SYSTEMS CHANGE LAB

TECHNICAL NOTE

METHODOLOGY UNDERPINNING THE SYSTEMS CHANGE LAB PLATFORM

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CONTENTS

Technical notes document the research or analytical methodology underpinning a publication, interactive application, or tool.

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ABSTRACT

The Systems Change Lab platform provides an overview of the world’s collective efforts to accelerate the system-wide transformations needed to limit global average temperature rise to 1.5°C, protect biodiversity, and advance equity. This technical note explains the methodology of the Systems Change Lab platform. We identify key global systems that must transform and choose the most critical shifts needed within each system. We then translate those shifts into global targets and assess the world’s progress in achieving them. This technical note covers the overall methodology that we applied to all systems on the platform; the methods that are specific to each system (e.g., power, transport) can be found on the methodology page of the platform. Research is ongoing on systems related to biodiversity and equity, so this technical note will be updated as more systems are added to the platform.

This technical note draws heavily on the technical note for the *State of Climate Action* series (Schumer et al. 2022), the *State of Climate Action 2021* report (Boehm et al. 2021), the *State of Climate Action 2022* report (Boehm et al. 2022), and the *State of Climate Action 2023* report (Boehm et al. 2023). Some parts of this technical note are directly derived from those publications. However, the Systems Change Lab platform is a larger undertaking than the *State of Climate Action* series in that it expands the coverage of climate-focused systems change and includes the protection of biodiversity and the advancement of equity as additional goals.

This is version 2 of the technical note. Changes from version 1 can be found in the update log.

1. Introduction

The Systems Change Lab platform (systemschangelab.org) focuses on three key goals: mitigating climate change, protecting biodiversity, and advancing equity. In their latest assessment reports, the world's most authoritative bodies on climate change and biodiversity find that limiting global temperature rise to 1.5°C above preindustrial levels, halting biodiversity loss, and ensuring just transitions will require systems change (IPCC 2022; IPBES 2019).

On the Systems Change Lab platform, we identify key global systems that must transform, the most critical shifts needed within each system, and targets that must be achieved for those shifts to be successful (Figure 1). We assess progress toward the global targets using relevant indicators and datasets, and if there is sufficient data we categorize recent efforts toward the targets as Right Direction and on Track, Right Direction but off Track, Right Direction but Well off Track, Right Direction but No Target, or Wrong Direction.

In this technical note, Section 2 describes our methodology for identifying key global systems. Section 3 explains how we chose the most critical shifts within each system. Sections 4 and 5 describe how we translated these shifts into global targets and selected indicators with accompanying datasets that we use to monitor change for each shift. Section 6 outlines our approach for assessing the world's collective progress made toward the targets. Section 7 details how we identify enabling conditions and barriers that can support or hinder transformations. Section 8 explains limitations to our methodology.

2. Selection of key systems

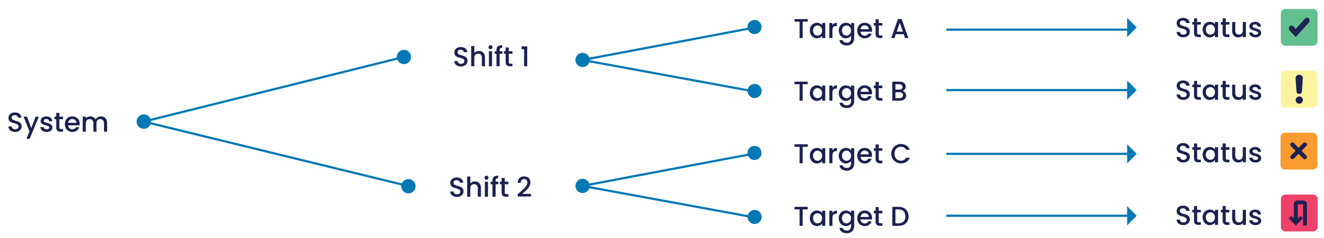
What is a system?

A system can be defined as "a configuration of interacting, interdependent parts that are connected through a web of relationships, forming a whole that is greater than the sum of its parts" (Holland 2000). More simply, it is a set of coherently organized, interconnected elements that produce a characteristic pattern of behaviors, which some classify as a function or purpose (Meadows 2008). These component parts can include biotic entities (e.g., plants, animals, and fungi) and abiotic entities (e.g., buildings, rocks, and water), as well as immaterial social, political, economic, and cultural institutions.

Systems exist at different scales. They can be as minute as a single beehive that produces honey or as large as the global food system that comprises fertilizer and seed companies, farmers, traders, manufacturers, distributers, and grocery stores that, together, feed the world's rapidly growing population. Smaller systems can also be nested within broader systems, such as a beekeeper within a national collective of farmers within the global food system.

Conceptualizations of systems can also vary by their components and relationships, with some focusing primarily on the interactions among people and technology (sociotechnical systems) and others on the connections between people and the natural world (social-ecological systems). Yet, in practice, it remains difficult to divide our highly interconnected world into such neatly defined and discrete systems. Food systems, for example, involve technologies, people, and natural resources and are deeply connected to terrestrial, freshwater, and marine ecosystems. Drawing the boundaries of a

FIGURE 1 | Structure of the Systems Change Lab platform



Source: Authors.

system by deciding to emphasize one component or interaction among elements over another, then, is ultimately a subjective exercise that depends on the system in question.

What is systems change?

Calls for systems change have gained traction throughout the global climate change community (IPCC 2018; 2022; Sachs et al. 2019; Steffen et al. 2018; Victor et al. 2019; IEA 2021a; Puri 2018; United Nations 2019; UNFCCC secretariat 2021; WBCSD 2021), reflecting an emerging consensus that current efforts have failed to spur deep greenhouse gas (GHG) emissions reductions, halt biodiversity loss, and reduce inequity at the speed and scale required to secure a more sustainable, prosperous, and just future for all. Yet there is no widely accepted definition of systems change, nor is there a shared understanding of how such a process would unfold in practice (Feola 2015; Patterson et al. 2017; Few et al. 2017; Hölscher et al. 2018).

We define systems change as the reconfiguration of a system, including its component parts and the interactions between these elements, such that it leads to the formation of a new system that behaves in a qualitatively different way. This definition draws on commonalities across well-cited definitions in global environmental change research (Walker et al. 2004; Olsson et al. 2006; Folke et al. 2010; Chapin et al. 2010; Biggs et al. 2010; IPCC 2022; Westley et al. 2011; Rotmans and Loorbach 2009; Geels et al. 2017b; Grin et al. 2010; Waddell et al. 2015).

Given the commonalities across definitions, we use the terms *transformation* and *transition* interchangeably with *systems change*. These terms all essentially describe a change from an initial state of a system to a new state with a different quality or character. Analyzing systems change requires understanding the starting and ending points of the required change—for example, a shift from a deforested pasture for beef cattle to a restored, healthy forest that sequesters CO_2, or from a transportation network dominated by fossil fuels to one that supports more sustainable forms of mobility like walking, bicycling, or electrified public transit. Such systems change entails “breaking down the resilience of the old and building the resilience of the new” (Folke et al. 2010). The exact starting and ending point will depend on the nature of the system in question.

Systems changes are often demarcated from incremental changes, which are defined as adjustments to elements or processes within an existing system that do not fundamentally alter its essence or integrity (Few et al. 2017; IPCC 2018, 2022). New policies that increase the energy efficiency of existing products, for example, can help reduce GHGs emitted from the current energy system in an incremental way, but efforts to phase out fossil fuels represent a transition to an entirely new system of energy delivery and behavior that supplies energy without releasing CO_2 into the atmosphere. Although sometimes conceptualized as binary, these typologies of change are not mutually exclusive. Incremental shifts can create an enabling environment for future transformations, and in some instances, a progressive series of these lower-order changes can come together in ways that successfully “lock in” a transition to a new system (Levin et al. 2012; ICAT 2020; Termeer et al. 2017). The Systems Change Lab platform identifies both transformational and incremental shifts that, taken together, can help transform nearly all major systems.

Systems included on the platform

For the Systems Change Lab platform, we chose to include global systems that when transformed will contribute to achieving the three objectives of stabilizing our climate, protecting biodiversity, and advancing equity. Some of the global systems we selected are most closely related to climate, others to biodiversity, and others to equity. However, most systems are relevant for multiple objectives.

In the following section, we explain our selection of systems as they relate to each of our three objectives.

Climate: In modelled pathways that limit global temperature rise to 1.5°C above preindustrial levels with no or limited overshoot,[1] GHG emissions peak immediately or before 2025 at the latest, and then fall by a median of 43 percent from 2019 levels by 2030 (IPCC 2022). By around mid-century, CO_2 emissions reach net zero in these pathways. The Intergovernmental Panel on Climate Change (IPCC) finds that achieving such deep GHG emissions reductions will require rapid transformations across power, cities and the built environment, industry, transportation, agriculture, forests, and land systems—as well as the immediate scale-up of carbon removal technologies to compensate for the significant proportion of the carbon budget that we have already spent and residual GHG emissions that will likely prove difficult to eliminate altogether (IPCC 2022).

Biodiversity: Similarly, the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) finds that achieving goals to conserve and sustainably use nature will require transformative changes, particularly across systems most responsible for land-use and sea-use change, direct exploitation of species, climate change, pollution, and the spread of invasive, alien species (IPBES 2019). These systems include power, industry, cities and the built environment, transportation, and agriculture, as well as our management of forests, land, freshwater, and ocean ecosystems.

Equity: Equity is an essential consideration as we pursue the other two goals, as well as an important goal in its own right. There is no one commonly agreed upon definition of equity (Putnam-Walkerly and Russell 2016), but in its most basic sense, equity is the quality of being fair according to circumstances. Closely connected to this definition is that of climate justice, which is “concerned with the equitable distribution of rights, benefits, burdens and responsibilities associated with climate change, as well as the fair involvement of all stakeholders in the effort to address the challenge” (Okereke 2018). Under the umbrella of equity, procedural equity measures the fairness in processes and procedures used in decision-making, while distributive equity measures the fairness in the distribution of benefits and burdens of policy action, initiatives, or interventions among different groups. We do not wish to duplicate efforts like the Sustainable Development Goals (SDGs), so on this platform we focus on equity as it relates to transitions to mitigate climate change and protect biodiversity. We monitor it to ensure that these transitions do not exacerbate existing inequities, but rather advance equity. In addition, we plan to include one system, Social Inclusion and Equity, that collects relevant cross-cutting information on equity.

