The fairness of net zero depends on how the burden of meeting the global target is shared across countries and within countries (e.g, between regions, industries and population groups). This is a long-standing challenge for climate action, now compounded by the need to ensure that carbon removals, for example through nature-based solutions, bolsters, rather than impedes, a just transition to zero-carbon societies.

The Paris Agreement is explicit about the need for an equitable transition. It urges global peaking of emissions, but emphasises that 'peaking will take longer for developing countries' and that net zero is to be achieved 'on the basis of equity' and in the context of 'sustainable development and efforts to eradicate poverty' (Article 4(1)). The Paris Agreement does not advocate undifferentiated uptake of net zero targets across all countries. Rather, the emphasis in the agreement on equity, sustainable development and poverty eradication suggests a thoughtful balancing of responsibilities between countries at different levels of development, a recognition of transitions tailored to 'different national circumstances', and concern for distributional impacts within a country (see also point 7 below).

This has at least three implications.[69] First, that some countries may need to reach net zero faster to create room for others that may take longer to reach net zero. Second, that every country may chart its own path to net zero tailored to its own specific national circumstances and constraints. The Paris Agreement privileges 'national circumstances' both by adding the clause 'in light of different national circumstances' to the principle of common but differentiated responsibilities and respective capabilities (Article 2(2)) as well as by centring its governance regime on nationally determined contributions. Third, that developing countries need to be supported – in terms of finance, technology and capacity building - in reaching net zero.[70,71]

The transition to net zero will thus necessarily take different paths in different countries, and the dominant narrative driving each such transition will reflect a mix of priorities and efforts to harness multiple benefits, such as creating jobs, addressing local air pollution, ensuring energy security, or protecting vulnerable population groups.

These equity guardrails are key to ensuring a sense of solidarity, collective ownership and political buy-in, thus enhancing the chances of real action with global impact. They also anchor net zero in the principle of sustainable development, which balances social, economic and environmental objectives.

Attribute 6 - Alignment with broader socio-ecological objectives

Climate change is one of several pressing socio-ecological challenges, most of them interlinked. In some cases, climate change is a "threat multiplier", exacerbating the negative impacts of other stressors (such as land use change) on ecosystems and the communities dependent upon them.[72] In others, climate change and other environmental stressors have the same root causes. For example, land-use change is both the biggest driver of biodiversity declines (accounting for approximately 30% declines in global terrestrial habitat integrity)[73] and the second biggest source of greenhouse gas emissions (accounting for 23%).[74]

Nature-based solutions, such as protecting or restoring natural ecosystems and sustainably managing working lands and seas, can therefore, in theory, simultaneously help limit surface warming and slow biodiversity declines, whilst also supporting human societies in countless essential ways including public health, livelihoods and food security.[73,75,76]

However, these multiple benefits are not guaranteed. Some activities are incorrectly badged as nature-based solutions, but are simply biological approaches to carbon storage, such as commercial plantations of exotic tree species in naturally treeless habitats. They can have negative outcomes for carbon storage, biodiversity and for local people.[77,78]

If nature-based solutions are to provide sustained benefits to people, the ecosystems involved must be healthy and resilient, that is, their ecological functions must be able to resist or recover from perturbations. Such ecological resilience is strongly determined by ecosystem connectivity and the genetic, functional and species richness at multiple trophic levels.[79] There is a deepening consensus about the critical importance of protecting, restoring and connecting a wide range of habitats across landscapes for the broad range of benefits they bring. There is also consensus around ensuring that nature-based solutions are designed and implemented by or in partnership with indigenous peoples and local communities through a process that fully respects and champions local rights and knowledge, and generates local benefits.[80,81] In other words, nature-based solutions must be biodiversity-based and people-led.[76]

Therefore, rather than narrowly pursuing one objective – carbon storage – net zero plans must acknowledge a full range of ecosystem services, and be embedded into broader strategies for socio-ecological sustainability. Shifting support for nature-based solutions from carbon-centric offsetting claims to unrestricted contributions could eliminate some of the above unintended consequences, and help protect and restore ecological resilience.

Attribute 7 – Pursuit of new economic opportunities

The scientific reality of a finite global carbon budget makes it easy to frame net zero as a zero-sum game. The narrative of burden sharing remains prominent in the international negotiations, and indeed how the remaining carbon space is allocated is an essential aspect of climate justice (as discussed in point 5 above). Yet, as attractive net zero solutions begin to emerge, it will increasingly become clear that net zero can also be an economic opportunity.[82]

The economics literature has started to document the channels through which net-zero prosperity may materialise. In the short term, this includes the contribution zero-carbon investment can make to a sustainable recovery from COVID-19, subject to debt constraints.[71,83] It also includes the removal of economically harmful market and policy failures, such as the prevalence of fossil fuel subsidies.[84] In the longer term, zero-carbon innovation may unleash a virtuous cycle of investment, renewal and growth.[40,82]

Realising these opportunities is key to a successful net zero transition. In the short-term, however, the pursuit of economic opportunities will be hindered by structural rigidities in the economy. The net-zero transition requires large-scale changes in the way economies are run, in the skills they demand and in the capital assets they require.

In developing countries, which are less locked into high-carbon activities, this creates a need to proactively train a young workforce in the skills of the 21st century and to make long-lived investment decisions with net zero in mind, which may affect returns.[85] In industrialised countries, it will create short-term pressure on some workers, who may have to be reskilled and redeployed,[86] and the risk of stranded assets in high-carbon industries.[43]

Addressing these transition risks is an integral part of net-zero prosperity. There are only a few examples of successful industrial transitions, such as in Germany's Ruhr region. They suggest that a just transition is possible, but it requires close collaboration between government, industry, labour unions and local communities, and substantial investment in education, skills and social protection.[87]

Conclusions

Limiting the rise in global average temperatures, to whatever level, ultimately requires a balance between the release of carbon dioxide into the atmosphere and their removal into sinks. The growth in net-zero commitments from countries, corporates and sub-national entities suggests that decision makers increasingly understand this scientific reality.

This paper offers a series of interpretations of what net zero means and how it should be achieved. They ensure consistency with global temperature goals, while embedding net zero into socio-political and legal contexts. We argue that it is possible to align net zero with sustainable development objectives, allow for different stages of development, and secure zero-carbon prosperity.

However, there are some clear constraints. Net zero commitments are not an alternative to urgent and comprehensive emissions cuts. Indeed, net zero demands greater focus on eliminating difficult emissions sources than has so far been the case. The "net" in net zero is essential, but the need for social and environmental integrity imposes firm constraints on the scope, timing and governance of both carbon dioxide removal and carbon offsets.

Not all these aspects are as yet sufficiently understood. The socio-political interpretation of net zero is therefore also a rich research agenda, and it will require input from many disciplines, from climate science, biology and geology to anthropology, law and economics.

There are clear risks of getting net zero wrong. However, the science leaves no alternatives if global temperature is to be stabilised. If interpreted right and governed well, net zero can be an effective frame of reference for climate action.

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Authors contribution

The production of the manuscript was coordinated by S.F., who also had overall editorial responsibility. All authors contributed to the content, structure and framing of the article. Drafting was led by K.A., M.A., S.F, L.R., N.S. and S.S.

Competing financial interests

There are not competing financial interests to declare.

Data availability

Not applicable.

Code availability

Not applicable.

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