nature climate change

PERSPECTIVE

https://doi.org/10.1038/s41558-021-01245-w

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The meaning of net zero and how to get it right

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The concept of net-zero carbon emissions has emerged from physical climate science. However, it is operationalized 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 emission reductions, which need to be front-loaded, and of coverage of all emission sources, including currently difficult ones. The attributes emphasize 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.

Climate policy has a new focus: net-zero emissions. Historically, climate ambition has either been formulated as a stabilized level of atmospheric concentrations (for example, in the 1992 United Nations Framework Convention on Climate Change) or as a percentage emissions reduction target (for example, 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 within 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 operationalization 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 several 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 Perspective 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 (https://racetozero.unfccc.int/, https://sciencebasedtargets.org/ and ref. [4]), the management and disclosure of climate risks[5], and the use of carbon offsets[6].

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[7–9] and the monotonic, near-linear (so far) relationship between cumulative net anthropogenic CO_2 emissions and CO_2-induced surface warming[10–13]. The corollary of this result is that CO_2-induced warming halts when net anthropogenic CO_2 emissions halt (that is, 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[14]. 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 rate similar to the thermal adjustment of the deep oceans to raised atmospheric CO_2 (acting to increase warming)[9,15].

Total anthropogenic warming is a function not only of CO_2, but also of a range of other greenhouse gases and forcings[16]. 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

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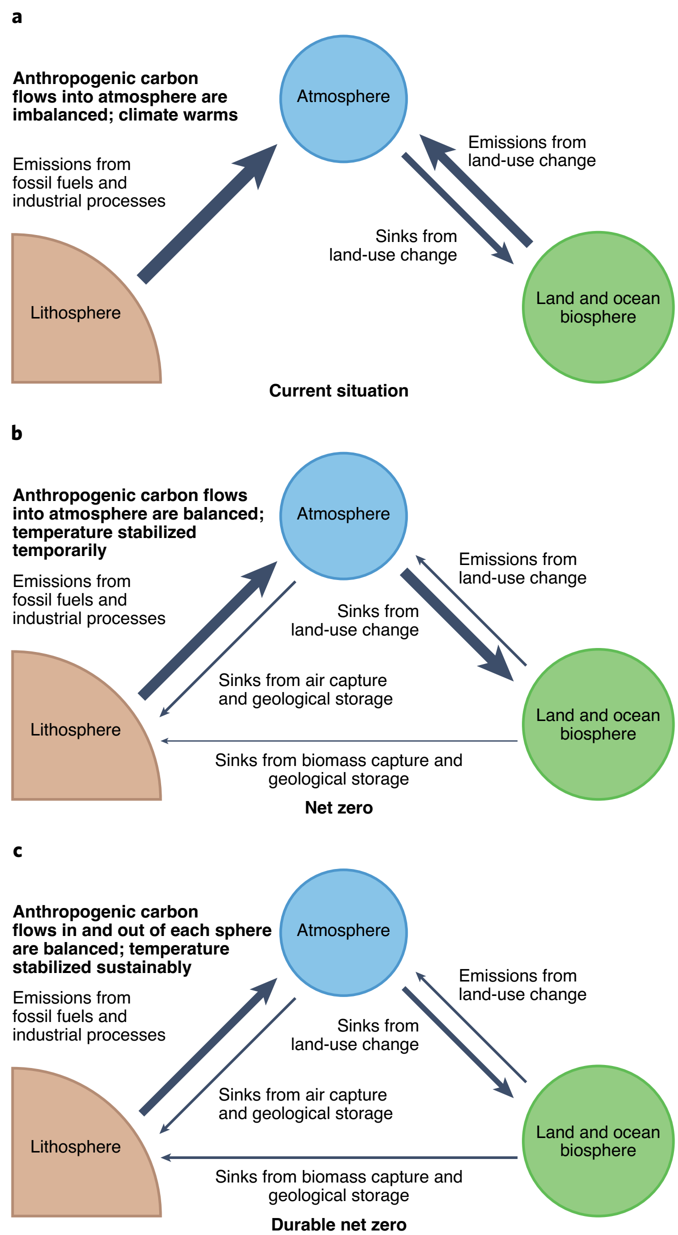