To help meet all three of these goals, other social, political, and economic transformations will be needed. To identify these critical transformations, we reviewed literature across academic disciplines and interviewed experts in topics such as sustainable development, just transition, and degrowth/post-growth. The main transformations we identified in the literature included moving toward a circular economy, good governance, a global financial system that supports sustainability, and a global economy that prioritizes human well-being over economic growth.

The Systems Change Lab platform plans to report on the following full list of systems:

- Power
- Industry
- Transport
- Cities
- Buildings
- Technological Carbon Removal
- Forests and Land
- Oceans
- Freshwater
- Food and Agriculture
- Finance
- Circular Economy
- Governance
- Social Inclusion and Equity
- New Economics for Climate and Nature

In November 2022, we launched the Power, Industry, Transport, Technological Carbon Removal, and Finance systems alongside our original technical note. This technical note is being updated in preparation for our upcoming system launches.

There is no one right way to arrange everything into distinct systems, so we have chosen an arrangement that is relatively comprehensive, compatible with the literature, and speaks to coalitions working in these areas. We use the term *systems* for the above list, but the types of systems covered vary widely. Some of these are systems that look at the relationships between people and technology or between people and the natural world. Others are systems of institutions or approaches that enable transformation in technical or environmental systems. Some are groupings of shifts that cut across systems but have a common theme, so we collect information on those shifts together. All of the systems on the platform overlap and interconnect with each other. Although we have not cataloged these relationships, we plan to do so in the future.

3. Translating system-wide transformations into a concrete set of shifts

To measure progress made in accelerating systems change, for each system we translated the change needed into a set of discrete shifts that could be monitored more easily. These shifts can be understood as categories of actions that need to take place to decarbonize the global economy, protect biodiversity, and/or advance equity. For example, we identified four shifts needed to transform the power system: phasing out unabated coal and gas electricity generation; rapidly scaling up renewable electricity generation; modernizing grids, scaling storage, and managing demand; and ensuring energy access and a just and equitable transition for all. We identified these shifts based on a review of the literature for each system and validated them through consultation with internal and external experts.

Some shifts are more closely related to our objectives on climate, others on equity, and others on biodiversity. However, the shifts can contribute to multiple objectives at once. For example, in the food system, reducing global food loss and waste is a shift that could simultaneously protect biodiversity by reducing the amount of agricultural land that is needed, reducing GHG emissions, and advancing equity and well-being by making food more accessible to all. Actions on climate, biodiversity, and equity can interact with each other in complex ways, so it is important to monitor all three of the goals to ensure that progress on one does not inadvertently lead to backsliding on another.

Shifts related to climate

For each of the climate-related systems, we chose a manageable set of critical shifts that, taken together, can help overcome the deep-seated carbon lock-in common to these systems (Seto et al. 2016). Identifying these critical shifts for each system, however, is an inherently subjective exercise, as there are many possible ways to translate a global temperature goal into a set of individual actions. So long as the overall carbon emissions budget is maintained, a range of strategies can be pursued to hold global warming to 1.5°C (e.g., assigning more rapid and ambitious carbon emissions reduction targets to the power system than to the transportation system, or vice versa).

However, because the remaining emissions budget is small, the degree of freedom to assign different weights to transformations that must occur in different systems is relatively limited, and the IPCC makes clear that, together, all systems will eventually have to dramatically lower emissions to limit global warming to 1.5°C (IPCC 2022). So, if a transformation across one system is slower than this global requirement, another needs to transition proportionately faster, or additional CO_2 must be removed from the atmosphere. Arguing that a system needs more time for decarbonization, then, can only be done in combination with asserting that another can transition faster, if our global temperature goal is to be met.[2] A good starting point is asking whether a system can fully decarbonize by 2050. If so, how and how quickly? And if not, why and how much can be done? (Climate Action Tracker 2020b).

To that end, we reviewed modeled pathways that hold global warming to 1.5°C with no or low overshoot from integrated assessment models (IAMS) included in (IPCC 2018) and (IPCC 2022),[3] studies that rely on bottom-up modeling to identify system-specific road maps that limit temperature rise to 1.5°C, and bottom-up assessments of mitigation potential, including those published in IPCC (2022). In mapping out multiple pathways that the world might take to meet this global temperature goal, these studies consider a range of factors (e.g., cost, interactions and trade-offs among mitigation actions, technical potential, environmental and social safeguards) when determining each system's mitigation potential, as well as the specific shifts that collectively deliver that system's contribution to limiting global temperature rise to 1.5°C. For each system, we identified both supply- and demand-side shifts common across these studies and then assessed their potential contributions to GHG emissions reduction and avoidance, as well as carbon removal. For inclusion in the Systems Change Lab platform, we prioritized shifts that featured prominently across all or nearly all studies reviewed and which collectively represent the primary actions needed to hold global temperature rise to 1.5°C. We considered additional criteria (e.g., data availability, environmental and social safeguards) when translating these critical shifts into quantitative targets for 2030 and 2050, as noted below.

Shifts related to biodiversity

The identification of shifts related to biodiversity is still under way. Methods under development currently focus on addressing the primary direct drivers of biodiversity loss across terrestrial, freshwater, and marine ecosystems. These top drivers of biodiversity loss include land-use and sea-use change, direct exploitation of species, climate change, pollution, and the spread of invasive alien species. Many of these shifts will sit within the Forests and Land, Oceans, and Freshwater systems, but we will also focus on biodiversity impacts in agriculture and the impacts of extractives and pollution on biodiversity as it relates to the circular economy. Further detail will be provided as we expand the systems covered on the platform. We may revisit our approach to biodiversity as more research is done.

Shifts related to equity

At present, the equity-focused shifts included in the platform focus largely on access to basic goods (e.g., energy, mobility, shelter, financial services) and a just transition. These shifts are designed to ensure that we reach our climate and biodiversity goals in a way that improves the livelihoods of historically marginalized and underserved communities or at least does not exacerbate existing inequities. More shifts on equity will be developed as we add the systems Good Governance and Social Inclusion and Equity to the platform.

We will mainly be considering equity as it relates to climate and biodiversity transitions. There will be individual targets and indicators related to equity distributed throughout other climate-related or biodiversity-related shifts to ensure that those shifts do not negatively affect equity (discussed in the following section). Our research is ongoing as to how to best integrate equity into our climate and biodiversity systems. We may revisit our approach to equity as more research is done.

4. Development of targets and indicators

Overall selection of targets and associated indicators

As noted above, the Systems Change Lab platform identifies key systems that must be transformed and a discrete set of critical shifts for each system. For each shift, we select multiple quantitative global targets to show what specific changes are needed for the shift to occur. The idea is that the sum of the targets in each shift and each system together represent systems change.

We selected targets for the near term (primarily 2030) and, in some cases, additional targets for the long term (primarily 2050). The near-term targets can inform immediate action during this decade and are what we use to categorize whether or not progress is on track. We prioritized the selection of near-term targets, but the long-term targets, when identified, indicate further shifts required to support transformations to a net-zero, equitable, nature-positive world.

We designed the targets to be compatible with the three primary objectives tracked by the Systems Change Lab platform: limiting global warming to 1.5°C, protecting biodiversity, and advancing equity (further detail for each is provided below). Most targets directly contribute to the main objective of the shift in which they are located, while other targets ensure that pursuing that objective is done in a way that does not negatively affect the other objectives. For example, within the shifts focused on climate, the majority of targets are aligned with limiting global warming to 1.5°C, but some of those shifts also include targets that ensure that the shift also advances equity or biodiversity goals.

Each target has an associated indicator that we can measure to see if progress is being made toward the target. As an example, in the Power system, one of the targets is that the share of coal in electricity generation falls to 4 percent in 2030 and 0–1 percent in 2040, and the indicator that corresponds with that target is the share of coal in electricity generation (%).

Some indicators are established in the literature as important to understand the general direction of progress toward broader climate, biodiversity, and equity goals but have no quantitative targets established in the literature. In these cases, we included the indicators on the platform as targets even though they do not yet have targets. Platform users can see whether the indicator is going in the right direction or not but not whether it is changing fast enough. We and our partners will attempt to derive new targets for these indicators or add new targets that are established in the literature in future updates to the Systems Change Lab platform. For now, the indicators without targets provide useful information on what is happening today, but we cannot assess whether the progress of the indicator is on track or say at what speed it should be moving.

In many cases, we did not fully capture every target and every indicator that could fit under a particular shift, but we aimed to select the most important or most representative targets. Some systems and some shifts have more targets and indicators than others, but that does not mean they are more important. It simply means that we have identified more discrete elements that can help track progress toward the overall goal.

While our analysis is focused on global systems and shifts, it is critical to consider that some countries and regions are starting from a different place than others and some will require more of a shift than others. Some countries and regions will also have more competing priorities than others. We have only developed global targets, not country targets, but the responsibility and timeline for meeting these global targets may vary among countries.

The reasons why we chose the particular global targets for each system are explained on the platform's system background content page. The targets and indicators were reviewed by several relevant experts for each shift to validate that they were the appropriate choices, and we will continue to gather feedback and update the targets over time.

Proxy indicators

We primarily selected indicators that correspond directly to our targets, such as the carbon intensity of electricity generation or the share of electric vehicles in light-duty vehicle sales. Some targets, however, cannot be tracked directly; and for those, we selected the best available proxy indicators. For example, we use tree cover gain to assess progress made toward our reforestation targets, yet tree cover gain does not exclusively measure reforestation. Instead, this indicator measures the establishment of tree canopy in areas that previously had no tree cover, including gains due to harvesting cycles in areas that are already established as plantations and afforestation in nonforested biomes. Despite these limitations, we use tree cover gain because its accompanying dataset relies on satellite imagery, rather than infrequent, often outdated field surveys. We provide explanations of proxy indicators where they are used in the system background content page on the platform.

Climate targets and indicators

Multiple sources informed our selection of climate-related targets, including modeled pathways holding global temperature rise to 1.5°C with no or limited overshoot from integrated assessment models assessed by the IPCC (2018, 2022), bottom-up modeling studies that identify system-specific mitigation pathways, and bottom-up assessments of both technical and cost-effective mitigation potential.