Fig. 1 | Net-zero balance of carbon emissions and removals. a–c, Current anthropogenic carbon flows to and from the atmosphere are not in equilibrium: emissions from fossil fuels, industrial processes and land-use change by far exceed the removal of carbon into land-use-related sinks (**a**)[16]. Net zero requires anthropogenic flows to and from the atmosphere to balance on aggregate. This necessitates a radical reduction in fossil-fuel- and land-use-related carbon emissions as well as an increase in geological and biological sinks (**b**). A durable net zero further recognizes that biological storage is limited in capacity and shorter-lived than geological storage. A durable net-zero state therefore requires that net anthropogenic flows to and from each sphere (not just the atmosphere) equal zero (**c**). Note that natural flows of carbon are not shown in this figure and involve a small net flow from the atmosphere to the biosphere when net zero is reached.

small correction for the long-term climate response to the average non-CO_2 forcing over a multi-decade to century time interval[17]. 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 through an unsustainable combination of fossil-fuel emissions and short-term removals is ultimately pointless. Carbon emissions and removals must balance over multi-decadal timescales (Fig. 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[18].

There are alternative interpretations of net zero. Sometimes, net zero is used simply to describe emissions trajectories consistent with 1.5 °C (https://sciencebasedtargets.org/). While a helpful shorthand, 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[19]. 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 decarbonization pathways for nation states, sub-national entities, companies and other organizations.

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[18,20–23], 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 to global net zero. There is no official yardstick against which the adequacy, ambition or fairness of nationally determined contributions is measured. Instead, the Paris Agreement relies on process. Regular stocktakes 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 organizations 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, such as 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 United Nations' Race to Zero campaign (https://racetozero.unfccc.int/). Progress is measured and assessed by frameworks such as CDP (https://www.cdp.net/en) and the Transition Pathway Initiative (https://www.transitionpathwayinitiative.org/).

At the time of writing, more than 100 regional governments, 800 cities and 1,500 companies have adopted organizational net-zero targets, often considerably earlier than mid-century[1]. One in five corporations 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 organizations have made net-zero pledges speaks to the unifying and galvanizing 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[24].

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 their pledges 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'[24,25].

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 that we believe a successful net-zero framework must have (Fig. 2).

Attribute 1—front-loaded emission reductions. There are many different pathways to bring down greenhouse gas emissions. The IPCC has identified over 200 scenarios that are consistent with either 1.5 °C or 2 °C global warming[2]. However, there are sound scientific and economic reasons to reduce emissions as much and as fast as possible.

Global temperature change is determined by cumulative emissions, that is, the total of all 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 of 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[26,27].

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 (such as more rapid thaw of permafrost) begin to add to anthropogenic emissions[28,29].

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[30–33]. Earlier action helps (or would have helped) to overcome the inertia in economic systems[34,35] and allows learning and scale effects to unfold, bringing down technology costs[36,37]. It maximizes the growth potential of clean innovation and reduces the risk of investing in stranded assets, particularly in growing economies[38–40].

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[41]. Both at the corporate and country level, they should be anchored in robust and enforceable legal frameworks (that is, contracts, legislation or enforceable regulation)[42,43].

Attribute 2—a comprehensive approach to emission 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 attribute 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 decarbonization[44]. 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[45]. The automotive industry appears to be at a similar tipping point, although the uptake of zero-emissions vehicles is still low[46].

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, such as heavy industries, buildings, food and agriculture, aviation, and mining. In most of these sectors, zero-carbon solutions exist, but they are still costly and not yet as established as incumbent technologies and infrastructures[47].

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[48,49]. In some countries, the climate debate has been energized by an increased role for participatory democracy in the form of citizens' assemblies and juries[50]. This broad-based societal support will be essential for a successful net zero and requires the concept to be 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 probably be constrained by cost considerations and 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 drastic scaling back of fossil-fuel use[24].

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 attribute 6 below). An additional concern is that climate change itself might already be destabilizing some terrestrial carbon reservoirs[51]. While this arguably strengthens the case for nature-based solutions

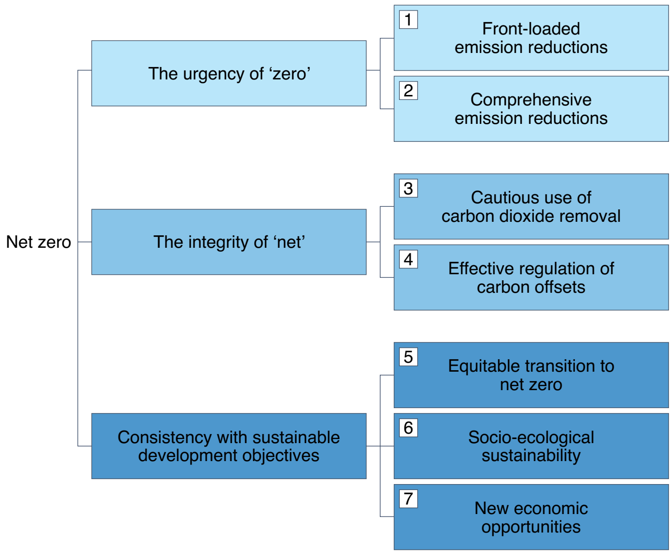

Fig. 2 | Attributes of net zero as a frame of reference.

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[52]. 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 mineralization need further development to ascertain their safety and effectiveness[53].

Prioritizing emission reductions neither equates 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 that 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 will form part of broader legal and governance frameworks on the capture, transport and storage of CO_2, which will 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 licence for carbon removal technologies[54].

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. Previous 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[55–57].

Because very few organizations 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[58,59]. 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[60], renewing concerns over their effectiveness.

Social and environmental concerns about carbon credits centre 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 attribute 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[6]. 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[61], and biophysical factors. Scientific understanding of the sequestration potential of different carbon sinks is 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[62,63] 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 (for example, 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) bolster, rather than impede, 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 emphasizes 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 attribute 7 below).

This has at least three implications[64]. First, some countries may need to reach net zero faster to create room for others that may take longer to reach net zero. Second, 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)), and by centring its governance regime on nationally determined contributions. Third, developing countries need to be supported—in terms of finance, technology and capacity building—in reaching net zero[65,66].

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 on them[67]. 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% of declines in global terrestrial habitat integrity)[68] and the second biggest source of greenhouse gas emissions (accounting for 23%)[69].

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 while also supporting human societies in countless essential ways, including public health, livelihoods and food security[68,70,71].

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[72,73].

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[74]. 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 (ref. [75] and https://nbsguidelines.info/). Thus, nature-based solutions must be biodiversity-based and people-led[71].

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 attribute 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[76].

The economics literature has started to document the channels through which net-zero prosperity may materialize. In the short term, this includes the contribution zero-carbon investment can make to a sustainable economic recovery from the COVID-19 pandemic, subject to debt constraints[66,77]. It also includes the removal of economically harmful market and policy failures, such as the prevalence of fossil-fuel subsidies[78]. In the longer term, zero-carbon innovation may unleash a virtuous cycle of investment, renewal and growth[35,76].

Realizing 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, the skills they demand and 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 twenty-first century and to make long-lived investment decisions with net zero in mind, which may affect returns[79]. In industrialized countries, it will create short-term pressure on some workers, who may have to be reskilled and redeployed[80], and the risk of stranded assets in high-carbon industries[38].

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[81].

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 its removal into sinks. The growth in net-zero commitments from countries, corporations and sub-national entities suggests that decision-makers increasingly understand this scientific reality.

This Perspective offers a series of interpretations of what net zero means and how it should be achieved. These interpretations 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 stabilized. If interpreted right and governed well, net zero can be an effective frame of reference for climate action.

Received: 19 May 2021; Accepted: 9 November 2021;
Published online: 20 December 2021