Consequently, we present targets as either a single number or a range of values. When applicable, we present a range of values to account for assumptions underlying distinct modeling approaches. The more and less ambitious bounds reflect varying degrees of trade-offs in decarbonization with other targets or systems, and/or uncertainty in terms of technical and economic feasibility (Climate Action Tracker 2020b). Reaching the least ambitious targets[4] across all systems will not likely be sufficient for achieving the Paris Agreement's 1.5°C global temperature goal. Consequently, only by achieving the more ambitious bound of some targets (e.g., phasing out coal as quickly as possible) will we create room for some systems to achieve their least ambitious bounds where decarbonization is difficult and therefore slower.

It is critical to note here that many selected targets are interdependent. Changes in one target can further or hinder another; for example, greater penetration of zero-carbon power on the electric grid would enable significant progress in decarbonizing industrial processes, while failure to sustainably increase crop yields could result in agricultural expansion across forests, spurring increases in deforestation.

Environmental safeguards

In selecting 1.5°C-aligned targets for inclusion in the Systems Change Lab platform, we employed several environmental and social safeguards where possible and appropriate to minimize risks associated with three common mitigation measures: bioenergy with carbon capture and storage (BECCS), afforestation and reforestation, and carbon capture utilization and storage (CCUS).

BECCS features prominently in many modeled pathways that limit global temperature rise to 1.5°C with no or limited overshoot assessed in IPCC (2022), with this technology delivering a median of 3.8 gigatonnes of carbon dioxide per year ($GtCO_2/yr$) of carbon removal by 2050 and, in some pathways, upwards of 14.6 $GtCO_2/yr$ (IIASA n.d.). Yet deployment of BECCS—a process in which biomass is combusted for energy production, its emissions are captured before they are released into the atmosphere, and then captured emissions are sequestered either via underground storage or storage in long-lived products—risks generating negative impacts on food security, biodiversity, and/or net emissions from land-use changes associated with producing biomass feedstocks (e.g., if land that would otherwise be used for crop production is used to produce monoculture biomass feedstocks for BECCS, that food production would need to happen elsewhere—perhaps displacing a natural carbon sink like a forest, thereby reducing biodiversity and increasing net GHG emissions due to the indirect land-use change) (Creutzig et al. 2021; Fajardy et al. 2019; Hanssen et al. 2022).

To minimize these risks, we excluded scenarios that rely too heavily on this technology when deriving targets from modeled pathways that limit warming to 1.5°C with no or limited overshoot from IPCC (2018) and IPCC (2022). See Box 2 and Box 3 in Jaeger et al. (2023) for more information on the filtering criteria that we applied to scenarios from IPCC (2022) and IPCC (2018), respectively. More specifically, we constrained BECCS deployment to an average of 5 $GtCO_2/yr$ from 2040 to 2060—a level considered sustainable by Fuss et al. (2018) and IPCC (2018). While more recent estimates of the sustainable mitigation potential for BECCS are lower than 5 $GtCO_2/yr$ (e.g., Roe et al. 2021; Creutzig et al. 2021), we retained this higher limit as a pragmatic approach. BECCS remains the primary carbon removal technology in most IAMs, which have yet to feature more nascent innovations like direct air carbon capture and storage and carbon mineralization. If we excluded these pathways with higher amounts of BECCS due to more stringent constraints, we would lose valuable insights from IAMs that do not yet incorporate other carbon removal technologies (Climate Analytics 2023).[5] Also, the median amount of BECCS deployment in these filtered scenarios falls well below our upper bound at 3.6 $GtCO_2/yr$ in 2050, an amount that is closer to more recent estimates of sustainable potential (e.g., Creutzig et al. 2021; Roe et al. 2021). Still, given pervasive uncertainty around the feasibility of large-scale carbon removal technologies, rapidly reducing GHG emissions to minimize reliance on these nascent innovations remains the most robust mitigation strategy (Grant et al. 2021), and we will continue to refine total and pathway-specific estimates of technological carbon removal as more carbon removal technologies are incorporated into IAMs.

We also limited carbon removals from afforestation and reforestation (A/R). When implemented appropriately (e.g., by focusing on recovering forests' ecological functions, rather than solely on reestablishing trees), this mitigation measure can generate substantial benefits for adaptation, sustainable development, and biodiversity at relatively low costs (IPCC 2022). But if deployed at large scale and without following forest landscape restoration principles, A/R can generate unintended consequences, such as fueling land competition, spurring increases in food prices, and intensifying food insecurity (IPCC 2022). Accordingly, we constrained our assessment of IPCC (2018) modeled pathways that limit warming to 1.5°C with no or limited overshoot to those that deploy an average of 3.6 $GtCO_2/yr$ from 2050 to 2100 (see Box 3 in Jaeger et al. 2023). For IPCC (2022) modeled pathways, we relied on updated filtering criteria from Climate Analytics (2023) and Grant et al. (2021), limiting deployment of A/R to an average of 3.6 $GtCO_2/yr$ from 2040 to 2060 and an average of 4.4 $GtCO_2/yr$ from 2050 to 2100, following the approach set out in CAT (2023) (see Box 2 in Jaeger et al. 2023).[6] These limits to A/R represent the upper bound of carbon removals within this filtered set of scenarios, and the median amount of A/R remains relatively low—for example, at less than 1 $GtCO_2/yr$ throughout the century in the filtered IPCC (2022) scenarios.

Similarly, when deriving targets from bottom-up sectoral modeling and estimates of technical and cost-effective mitigation potentials for forests and land and food and agriculture, we selected those that, if achieved, would not threaten food security, spur biodiversity loss, or limit fiber production. All targets for reforestation and restoration, specifically, do not exceed the areas associated with Griscom et al. (2017)'s global "maximum additional mitigation potentials," which are technical estimates of mitigation potential constrained by social and environmental safeguards. In calculating this maximum additional mitigation potential for reforestation, for example, Griscom et al. (2017) limited forest cover gain to lands that are ecologically appropriate for forests, removed all existing croplands from their estimate of maximum potential extent to avoid dampening yields, and excluded the boreal region due to changes in albedo that would have a net warming effect. The area associated with this maximum additional mitigation potential is 678 million hectares (Mha) (Griscom et al. 2017), which our reforestation target of 300 Mha does not exceed (Roe et al. 2021). Similarly, our food and agriculture targets seek to avoid additional ecosystem conversion and to free up farmland for reforestation and restoration by reducing agriculture's land footprint below its 2010 global extent, while mitigating GHG emissions from production processes and feeding 10 billion people (Searchinger et al. 2019, 2021).

Large-scale deployment of carbon capture and utilization (CCU) and carbon capture and storage (CCS)—technologies that capture CO_2 at a point source (e.g., a power plant or oil refinery) and then either use that CO_2 in various processes and products (e.g., production of chemicals and concrete) or store that CO_2 underground in suitable geological formations—also generates risks. Accordingly, we limited reliance on these technologies in the definition of Paris-compatible targets.[7] More specifically, these technologies can cause harmful environmental impacts (e.g., through high water requirements) as well as increase energy demand and, subsequently, GHG emissions from upstream fossil fuel production, including fugitive methane emissions. Carbon capture technologies used in both CCU and CCS also face the challenge of incomplete CO_2 capture rates, and are therefore not zero-carbon in operation. While these capture rates do vary, generally they are lowest for industrial process emissions—for example, carbon capture technologies installed on retrofitted blast furnaces capture only about 50 to 60 percent of CO_2 emissions (Fan and Friedmann 2021). In fossil power generation applications, these rates are higher. Today's technologies can capture about 90 percent of CO_2 emissions from an individual facility (IEA 2021a), although many existing facilities report lower values (Robertson and Mousavian 2022). Future capture rates may increase, but even under the most idealized, theoretical conditions most systems would still fall short of capturing 100 percent of CO_2 emissions (Brandl et al. 2021).[8] And for CCU, specifically, captured CO_2 is held only temporarily in products, many of which have short lifetimes after which the captured CO_2 is rereleased into the atmosphere. CCU's efficacy in reducing CO_2 emissions, then, depends on the source of CO_2, the emissions intensity of energy required for converting the captured CO_2 into the product, and that product's lifetime (e.g., if a product is recycled, less CO_2 would be released into the atmosphere than if it were incinerated). Relying too heavily on either CCS or CCU risks locking in GHG emissions–intensive infrastructure and associated emissions.

To minimize these risks, we limited deployment of both CCU and CCS technologies in industrial decarbonization. Note that we did not need to constrain deployment of CCU and CCS in the power sector as our filtered scenarios from IAMs included in IPCC (2022) showed an extremely limited role for both technologies in this sector. For Industry, we adopted targets from CAT (2020a), which relied primarily on bottom-up, sectoral modeling to establish a Paris-aligned road map for industry. In contrast to the power sector, reliance on CCU and CCS cannot be constrained through scenario filtering; rather, CAT prioritized other decarbonization technologies where available and to the extent possible when constructing bottom-up scenarios. For example, alternative binders play a prominent role in the cement sector to avoid process emissions, while the steel sector sees a high reliance on the development of green hydrogen-based ironmaking (CAT 2020a). Each of these alternative technologies has a lower emissions intensity than CCS, so we prioritized them accordingly.

Finally, we did not systematically consider cost in selecting our targets. We derived some targets from models that optimize for least-cost pathways (e.g., IEA 2021 and BloombergNEF 2021), while for others, we selected those that the literature considers cost-effective at specific carbon prices (e.g., Roe et al. 2021). For targets presented as ranges, the less ambitious bound is often informed by least-cost scenarios modeled by IAMs, and the more ambitious bound does not account for cost-effectiveness (e.g., Climate Action Tracker 2020a; 2023). Other targets, particularly those focused on mitigation across the global food system, still do not include cost considerations (e.g., Searchinger et al. 2019). This variation reflects the broader diversity in top-down and bottom-up estimates of mitigation potential for specific actions, as well as our decision to prioritize other factors, such as social and environmental safeguards, over cost in our selection of targets.

We will aim to identify further safeguards related to biodiversity and equity as we expand our analysis on the platform.

Biodiversity targets and indicators

Efforts to identify biodiversity-related targets and indicators are under way and will be launched as new systems are added to the platform, focusing on the direct drivers of biodiversity loss in Forests and Land, Oceans, Freshwater, Food, and the Circular Economy. It is an open question whether we want to include biodiversity-related targets and indicators for the systems that are already on the platform to assess their impact on biodiversity.