References

1. Black, R. et al. *Taking Stock: A Global Assessment of Net Zero Targets* (ECIU and Oxford Net Zero, 2021).

2. IPCC *Special Report on Global Warming of 1.5 °C* (eds Masson-Delmotte, V. et al.) (WMO, 2018).
3. Levin, K., Rich, D., Ross, K., Fransen, T. & Elliott, C. *Designing and Communicating Net-Zero Targets* (World Resources Institute, 2020).
4. *Navigating the Nuances of Net-Zero Targets* (New Climate Institute & Data-Driven EnviroLab, 2020).
5. *Recommendations of the Task Force on Climate-Related Financial Disclosures* (TCFD, 2017); https://www.fsb-tcfd.org/publications/
6. Allen, M. et al. *The Oxford Principles for Net Zero Aligned Carbon Offsetting* (Smith School of Enterprise and the Environment, Univ. of Oxford, 2020).
7. Archer, D. Fate of fossil fuel CO_2 in geologic time. *J. Geophys. Res. Oceans* **110**, C09S05 (2005).
8. Matthews, H. D. & Caldeira, K. Stabilizing climate requires near-zero emissions. *Geophys. Res. Lett.* **35**, L04705 (2008).
9. Solomon, S., Plattner, G.-K., Knutti, R. & Friedlingstein, P. Irreversible climate change due to carbon dioxide emissions. *Proc. Natl Acad. Sci. USA* **106**, 1704–1709 (2009).
10. Allen, M. R. et al. Warming caused by cumulative carbon emissions towards the trillionth tonne. *Nature* **458**, 1163–1166 (2009).
11. Meinshausen, M. et al. Greenhouse-gas emission targets for limiting global warming to 2 °C. *Nature* **458**, 1158–1162 (2009).
12. Matthews, H. D., Gillett, N. P., Stott, P. A. & Zickfeld, K. The proportionality of global warming to cumulative carbon emissions. *Nature* **459**, 829–832 (2009).
13. Zickfeld, K., Eby, M., Matthews, H. D. & Weaver, A. J. Setting cumulative emissions targets to reduce the risk of dangerous climate change. *Proc. Natl Acad. Sci. USA* **106**, 16129–16134 (2009).
14. MacDougall, A. H. et al. Is there warming in the pipeline? A multi-model analysis of the Zero Emissions Commitment from CO_2. *Biogeosciences* **17**, 2987–3016 (2020).
15. Smith, M. A., Cain, M. & Allen, M. R. Further improvement of warming-equivalent emissions calculation. *NPJ Clim. Atmos. Sci* **4**, 19 (2021).
16. IPCC *Climate Change 2021: The Physical Science Basis* (eds Masson-Delmotte, V. et al.) (Cambridge Univ. Press, in the press).
17. Zickfeld, K. & Herrington, T. The time lag between a carbon dioxide emission and maximum warming increases with the size of the emission. *Environ. Res. Lett.* **10**, 31001 (2015).
18. Robinson, M. & Shine, T. Achieving a climate justice pathway to 1.5 °C. *Nat. Clim. Change* **8**, 564–569 (2018).
19. Rogelj, J., Geden, O., Cowie, A. & Reisinger, A. Three ways to improve net-zero emissions targets. *Nature* **591**, 365–368 (2021).
20. Agarwal, A. & Narain, S. *Global Warming in an Unequal World* (Centre for Science and Environment, 1991).
21. Agarwal, A., Narain, S. & Sharma, A. in *Environmental Justice: Discourses in International Political Economy* (eds Byrne, J. et al) 171–199 (Routledge, 2017).
22. Ringius, L., Torvanger, A. & Underdal, A. Burden sharing and fairness principles in international climate policy. *Int. Environ. Agreem.* **2**, 1–22 (2002).
23. Robinson, M. *Climate Justice: Hope, Resilience, and the Fight for a Sustainable Future* (Bloomsbury, 2018).
24. Dyke, J., Watson, R. & Knorr, W. Climate scientists: concept of net zero is a dangerous trap. *The Conversation* (22 April 2021); https://theconversation.com/climate-scientists- concept-of-net-zero-is-a-dangerous- trap-157368
25. *Chasing Carbon Unicorns: The Deception of Carbon Markets and 'Net Zero'* (Friends of the Earth, 2021).
26. Allen, M. R. & Stocker, T. F. Impact of delay in reducing carbon dioxide emissions. *Nat. Clim. Change* **4**, 23–26 (2014).
27. Leach, N. J. et al. Current level and rate of warming determine emissions budgets under ambitious mitigation. *Nat. Geosci.* **11**, 574–579 (2018).
28. Turetsky, M. R. et al. Carbon release through abrupt permafrost thaw. *Nat. Geosci.* **13**, 138–143 (2020).
29. Gasser, T. et al. Path-dependent reductions in CO_2 emission budgets caused by permafrost carbon release. *Nat. Geosci.* **11**, 830–835 (2018).
30. *The Sixth Carbon Budget: Methodology Report* (Committee on Climate Change, 2020).
31. Grubler, A. et al. A low energy demand scenario for meeting the 1.5 °C target and sustainable development goals without negative emission technologies. *Nat. Energy* **3**, 515–527 (2018).
32. Wilensky, M. Climate change in the courts: an assessment of non-U.S. climate litigation. *Duke Environ. Law Policy Forum* **26**, 131–179 (2015).
33. Duan, H. et al. Assessing China's efforts to pursue the 1.5 °C warming limit. *Science* **372**, 378–385 (2021).
34. Aghion, P., Dechezleprêtre, A., Hemous, D., Martin, R. & van Reenen, J. Carbon taxes, path dependency, and directed technical change: evidence from the auto industry. *J. Polit. Econ.* **124**, 1–51 (2016).
35. Aghion, P., Hepburn, C., Teytelboym, A. & Zenghelis, D. in *Handbook on Green Growth* (ed. Fouquet, R.) Ch. 4 (Edward Elgar, 2019).