There is no internationally negotiated acceptable amount of biodiversity loss, unlike in the climate change community, where 1.5°C is a politically agreed upon target for climate. Therefore, we are developing methods to select targets that maximize the protection of biodiversity in all its forms (e.g., genes, species, ecosystems), while minimizing trade-offs that could impede efforts to deliver basic goods, services, and opportunities to all or constrain efforts to mitigate climate change. Even if we are unable to identify specific, quantitative targets for biodiversity, monitoring biodiversity indicators will provide useful information that will help platform users determine whether the world is moving in the right direction on these goals. We will provide further detail as we expand the biodiversity-related content on the platform.

Equity targets and indicators

Equity is a key consideration as we meet our objectives of limiting global temperature increase to 1.5°C and protecting biodiversity. It is also an important objective in its own right. However, it is not a given that equity will automatically improve as a result of improvements in the other systems. It is possible to achieve systems transformations for climate and biodiversity in which inequities are exacerbated. Therefore, we include equity targets and indicators within the climate- and biodiversity-focused systems and shifts, as well as the equity-specific shifts.

However, defining and developing global equity targets is a challenging task, given the complexity of the issue and the lack of international consensus on the definition of equity. Equity targets are not directly derived from a specific overall goal (like the 1.5°C goal is for climate targets), but rather are representative of a series of dimensions relating to justice and equity that are relevant for systems transitions (Muñoz Cabré and Vega Araújo 2022; Heffron and McCauley 2017, 2022). Our equity-related targets and indicators are not comprehensive, as it would be extraordinarily difficult to ensure that we were accounting for every individual variable in determining equity. Instead, we focused on finding an indicative selection of equity targets and indicators that were related to climate and biodiversity for the systems in question. We focused first on including equity indicators where data were available, then identified other key indicators where data were not available. Many equity indicators do not have targets, but for some indicators we derived targets from the SDGs or other commonly agreed-upon sources. We will expand coverage of equity more in the future.

The two guiding principles for equity targets and indicators were access to goods and services and the distribution of positive and negative impacts. As of yet, we have not been able to identify sufficient indicators for procedural justice.

On access, targets and indicators were selected relating to access to basic needs and access to sustainable technologies and services. This includes indicators covering access to electricity, access to zero-emission mobility, and access to clean cooking.

On achieving an equitable distribution of positive and negative impacts, the philosophy in defining the indicators was to have indicators representative of the following dimensions: jobs, gender, human rights, health, inequality between developed and developing countries, and distributions of investment and economic benefits. In some cases, these dimensions apply to access as well. All of these indicators can have very different outcomes in different geographic areas, so we aim to provide country-level data on the platform where possible using our map view.

Within the jobs dimension, we also considered subcategories focused on three elements of a just transition: (i) decent work opportunities and income for workers, (ii) access by workers to training and skills for new occupations, and (iii) support for workers displaced by closures or measures related to climate change. We did not include a range of additional variables with the ability to assess the fairness of the transition. For example, the just transition framework of the International Labour Organization emphasizes social dialogue and the respect for fundamental labor principles and rights (ILO 2015), but measurable indicators do not currently exist for all elements of this framework. Concepts related to the green economy are being incorporated gradually within labor statistics, and the lack of data is a methodological challenge affecting almost all indicators of just transition.

Given the vast array of potential indicators to convey progress (or lack thereof) on these dimensions, priority was given to those indicators where robust and publicly accessible data are available. For some of the indicators, we derived targets from the SDGs, while others do not have targets. More details on all of these targets and indicators can be found in the system background content pages on the platform.

5. Selection of datasets

To assess global progress made toward the targets for 2030, we first collect historical data for every indicator. If data limitations prevent us from assessing global progress toward a target, we note these accordingly. For all indicators on the platform, we plan to update the data annually.

Our selection of datasets follows these six principles to ensure that all data are open, independent of bias, reliable, and robust:

- **Relevance**. Datasets selected directly measure each indicator, meaning they were created following a methodology and using the type of units that are consistent with or convertible to the units of the indicator in question.
- **Accessibility**. Datasets are readily accessible to the public. They generally are not hidden behind paywalls, and ideally they are subject to an open data license. When applicable, we note limitations with data accessibility (e.g. when data are behind a paywall or not readily available and thus a data-sharing agreement is established for SCL). Within the Systems Change Lab platform, the datasets used to assess global progress are clearly noted for each indicator with original data sources linked.
- **Accuracy**. Datasets are from reputable, trustworthy sources and have well-documented, openly accessible, and peer-reviewed methodologies that clearly note limitations. They are taken from data providers, including both authors of articles and organizations hosting datasets, that are either well recognized as core data providers or known experts in their fields (as suggested by authors and reviewers).
- **Completeness**. Datasets have sufficient temporal and spatial coverage. We note where the best available data are not globally available or are not published annually.
- **Timeliness**. Datasets selected represent the most up-to-date data available to reflect recent developments, and there is evidence that data have been and will be updated regularly. However, in many instances, there is a time lag before the best available data are published, and as such, the year of most recent data varies among indicators.
- **Ease of Collection**. Datasets prioritized for each indicator are relatively easy to collect and update (e.g., those that require minimal processing or that are directly downloadable). However, in some instances, data selected requires some calculations and processing (e.g., geospatial data).

If multiple potential datasets for an indicator are similar, we choose the dataset that best follows the above criteria. Our first priority is to identify global data, but we also collect and present data at the country level and disaggregated by individual technology or other relevant component parts when the data are relevant and available. We do not assess progress at the country level.

We attempt to follow these six principles as closely as possible, but given that there are many cases with data limitations, following them too strictly would leave more of the platform empty. Therefore, in some cases we make the decision to include data that do not meet all six principles (e.g., ease of collection or timeliness) when we deem that it is still useful to understand the topic and assess progress. When relevant, we note any limitations in the indicator tooltip.

As of the most recent update of the technical note, the majority of data we have collected meets all of the criteria above. The presentation of outdated datasets does not affect our confidence in the years of data we do have. In the future as we add more systems that do not have as much quality data (e.g., land-use-based systems), we may consider other options for highlighting data limitations.

6. Assessment of progress toward targets

Selecting targets, indicators, and datasets allows us to learn about the recent progress that has been made and evaluate whether the world is on track to meet the goals of stabilizing the climate, protecting biodiversity, and advancing equity. Our assessment provides a snapshot of global progress across each system and each shift that can help the world take stock of shared efforts.

Assessing the gap between recent progress and future action needed to meet our targets requires us to project a trajectory of future change for each indicator. The simplest way would be to assume that growth continues at its current rate of change following a linear trajectory, and indeed this is an effective method for many indicators. However, it is unlikely that all indicators will follow a linear path. In this section we first provide background on why some indicators, and particularly those focused on technology adoption, may follow nonlinear paths. Then we explain the methods we use to determine whether indicators are on track to meet their targets, which requires adjustments for indicators that are likely to follow nonlinear paths.

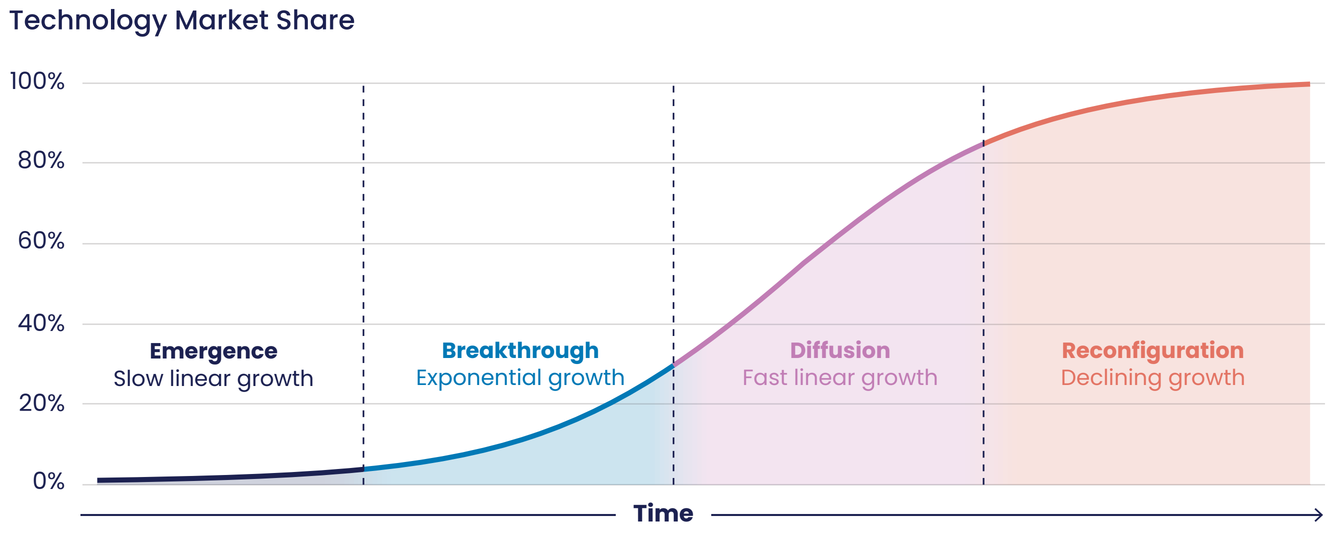
Background on the potential for nonlinear change

Many mainstream assessments still use linear assumptions for technology adoption forecasts where they are not always applicable. For example, in its Stated Policies Scenarios, the International Energy Agency (IEA) has historically assumed that future growth in solar photovoltaic (PV) generation would be largely linear. However, it has had to repeatedly increase these forecasts, as growth in solar PV accelerated. In 2012, for example, the IEA estimated that global solar energy generation would increase to 550 terawatt-hours in 2030, but that number was instead reached by 2018. More recent IEA projections for solar now account for some nonlinear acceleration, as adoption of supportive policies continues to increase (IEA 2022). However, the same linear assumptions are still being used for other technologies like electric vehicles (IEA 2023). For example, the IEA predicted that it would take four years (2021–2025) for light-duty all-electric vehicles and plug-in hybrid electric vehicles to grow from 9 percent to 13 percent, but it took only one year. Even if it is likely that most technologies will grow in a nonlinear manner, it is difficult to predict the exact path they will follow, which is one reason projections stick to linear assumptions. Linear assumptions often suffice for short-term projections, but longer-term projections should consider the potential for systems change and nonlinear growth.