36. Nordhaus, W. D. The perils of the learning model for modeling endogenous technological change. *Energy J.* **35**, 1–13 (2014).
37. Söderholm, P. & Sundqvist, T. Empirical challenges in the use of learning curves for assessing the economic prospects of renewable energy technologies. *Renew. Energy* **32**, 2559–2578 (2007).
38. Caldecott, B. *Stranded Assets and the Environment: Risk, Resilience and Opportunity* (Routledge, 2018).
39. Pfeiffer, A., Millar, R., Hepburn, C. & Beinhocker, E. The '2 °C capital stock' for electricity generation: committed cumulative carbon emissions from the electricity generation sector and the transition to a green economy. *Appl. Energy* **179**, 1395–1408 (2016).
40. Creutzig, F. et al. Beyond technology: demand-side solutions for climate change mitigation. *Annu. Rev. Environ. Resour.* **41**, 173–198 (2016).
41. Hovi, J., Sprinz, D. F. & Underdal, A. Implementing long-term climate policy: time inconsistency, domestic politics, international anarchy. *Glob. Environ. Polit.* **9**, 20–39 (2009).
42. Averchenkova, A., Fankhauser, S. & Nachmany, M. *Trends in Climate Change Legislation* (Edward Elgar, 2017).
43. Averchenkova, A., Fankhauser, S. & Finnegan, J. J. The impact of strategic climate legislation: evidence from expert interviews on the UK Climate Change Act. *Clim. Policy* **21**, 251–263 (2021).
44. *Making Clean Electrification Possible: 30 Years to Electrify the Global Economy* (Energy Transition Commission, 2021).
45. *Renewables 2020: Analysis and Forecasts to 2025* (IEA, 2020).
46. *Global EV Outlook 2020* (IEA, 2020).
47. Davis, S. J. et al. Net-zero emissions energy systems. *Science* **360**, eaas9793 (2018).
48. Dikau, S. & Volz, U. Central bank mandates, sustainability objectives and the promotion of green finance. *Ecol. Econ.* **184**, 107022 (2021).
49. Eskander, S., Fankhauser, S. & Setzer, J. Global lessons from climate change legislation and litigation. *Environ. Energy Policy Econ.* **2**, 44–82 (2021).
50. Willis, R. *Too Hot to Handle? The Democratic Challenge of Climate Change* (Policy Press, 2020).
51. Hubau, W. et al. Asynchronous carbon sink saturation in African and Amazonian tropical forests. *Nature* **579**, 80–87 (2020).
52. Pianta, S., Rinscheid, A. & Weber, E. U. Carbon capture and storage in the United States: perceptions, preferences, and lessons for policy. *Energy Policy* **151**, 112149 (2021).
53. Fuss, S. et al. Negative emissions—Part 2: costs, potentials and side effects. *Environ. Res. Lett.* **13**, 63002 (2018).
54. Lezaun, J., Healey, P., Krueger, T. & Smith, S. M. Governing carbon dioxide removal in the UK: lessons learned and challenges ahead. *Front. Clim.* **89**, 684063 (2021).
55. Wara, M. Is the global carbon market working? *Nature* **445**, 595–596 (2007).
56. Victor, D. G. & Cullenward, D. Making carbon markets work. *Sci. Am.* **297**, 70–77 (2007).
57. Haya, B. et al. Managing uncertainty in carbon offsets: insights from California's standardized approach. *Clim. Policy* **20**, 1112–1126 (2020).
58. *Greenhouse Gas Removal Policy Options* (Vivid Economics, 2019); https://www.vivideconomics.com/ casestudy/ greenhouse-gas-removal-policy- options/
59. Bednar, J. et al. Operationalizing the net-negative carbon economy. *Nature* **596**, 377–383 (2021).
60. *Future Demand, Supply and Prices for Voluntary Carbon Credits: Keeping the Balance* (Trove Research, 2021); https://trove-research.com/research-and-insight/carbon-credit-demand- supply-and-prices-june-2021/
61. Carton, W., Asiyanbi, A., Beck, S., Buck, H. J. & Lund, J. F. Negative emissions and the long history of carbon removal. *Wiley Interdiscip. Rev. Clim. Change* **11**, e671 (2020).
62. Elgin, B. These trees are not what they seem. *Bloomberg Green* (9 December 2020).
63. Song, L. Why carbon credits for forest preservation may be worse than nothing. *ProPublica* (22 May 2019).
64. Dubash, N. K., Winkler, H. & Rajamani, L. Developing countries need to chart their own course to net zero emissions. *The Conversation* (4 May 2021); https://theconversation.com/developing- countries-need-to-chart-their-own-course-to-net-zero-emissions-159655
65. Buchner, B. et al. *Global Landscape of Climate Finance 2019* (Climate Policy Initiative, 2019).
66. Dibley, A., Wetzer, T. & Hepburn, C. National COVID debts: climate change imperils countries' ability to repay. *Nature* **592**, 184–187 (2021).
67. Newbold, T. Future effects of climate and land-use change on terrestrial vertebrate community diversity under different scenarios. *Proc. R. Soc. B* **285**, 20180792 (2018).
68. Brondizio, E. S., Settele, J., Diaz, S. & Ngo, H. T. *Global Assessment Report on Biodiversity and Ecosystem Services* (IPBES, 2019).
69. IPCC *Special Report on Climate Change and Land* (eds Shukla, P. R. et al.) (WMO, 2019).
70. Girardin, C. A. J. et al. Nature-based solutions can help cool the planet—if we act now. *Nature* **593**, 191–194 (2021).