When considering how to track nonlinear progress, it is important to consider that the adoption of new technologies has often followed a roughly S-curve trajectory (Figure 2). At the emergence stage of an S-curve, annual growth rates are high as promising research, development, and demonstration projects are under way, but adoption of the new technology remains quite low. Then, in the breakthrough stage, adoption of the technology bends upward, with sustained exponential growth rates. Once the technology begins to diffuse more widely, the rate of adoption of the technology reaches its steepest slope; and exponential growth begins to decay. Finally, as society reconfigures around the new technology, adoption reaches a saturation point, and growth rates approach zero. This S-curve concept can also be expanded beyond a specific technology to describe the broader transition from one socio-technical system to another, such as transformation across the entire power sector (Victor et al. 2019).

The point at which an S-curve reaches the breakthrough stage can also be conceptualized as a tipping point, defined broadly as a critical threshold beyond which a system reorganizes often abruptly or irreversibly (IPCC 2022). In the context of technology adoption, a tipping point generally occurs when the cost of a new technology falls below that of the incumbent, such that the value of switching to the new technology is greater than its cost. Factors

FIGURE 2 | Illustration of an S-curve



Source: Authors.

beyond monetary cost, such as an improvement in the technology or an increase in the value of the technology as more people adopt it, can also push technology adoption past a tipping point. Often, seemingly small changes in these factors can trigger disproportionately large responses within systems that catalyze the transition to different future states (Lenton et al. 2008; Lenton 2020).

Once tipping points are crossed, self-amplifying feedbacks help accelerate the diffusion of new technologies by lowering costs, enhancing performance, and increasing social acceptance (Arthur 1989; Lenton et al. 2008; Lenton 2020). Learning by doing in manufacturing, for example, can generate progressive advances that lead to more efficient production processes, while reaching economies of scale enables companies to progressively lower unit costs. Similarly, as complementary technologies (e.g., batteries) become increasingly available, they can boost functionality and accelerate the uptake of new innovations (e.g., electric vehicles) (Sharpe and Lenton 2021). These gains allow companies that adopt new technologies to expand their market share, deepen their political influence, and amass the resources needed to petition for more favorable policies. More supportive policies, in turn, can reshape the financial landscape in ways that incentivize investors to channel more capital into these new technologies (Butler-Sloss et al. 2021).[9] These reinforcing feedbacks spur adoption and help new innovations to supplant existing technologies (Victor et al. 2019).

Widespread adoption of new technologies, in turn, can have cascading effects, requiring the development of complementary innovations, the construction of supportive infrastructure, the adoption of new policies, and the creation of regulatory institutions. It can also prompt changes in business models, behaviors, social norms, and availability of jobs, thereby creating a new community of people who support (or sometimes oppose) further changes (Victor et al. 2019).

Meanwhile, incumbent technologies may become caught in a vicious spiral, as decreases in demand cause overcapacity and lead to lower utilization rates. These lower utilization rates, in turn, can increase unit costs and lead to stranded assets. Thus, for technologies with adoption rates that are already growing nonlinearly or could be expected to grow at an exponential pace in the future, it is unrealistic to assess progress by assuming that future uptake will follow a linear trajectory (Abramczyk et al. 2017; Mersmann et al. 2014; Trancik 2014).

Finally, it is important to note here that in addition to technology adoption, social and political forces can also contribute to or hinder nonlinear change (Moore et al. 2022). Our assessment of recent progress made toward near-term targets does not consider them fully, given the challenges of modeling these effects and data limitations. However, a body of research is emerging on this topic, and we will aim to consider these effects in future iterations of the platform as we expand the systems included.

Methodology for assessment of progress toward targets

To assess global progress made toward our targets, we first determine the likelihood that indicators will follow an S-curve and classify their trajectories as S-curve likely, S-curve possible, and S-curve unlikely. We then employ different methods to assess progress for each group of indicators.

Determining each indicator's potential for nonlinear change

We first evaluate the likelihood that each indicator will follow an S-curve trajectory in the future and place indicators into one of three categories based on our understanding of the literature and consultations with experts:

- *S-curve unlikely*: We identify indicators that we do not expect to follow the S-curve dynamics seen in technology diffusion, given that they do not directly track technology adoption. These often fall within systems related to agriculture, forestry, and other land uses, as well as finance (e.g., reforestation, ecosystem restoration, reducing food waste, increasing finance flows).
- *S-curve likely*: We consider indicators that directly track the adoption of specific technologies, or in some instances a set of closely related technologies, to be prime candidates for following S-curve dynamics. These technologies are innovative, often displacing incumbent technologies (e.g., zero-carbon electricity, electric vehicles, green hydrogen). Critically, categorizing an indicator as S-curve likely does not guarantee that it will experience rapid, nonlinear change over the coming years; rather, it signifies that, if and when adoption rates of these technologies begin to increase, such growth will likely follow an S-curve.
- *S-curve possible*: Finally, we identify indicators that do not fall neatly within the first two categories. These indicators do not track technology adoption directly, but adoption of new technologies will likely have some impact on their future trajectories, alongside many other factors, such as increases in resource efficiency. Thus, although these indicators have generally experienced linear growth in the past, they could experience some unknown form of nonlinear, exponential change in the coming decades if the nonlinear aspects grow to outweigh the linear aspects. For example, reducing carbon intensity in the power sector is dependent on multiple trends: an increase in the efficiency of fossil fuel power, which is linear; a switch between higher-emitting and lower-emitting fossil fuel power, which is generally nonlinear; and a switch from all types of fossil fuel power to zero-emissions power, which is expected to be nonlinear. If the nonlinear growth in zero emissions power overtakes the linear growth in efficiency, the trajectory of carbon intensity could follow an inverted S-curve.

S-curve unlikely indicators: assessment of progress based on linear trendline

For "S-curve unlikely" indicators with sufficient historical data, we calculate a linear trendline based on the most recent five years of data.[10] In some cases, most notably in the forests and land systems, we calculate a linear trendline based on the most recent 10 years of data to account for natural interannual variability, where possible.[11] We then extend this trendline out to the near-term target and compare this projected value to the indicator's target for that same year. Doing so enables us to assess whether or not recent progress made toward the target is on track.

Next, we calculate an "acceleration factor" for each indicator with sufficient historical data by dividing the average annual rate of change needed to achieve the indicator's near-term target[12] by the average annual rate of change derived from the historical five-year (or ten-year) trendline. For example, over the past five years, if an indicator has fallen on average by 5 units per year, but it needs to fall by 40 units on average every year until 2030; 40 units divided by 5 units equals an acceleration factor of eight times. These acceleration factors quantify the gap in global action between current efforts and the targets. They indicate whether recent historical rates of change need to increase by twofold, fivefold, or tenfold, for example, to meet near-term targets.[13] We then use these acceleration factors to assign our indicators one of six categories of progress:

Right Direction, On Track. The recent historical rate of change is equal to or above the rate of change needed. Indicators with acceleration factors between 0 and 1 fall under this status. However, we do not present these acceleration factors, since the indicators are on track.

Right Direction, Off Track. The historical rate of change is heading in the right direction at a promising yet insufficient pace. Extending the historical linear trendline would get the indicators more than halfway to their near-term targets. Indicators with acceleration factors between 1 and 2 fall under this status.

Right Direction, Well Off Track. The historical rate of change is heading in the right direction but well below the pace required to achieve the 2030 target. Extending the historical linear trendline would get them less than halfway to their near-term targets. Indicators with acceleration factors of greater than or equal to 2 fall under this status, meaning that they need to more than double their pace to be on track.

Right Direction, No Target. The historical rate of change is heading the right direction, but we do not have a specific target to evaluate whether it is on track, off track, or well off track.

Wrong Direction. The historical rate of change is heading in the wrong direction entirely. Indicators with negative acceleration factors fall under this status. However, we do not present acceleration factors for these indicators, as a reversal in the current trend is needed, rather than an acceleration of recent change.

Insufficient Data. Limited historical data make it impossible to estimate the historical rate of change relative to the required action.

Note that we calculate acceleration factors and assess progress needed to reach only the near-term (e.g., 2030) targets, not the long-term (e.g., 2050 targets) for the indicators that have them. We note any deviations in our methods of calculating acceleration factors in the indicator tooltip (e.g. the removal of the 2020 value from the calculation due to the COVID-19 pandemic, as described in Box 1).

BOX 1 | COVID-19's impact on assessment of progress

Government responses to the COVID-19 pandemic caused widespread changes in human behavior in 2020, such as people spending less time in commercial building spaces and making fewer trips, that likely affected many of the indicators tracked in this report. In some cases, these changes are likely to be temporary, as there is little evidence that they have spurred structural changes; and preliminary analysis suggests that GHG emissions are already rebounding (e.g., buildings-sector emissions dropped by around 10 percent from 2019 to 2020, but initial evidence from 2021 and 2022 suggests that emissions in the sector have already rebounded and the progress was likely not sustained (IEA 2022; UNEP 2021a).

But for others, new policies or practices adoption during COVID-19 may have long-term impacts (e.g., the rollback of environmental regulations in some countries or increased public financing for fossil fuels). It may take many decades to evaluate the permanence of measures adopted during the pandemic, as well as their impacts on global progress made toward our targets. Changes in carbon intensity indicators, for example, cannot be clearly attributed to measures adopted to slow the spread of COVID-19.

Thus, for each indicator with a 2020 data point, we include this value in our linear trendline calculations unless the latest science indicates that this change was temporary. We consider whether there has already been a rebound in annual data for 2021 or later. If annual data are not available, we consider semiannual data in our determination. We also consider other qualitative research and observations if necessary. In these instances where the change does appear to be temporary, we show the 2020 value in the chart, but exclude it from our linear trendline calculations and categorizations of progress. More specifically, if 2020 was our most recent year of data, we calculated the linear trendline based on five years of data from 2015 to 2019. But if 2020 was not the most recent data point and data were available after 2020, we calculated the linear trendline using four years of data, rather than five (e.g., a trendline of 2022, 2021, 2019, and 2018). The removal of the 2020 value is noted where applicable.

S-curve possible indicators: assessment of progress based on linear trendline

For indicators categorized as "S-curve possible," we follow the same methods as above and use a linear trendline to calculate acceleration factors and categorize progress, as recent historical data for these indicators have been following roughly linear trajectories. However, we note in our analysis that, should nonlinear change begin, progress could unfold at significantly faster rates than expected, and the gap between the existing rate of change and required action would shrink.

S-curve likely indicators: assessment of progress accounting for nonlinear change

For indicators that will likely follow an S-curve, acceleration factors based on linear trendlines would be inappropriate. Instead, we base our assessment of progress on multiple lines of evidence, including literature reviews, expert consultations, and fitting S-curves to the historical data where appropriate. More specifically, we follow these five steps:

Step 1: Calculate an acceleration factor following the methods described above and use this linear assessment as a starting point. While relying on a purely linear assessment of progress would be inappropriate, it does provide a baseline for some indicators' progress. For indicators in the early stages of an S-curve, for example, future growth will likely be steeper than the current linear trendline. But for other indicators in the later stages of an S-curve, future growth will likely be less steep than the current linear trendline. Given these limitations, we do not present acceleration factors in the report for "S-curve likely" indicators.

Step 2: Review the literature and consult with experts to consider nonlinear growth: For some indicators, existing literature evaluating their progress already employs a range of methodologies to consider nonlinear change. This could be in the academic peer-reviewed literature or the gray literature. For example, current policy projections from institutions like BloombergNEF and the IEA now account for nonlinear growth in some of their forecasts. We review these studies and reports to assess the likelihood that each indicator's future growth will outperform (or underperform) what is suggested by the linear trendline, weighing the results based on the methods' rigor and the extent to which consensus exists across sources. Given time constraints, we are not able to review all available literature. The literature review is particularly important when considering indicators that track the adoption of relatively nascent technologies, where data limitations prevent an analysis of five-year trends. If the literature shows that the development and deployment of these technologies is advancing, even in the emergence stage, we can reasonably say the indicator is progressing in the right direction but is "well off track" at a minimum. If the literature clearly indicates that a breakthrough is near, we consider upgrading the category further to "off track".

System experts around the world review our categorizations, commenting on the extent to which they agree with our assessment of each indicator's progress. We take these comments into consideration when categorizing progress.

Step 3: Consider what stage of an S-curve the indicator is in. The future path of an S-curve depends on which stage—emergence, breakthrough, diffusion, or reconfiguration—the technology is in. More specifically, our confidence that an indicator's growth will follow an S-curve in the near term increases as it moves from the emergence stage to the breakthrough stage, and the stage of the S-curve also affects whether future growth will outperform or underperform a linear trajectory.

To help identify which stage of an S-curve the indicator is in, we consider both the shape of the curve and how far the curve has progressed toward its saturation level (i.e., the maximum level that the indicator is expected to achieve). We first calculate what the current value of the indicator is as a proportion of its saturation level, which we assume is the same as the upper bound of the long-term target. For example, the share of electric vehicles in light-duty vehicle sales needs to reach 100 percent by 2035. The current share of 10 percent means that the indicator has achieved 10 percent of its final saturation level. In another example, green hydrogen production needs to reach 330 Mt by 2050. The current amount of 0.027 Mt means that the indicator has achieved 0.008 percent of its saturation value. These are not always perfect estimates but are useful approximations. Next, we evaluate each indicator's shape of change over the last five years by comparing the historical data to a linear trendline, an exponential trendline, and a logarithmic trendline. We determine which of these trendlines is the best fit to the historical data. Using these two elements, we place each indicator into one of the four stages of the S-curve.

- An indicator is in the **emergence stage** if the current value is less than 5 percent of the way to its saturation level, or if there are not enough data because the technology is so nascent.
- An indicator is in the **breakthrough stage** if the current value is between 5 percent and 50 percent of its saturation level, and the exponential trendline is the best fit for the past five years of data.
- An indicator is in the **diffusion stage** if the current value is between 5 percent and 80 percent of its saturation level, it is going upward, and the linear trendline is the best fit for the past five years of data.
- An indicator is in the **reconfiguration stage** if the current value is greater than 50 percent of its saturation level, and the logarithmic trendline is the best fit for the past five years of data.

We also determine instances in which an indicator is **not following a smooth S-curve** because none of these criteria are met. This is the case if an indicator is experiencing flat or logarithmic growth before reaching 50 percent of the saturation value or is going downward at any point. It also may be that no type of trendline is a good fit. Many technologies run into obstacles or barriers, which could prevent them from following a smooth S-curve.

Note that sources in the literature do not agree on where to delineate the stages of an S-curve or on the names for these stages. We have chosen the criteria above such that the stages have the most relevance for informing trajectories of future growth. We will continue to monitor the literature and consider the need to amend the stages or their criteria.

Step 4: Fit an S-curve to the existing historical data where appropriate. For indicators with sufficient data in the breakthrough, diffusion, or reconfiguration stages, we fit an S-curve to the historical data. We use a standard logistic S-curve function, which is based on three main inputs: the saturation level, which we assumed to be the indicator's long-term target; the maximum growth rate; and the midpoint of the S-curve. We then adjust the growth rate and the midpoint of the function until the S-curve most closely fit all historical data. To do this, we minimize the sum of squared residuals between the historical data and the S-curve.

We then compare the S-curve's projected value for 2030 to our near-term target for each indicator. An S-curve extrapolation above the target suggests that the indicator is "on track." An S-curve that gets more than half of the way from the current value and the 2030 target indicates that the indicator is likely to be "off track"; and if the extrapolation is less than half of the way from the current value to the 2030 target, the indicator is likely to be "well off track." For the few indicators for which this analysis is appropriate, we present the full results of the S-curve fitting in the appendix of the report.

For indicators in the emergence stage, we do not fit an S-curve to historical data due to uncertainties in the early stages. Rather, we default to "well off track" at a minimum in our categorization of progress. But where we find compelling evidence that a breakthrough was near based on the literature and expert consultation, we upgrade the indicator to a higher category than "well off track."

Similarly, for indicators that are not following a smooth S-curve, we do not fit an S-curve to the historical data, and we rely on linear acceleration factors, a review of the literature, and consultation with experts to assess recent progress.

Ultimately, determining whether "S-curve likely" indicators are on track or not carries considerable uncertainties, which is why we never use S-curve extrapolations as the only line of evidence for categorizing an indicator. Accurately projecting adoption rates for new technologies that are just beginning to emerge or diffuse across society is an enormously difficult endeavor. Any small fluctuations in the initial growth rate will create statistical noise, which introduces uncertainty into predictions that can reach orders of magnitude (Kucharavy and De Guio 2011; Crozier 2020; Cherp et al. 2021). Indeed, it is not until growth has reached its maximum speed (the steepest part of an S-curve trajectory) that robust projections for future growth can be made with more confidence (Cherp et al. 2021). Even then, additional assumptions must be made about the shape of the S-curve and the saturation point at which growth rates stabilize. For example, whether deceleration at the end of the S-curve mirrors the acceleration at the beginning significantly affects the speed at which a technology reaches full saturation. Yet no

S-curve in the real world is perfectly symmetric, and new evidence from past transitions suggests that S-curves can be highly asymmetric (Cherp et al. 2021). Technologies can also encounter obstacles as they diffuse—such as supply-chain constraints—that alter or limit the shape of the growth, but these challenges are similarly difficult to anticipate.

Step 5: Categorize progress. If we find relative consensus across multiple lines of evidence from the previous steps, then the decision is straightforward. If sources disagree, we make a judgment call about which lines of evidence are most compelling and explain our reasoning. We will likely adjust these methods as data availability improves and the literature on nonlinear growth increases. But given the immediate need to move beyond linear thinking, it is important to acknowledge and grapple with the possibility of nonlinear growth, while also recognizing that assessing it entails considerable uncertainties.

Drawing illustrative s-curves

In addition to fitting S-curves to the historical data for certain “S-curve likely” indicators to show the current trend, we also use S-curves to show one possible pathway for what is needed to meet the near-term and long-term targets, starting from wherever we are at today. These S-curves are simply illustrative drawings. They are not intended to be the only pathways to reach the targets and are not predicting what future growth will be. We use a simple logistic S-curve formula to create these figures but also adjust the S-curves manually in some cases to ensure they match up with the targets and are not too steep or shallow. Generally, our drawings are symmetrical, with the speed of acceleration in the first half mirrored by the speed of deceleration in the second half, but this may not be the case in reality. Another limitation is that when we draw S-curves, we ensure that the target years are aligned with 1.5°C, but we are not able to determine whether all the other years on the curve are consistent with 1.5°C based on an accounting of the carbon budget.

7. Selection of enablers and barriers

In addition to presenting targets and assessing progress made toward them, we also identify enabling conditions and barriers that influence systems change. These differ from the targets described above because they do not directly reflect progress on high-level outcomes (e.g., number of electric vehicles on the road, number of hectares reforested) that contribute to our goals of mitigating climate change, protecting biodiversity, and improving equity. Instead, they may contribute to or hinder the achievement of these targets. Given the complexity of determining causal connections, we present on the platform a range of significant enablers and barriers, rather than a comprehensive accounting of every possible enabler or barrier within each system.

The specific enabling conditions that support systems change range widely, but in the *State of Climate Action* series, we identified five common categories that enable climate action: innovations, regulations and incentives, strong institutions, leadership from key change agents, and shifts in behavior and social norms (Table 1). We use these same categories as the basis for identifying enabling conditions for the systems in the Systems Change Lab platform. While we present these five categories of enabling conditions as discrete from one another, we also recognize that, in reality, supportive measures may fall into more than one category.

Our selection of these five categories was informed by a review of the academic literature on transition, transformation, and systems change theory in the global environmental change research. We also assessed case studies of historical transitions of sociotechnical systems (e.g., power, transportation, and industry) and transformations of social-ecological systems (e.g., management of forests and wetlands).