71. Seddon, N. et al. Getting the message right on nature-based solutions to climate change. *Glob. Change Biol.* **27**, 1518–1546 (2021).
72. Lewis, S. L., Wheeler, C. E., Mitchard, E. T. A. & Koch, A. Restoring natural forests is the best way to remove atmospheric carbon. *Nature* **568**, 25–28 (2019).
73. Veldman, J. W. et al. Comment on 'The global tree restoration potential'. *Science* https://doi.org/10.1126/science.aay7976 (2019).
74. Cardinale, B. J. et al. Biodiversity loss and its impact on humanity. *Nature* **486**, 59–67 (2012).
75. *Guidance for Using the IUCN Global Standard for Nature-Based Solutions* (IUCN, 2020).
76. Stern, N. *Why Are We Waiting? The Logic, Urgency, and Promise of Tackling Climate Change* (MIT Press, 2015).
77. Hepburn, C., O'Callaghan, B., Stern, N., Stiglitz, J. & Zenghelis, D. Will COVID-19 fiscal recovery packages accelerate or retard progress on climate change? *Oxf. Rev. Econ. Policy* **36**, S359–S381 (2020).
78. Coady, D., Parry, I., Sears, L. & Shang, B. *How Large are Global Energy Subsidies?* (IMF, 2015).
79. Bhattacharya, A., Oppenheim, J. & Stern, N. Driving sustainable development through better infrastructure: key elements of a transformation program. *Brookings* (10 July 2015); https://www.brookings.edu/research/driving-sustainable-development-through- better-infrastructure-key-elements-of-a-transformation-program/
80. Bowen, A., Kuralbayeva, K. & Tipoe, E. L. Characterising green employment: the impacts of 'greening' on workforce composition. *Energy Econ.* **72**, 263–275 (2018).
81. Gambhir, A., Green, F. & Pearson, P. J. G. *Towards a Just and Equitable Low-Carbon Energy Transition* Grantham Institute Briefing Paper No. 26 (Imperial College, 2018).

Acknowledgements
All authors are part of Oxford Net Zero, which is supported by the University of Oxford's Strategic Research Fund. We also acknowledge funding from ClimateWorks (grant 19-1501), the Economic and Social Research Council (grant ES/S008381/1), EU Horizon 2020 (grants 869192 and 869357) and the Natural Environment Research Council (grant NE/V013106/1). The charts were produced by S. Littlewood.

Author contributions
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.M.S.

Competing interests
The authors declare no competing interests.

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Peer review information *Nature Climate Change* thanks Hongbo Duan, Daniel Huppmann and Sally Benson for their contribution to the peer review of this work.