We used these overarching categories of enabling conditions that support systems change to identify them for each shift. We reviewed the academic literature, as well as peer-reviewed, well-cited papers published by independent research institutions, United Nations agencies, and high-level sectoral coalitions (e.g., the Energy Transitions Commission and the High-Level Panel for a Sustainable Ocean

TABLE 1 | Enabling conditions for systems change for climate action

CATEGORIES OF ACTION	EXAMPLES OF SPECIFIC ACTIONS	DESCRIPTION (examples focus on climate action, but the categories of action can also be applied to other goals)
Innovations in Technology, Practices, and Approaches	Development and adoption of complementary technologies Investments in research and development Research networks and consortiums Education, knowledge sharing, and capacity building Experimentation, pilot projects, demonstrations, and other early application niches	Innovations, which broadly encompass new technologies, practices, and approaches, often offer solutions to seemingly intractable challenges. Investments in research and development, support for research networks and consortiums, and universal access to education provide a strong foundation for innovation. Similarly, creating protected spaces for experimentation, pilot projects, and small-scale demonstrations facilitates learning that can lead to improvements in performance and reductions in cost. Developing complementary technologies (e.g., batteries and charging infrastructure for electric vehicles) can also boost functionality and support widespread adoption of innovations.
Regulations and Incentives	Economic incentives, such as subsidies and public procurement; economic disincentives, such as subsidies reform, taxes, and financial penalties Noneconomic incentives, including removal of bureaucratic hurdles, measures that spotlight good or bad behavior to influence reputations, transitional support to affected communities, or giving ownership of natural resources to local communities Quotas, bans, regulations, and performance standards	By establishing standards, quotas, bans, or other command-and-control regulations, governments can not only mandate specific changes but also create a stable regulatory environment, often cited as a prerequisite for private-sector decarbonization. Using noneconomic or market-based instruments to create incentives (or disincentives) can also shape action from companies, nonprofit organizations, and individuals—and, in some contexts, may be more politically feasible than command-and-control regulations. For subsidies in particular, revenues must be raised to cover these costs, and the mechanisms to do so will also vary by system and region.
Strong Institutions	Establishment of international conventions, agreements, and institutions Creation of national ministries, agencies, or interagency task forces Changes in governance, such as more participatory, transparent decision-making processes or natural resource management Efforts to strengthen existing institutions by, for example, increasing staff, funds, or technological resources	Establishing new institutions or strengthening existing ones can ensure that the policies designed to reduce GHG emissions are effectively implemented. These institutions can enforce laws, monitor compliance with regulations, and penalize those who break the rules. Creating more transparent, participatory decision-making processes at all levels of government can also help reconfigure unequal power dynamics and enable marginalized communities—those who have often suffered from business-as-usual actions and who generally have the most to gain from transitions to new systems—to steer transformations to a net-zero future.

TABLE 1 | Enabling conditions for systems change for climate action (cont.)

CATEGORIES OF ACTION	EXAMPLES OF SPECIFIC ACTIONS	DESCRIPTION (examples focus on climate action, but the categories of action can also be applied to other goals)
Leadership from Change Agents	Leadership from national and subnational policymakers, such as setting ambitious targets and developing plans to achieve them Leadership from incumbents in the private sector, such as establishing ambitious climate commitments and adopting good practices to implement them Diverse, multistakeholder coalitions Beneficiaries of transitions Civil society movements	Successful transitions often depend on sustained, engaged leadership from a wide range of actors who envision new futures, develop road maps for change, initiate actions, and build coalitions of those willing to help implement these plans. While these champions may lead governments, companies, and nonprofit organizations, they need not always sit at the helm of an institution. Civil society organizations, as well as social movements, can effectively pressure those in power to accelerate transitions, and beneficiaries of these changes play an important role in resisting attempts to return to business as usual. Diverse, multistakeholder coalitions that bring these champions together can be a powerful force for change, unifying disparate efforts, pooling resources, and counterbalancing well-organized, influential incumbents.
Behavior Change and Shifts in Social Norms	Changes in behavior Shifts in social norms and cultural values	Through educational initiatives, public awareness campaigns, information disclosure, or targeted stakeholder engagement, agents of change can make a clear, compelling case for transitions, explain the consequences of inaction, and identify concrete steps that individuals can take to help collectively accelerate transitions. They can build consensus for a shared vision of the future, as well as prime people for behavior-change interventions. As social norms begin to shift, so too will the policies that communities support, the goods and services they demand, and their consumption patterns.

Sources: Enabling conditions were identified from a synthesis of the following studies: Chapin et al. 2010; Few et al. 2017; Folke et al. 2010; Geels et al. 2017a; Geels and Schot 2007; Hölscher et al. 2018; ICAT 2020; Levin et al. 2012; M.-L. Moore et al. 2014; Olsson et al. 2004; Otto et al. 2020; O'Brien and Sygna 2013; Patterson et al. 2017; Reyers et al. 2018; Sharpe and Lenton 2021; Sterl et al. 2017; Victor et al. 2019; Westley et al. 2011; Levin et al. 2020; Bergek et al. 2008; Hekkert et al. 2007.

Economy) to identify critical barriers to transformational change within each system, as well as key enabling conditions across these five overarching categories that may help decision-makers surmount such obstacles.

We also identified equity-related enabling conditions that apply to equity-related shifts and equity-related targets in other shifts. These enablers were selected based on the five categories, but not limited to those categories. So far, most of the enablers and barriers that we have included relate to just transition. These indicators were selected with three categories in mind: improving skills, institutional factors, and economic factors. For example, we selected enabling conditions related to the number of active programs to relocate fossil fuel workers to other jobs, the number of firms offering training in skills for clean energy, and the number of jobs in green sectors. Our analysis of equity-related enabling conditions and barriers will become more systematic and expansive as we develop the equity-focused systems on the platform and as we further explore equity considerations for all systems.

Exogenous changes, including both shocks (e.g., economic recessions, conflicts, or pandemics) and slower-onset events (e.g., demographic shifts), can also create windows of opportunity for transformation by destabilizing existing systems. These external forces, for example, can focus public attention on reducing previously unseen risks, motivate policymakers to adopt niche innovations to address new crises, or create space for leaders who support transforming existing systems to win elections. On the other hand, exogenous shocks can also spur backlash against change. Given that such crises are often immediate, unforeseen, and disruptive, we do not include them in our identification of enablers and barriers.

After we identify which enablers and barriers to focus on, we then attempt to find indicators and datasets that most closely reflect them. We specify whether each is an enabler or a barrier. Enablers help support transformations—for example, supportive policies, investments, and infrastructure.

Barriers prevent transformations—for example, high costs or unsupportive regulations. In a sense, many of these can be considered both enablers and barriers, because the lack of a supportive enabler can also be considered a barrier, while the removal of a barrier can enable change. However, we have attempted to specify whether which indicators are enablers and which are barriers as a helpful reference for the direction of change needed.

We do not identify targets for these enablers or barriers. Given that there are no targets, and that some are barriers while some others are supportive measures, it does not always mean that it is a positive development if the indicator is going up. In future updates of the Systems Change Lab platform, we plan to expand and improve our analysis of enablers and barriers across all of our goals.

8. Key limitations

Improvements to address these limitations will be sought in future iterations of the platform.

Incomplete consideration of all systems

We launched the Power, Industry, Transport, Technological Carbon Removal, and Finance systems alongside the original technical note in November 2022. This technical note is being updated in preparation for our additional system launches. Our upcoming systems focus on Cities, Buildings, Forests and Land, Oceans, Freshwater, Food and Agriculture, Circular Economy, Governance, Social Inclusion and Equity, and New Economics for Climate and Nature. As we add these systems, we will further refine our consideration of biodiversity and equity as they relate to the existing systems as well.

Lack of prioritization of systems, shifts, or targets

Systems change requires a complex web of shifts. Accordingly, this introduces limitations in the way that the findings on the Systems Change Lab can be interpreted.

On the platform, we do not evaluate which systems and shifts are more important than others in terms of reaching the overall goals of reducing climate change, protecting biodiversity, or improving equity. For example, in terms of climate, some systems are the cause of more emissions than others, but we do not rank or categorize these systems differently. Prioritization is challenging, in part, because there are many different criteria that could be applied (e.g., mitigation potential, contributions to all three goals, cost-effectiveness) and because these systems are related. For example, an increase in the use of renewable electricity in the power system will enable emissions reductions in other systems like transportation and industry, which need to shift to electrify a greater proportion of their energy use.

In addition, we do not systematically consider hierarchies, interconnections, or overlaps among indicators and targets. For example, in the power system, we have a shift, “rapidly scale up renewable energy generation,” which contains a hierarchy of indicators. In this shift, an increase in the indicator “annual capacity additions of renewable energy” contributes to the indicator “renewables share of total capacity,” which in turn contributes to the indicator “Share of zero-carbon power in electricity generation.” In this particular shift, the ultimate goal is a higher share of zero-carbon power in electricity generation, but we display data for all of these as indicators. In many cases, hierarchies among indicators are too complex to define. Interconnections among indicators are also complicated. For example, an increase in the “share of zero-carbon power in electricity generation” will likely have a corresponding decrease in the “share of coal in electricity generation,” which is part of a separate shift in the Power system. We present them as separate shifts, but these two transformations are happening in tandem, with each affecting the other and being affected by other shifts as well.

The shifts and targets on this platform are a complicated network of hierarchies, interconnections, and overlaps like these, so it is impossible to map out and communicate all these relationships. Likewise, we do not fully consider trade-offs between shifts and targets when there are multiple pathways to reach a goal, or there are goals that conflict with each other. For example, a shift to electric vehicles is needed to meet our climate goals, but it could have a negative impact on biodiversity due to the impacts of mining for critical minerals for EV batteries, or on equity if there are human rights violations in the course of the mining. This is why we track all of the goals separately: to ensure that progress on one does not lead to backsliding on the others.

Finally, some systems and some shifts have more indicators than others, but that does not mean that they are more important. It simply means that there are more discrete transformations that can help track progress toward the goal.

Therefore, simply counting the number of targets that are on track or off track cannot provide a complete picture of progress. If two of out five indicators in a particular shift are on track to meet their targets, it does not mean that that shift is 40 percent on track.

The Systems Change Lab will attempt to define these relationships more rigorously in the future by identifying causal connections, but a straightforward hierarchy is impossible given the nature of complex systems.

Constraints in aggregating climate targets

As described in “Selection of Targets and Indicators,” we selected near- and long-term targets for all sectors from a number of underlying sources and using a variety of methods—an approach that comes with several limitations. Because our targets are not all derived from one common model or model ensemble, we cannot definitively state that achieving all targets, together and on time, would collectively deliver all of the GHG emissions reductions and carbon removals needed to limit warming to 1.5°C with no or limited overshoot. Similarly, because the targets on this platform do not cover every single shift needed to transform all global systems, the collective mitigation potential of all targets together may also fall short of holding global temperature rise to 1.5°C. Rather, each individual target is aligned with a 1.5 °C pathway. We opted for this approach—adopting different targets from different studies—because there are merits and drawbacks to strategies for developing targets that vary significantly across each power, buildings, industry, transportation, technological carbon removal, land, food and agriculture, and finance. To accommodate these challenges, we strove to select the best available targets using the most appropriate and rigorous methods for each unique system. Doing so allowed us to identify targets across a more comprehensive set of GHG emissions–intensive sectors.

Finally, because we take the approach of aggregating individual 1.5°C-aligned targets across each of our eight systems, we cannot robustly account for interaction effects that likely occur between systems. For example, different models allocate different quantities of land for various emissions reduction and removal approaches. The competition for this land area for food production, energy production, carbon removal, and more may not be thoroughly accounted for when all targets are aggregated.

Challenges associated with global measurements of equity and biodiversity

Our methodological approach focuses on tracking global progress, and while considerable efforts have been made to develop worldwide indicators to monitor equity, as well as biodiversity and drivers of biodiversity loss, such as those supporting the post-2020 Global Biodiversity Framework and the Sustainable Development Goals, there are considerable challenges in aggregating highly localized indicators up to the global level. Commonly monitored water quality indicators, for example, typically include dissolved oxygen, total dissolved solids, and pH levels, among others. When considered together, these indicators can provide a comprehensive picture of levels of pollution in an aquatic ecosystem, but they cannot be tracked at a global level; nor can they be combined in a meaningful way. Instead, existing global indicators approximate water quality by tracking the proportion of domestic and industrial wastewater flows that are safely treated or the proportion of water bodies with good ambient water quality.

Equity indicators are even more complex, as “fairness” can be conceptualized differently across cultures, and historical patterns of marginalization vary immensely among countries. Moreover, indicators that are easier to track quantitatively—for example, those that monitor access—often measure binaries that leave out important nuance (e.g., does a person have access to electricity, yes or no?). But many people that technically have access to the service or good in question often struggle with quality issues, affordability, and more. Efforts are under way to adopt more nuanced definitions of access—for example, the World Bank's multi-tier framework for evaluating off-grid service provision—but that framework only includes data for a handful of countries.

Where possible, we plan to present disaggregated data (e.g., by nation, ecoregion, species type) alongside global data. But even these data may still only approximate changes in equity and biodiversity occurring at local levels. As we develop the Systems Change Lab platform, we will continue to explore approaches for managing this limitation and may revisit our current methods in the future.

Data limitations

A lack of high-quality, consistently updated, and publicly available data constrains our assessment of global progress across many systems and shifts. For some indicators, data are patchy, and continuous time series of annual data are not available. While the data that are available do provide some indication of progress, these data do not allow us to conduct robust trend analysis. Similarly, for other indicators, we could only find a single historical data point, and this lack of data prevented us from projecting a linear trendline and categorizing progress in a quantitative way. Still other indicators lacked even a single historical data point. We still present these on the platform to show that they are important, but we cannot present useful quantitative information. Likewise, we cannot assess progress for the indicators that do not have targets. Indicators without enough data or without targets are also important even though we are unable to categorize their progress. If data become available, we will add them to subsequent updates.

Inherent uncertainty of assessing nonlinear change

Assessing whether an indicator is on track to reach its targets comes with inherent uncertainties. Even at the outset, classifying indicators as "S-curve likely," "S-curve possible," or "S-curve unlikely" is subjective. While we used criteria to determine which indicators fit into which category, the decisions are not always clear-cut and we ultimately relied on author judgment to finalize them. Relatedly, the terms "likely," "possible," and "unlikely" also do not refer to specific likelihood percentiles, as they do in other research publications, such as IPCC reports. Instead, they are descriptive categories assigned by the authors based on the nature of the indicator (i.e., whether the indicator is based on technology adoption fully, partially, or not at all).

For "S-curve likely" indicators, if nonlinear change does occur, the shape of that change is impossible to predict in the early stages. Many of the technologies that we track in the platform are very early in their development, so small fluctuations in the growth rate introduce uncertainty into predictions (Kucharavy and De Guio 2011; Crozier 2020; Cherp et al. 2021). Moreover, with limited data, we cannot yet know what the exact shape, midpoint, or saturation point of an S-curve will be. This is why we relied on author judgment based on a variety of factors in addition to S-curve fitting to determine whether "S-curve likely" indicators are on track. And, as described in "Methodology for assessment of progress toward targets," when we present S-curves in this report, either as current trendlines or as indications of the pace needed to reach targets, they are for illustrative purposes.

For the "S-curve possible" indicators, many of these same limitations also apply. Moreover, even for the "S-curve unlikely" indicators, there is still some nonquantifiable possibility of nonlinear change. For indicators within both categories, we default our methods to looking at acceleration factors assuming continued linear change, as described above. However, these values should be seen as just a general guide to inform how much faster change needs to occur compared to what has occurred over the past five years. We do not make quantitative predictions based on changing economics, supply-chain constraints, or expected policy factors, and we acknowledge that there are multiple potential pathways that these targets may follow.

Lack of causal analysis to identify enablers and barriers

The enabling conditions and barriers that we present on the platform are by no means exhaustive, given how complex systems change can be. Rather, they represent a critical subset of relevant factors that may contribute to or stymie these shifts. We did not conduct a causal analysis to ensure that the enablers and barriers we included for a given system directly contribute to our targets in that system. Likewise, we did not prioritize between the enablers and barriers included on the platform when there were multiple pathways to achieve transformation or when there were trade-offs between pursuing one pathway versus another.

Given how complex systems change can be, there is no perfect way to arrange the enablers and barriers. Some of the enabling conditions contribute to a specific target, while others promote general progress within a shift. Enabling conditions may also contribute to other enabling conditions. In some cases, the shifts themselves may act as enabling conditions for other shifts, which means that it is sometimes difficult to disentangle the shifts from the factors that support them.

Despite these limitations, our aim is to provide useful information for users of the platform to further understand what is happening in the world beyond the targets alone.

ENDNOTES

1. The IPCC developed its category of "no and limited overshoot" pathways in its Special Report on Global Warming of 1.5°C. The IPCC's recent AR6 Working Group III report, Climate Change 2022: Mitigation of Climate Change, uses the same definition for its category C1 pathways, which are defined as follows: "Category C1 comprises modelled scenarios that limit warming to 1.5°C in 2100 with a likelihood of greater than 50%, and reach or exceed warming of 1.5°C during the 21st century with a likelihood of 67% or less. In this report, these scenarios are referred to as scenarios that limit warming to 1.5°C (>50%) with no or limited overshoot. Limited overshoot refers to exceeding 1.5°C global warming by up to about 0.1°C and for up to several decades" (IPCC 2022). The report also notes that "Scenarios in this category are found to have simultaneous likelihood to limit peak global warming to 2°C throughout the 21st century of close to and more than 90%" (IPCC 2022).

2. It is important to note here that, given the nature of links between systems, moving more slowly in one system may in some cases make it harder to move faster in another; for example, electric vehicle uptake in the transportation system cannot adequately decarbonize the system until the emissions intensity of the power system declines.

3. Benchmarks from the IPCC's AR6 will continue to be incorporated more comprehensively in future iterations of the Systems Change Lab platform.

4. It is important to note here that, because some of our targets call for reductions (e.g., phasing out of coal), the lower bound of a target range is not always the less ambitious bound.

5. Many IAMs still do not represent direct air capture with carbon storage (DACCS) at all, nor do they represent low-temperature direct air capture technology, which offers the most promising route for DACCS deployment. Pathways with more DACCS deployment tend to rely less heavily on BECCS. We applied a less stringent threshold for BECCS, based on the assessment that DACCS potential is likely underestimated in most IAM scenarios. However, we did not consider BECCS a perfect proxy for other technical carbon dioxide removal options because of the different land and energy system implications (e.g., BECCS produces energy while DACCS uses energy, so they cannot be seen as interchangeable from a modeling perspective). As modelers strive to represent a wider range of carbon removal technologies in IAMs, this approach could evolve to include specific filters for individual carbon removal technologies. However, given pervasive uncertainty around the feasibility of large-scale carbon removal technologies, the most robust strategy remains to cut GHG emissions as fast as possible to minimize reliance on these nascent innovations.

6. Grant et al. (2021) used expert interviews to determine limits for A/R of 3.6 $GtCO_2$/yr in 2050 and 5.3 $GtCO_2$/yr in 2100. We filtered pathways so that the average A/R deployment over 2050–2100 doesn't exceed the average of these two limits (4.4 $GtCO_2$/yr).

7. It is important to distinguish between CCS used for emissions reductions (e.g., from fossil fuel combustion and in industrial applications) and technological carbon dioxide removal applications that rely on geological CO_2 storage. In the former, CCS reduces fossil fuel or industrial process emissions, although in many cases there are alternative decarbonization options that could do so more cheaply and/or sustainably. In the latter, the net effect of capturing and storing CO_2 in geological storage is a removal or negative emission, which is important for ultimately lowering atmospheric CO_2 concentrations. There are two main types of carbon dioxide removal in this category. Direct air capture and storage involves capturing the CO_2 that is already in the atmosphere, rather than from an emissions source. BECCS involves the application of CCS technology to a bioenergy facility, meaning that biogenic CO_2 is captured and stored. Since CO_2 is drawn down as the bioenergy feedstocks grow, BECCS can also lead to removals.

8. An exception is a variation on CCUS—the Allam Cycle—which is in development and involves combustion of natural gas in a high oxygen environment. It would theoretically be able to capture 100 percent of direct emissions from natural gas combustion and has been demonstrated at a 50-megawatt scale, but not yet at a large scale (Yellen 2020).

9. While discussed in the context of low-carbon technologies, this self-amplifying feedback loop is not inherently positive. Private-sector institutions that expand their market shares, deepen their political influence, and amass the resources needed to petition for more supportive policies do not always use their power for the public good. Some may leverage their influence to advance their own interests that are odds with societal goals (e.g., tampering innovation of other low-carbon technologies, advocating for less restrictive regulations across other environmental harms, petitioning for policies that protect their profit margins). Governments have a critical role to play in effectively regulating the private sector on behalf of the public and in service to societal goals.

10. In some cases, if we do not have five years of historical data to calculate a line of best fit but do have the values for five years ago and today, we simply draw a straight line between the two and use that as the trajectory of progress. Deviations from our standard methods are noted accordingly.

11. Deviations from our standard method are noted accordingly.

12. Note that for the indicators with targets presented as a range, we assess progress based on the midpoint of that range—that is, we compare the historical rates of change to the rates of change required to reach the midpoint.

13. For acceleration factors between 1 and 2, we round to the tenth place (e.g., 1.2 times); for acceleration factors between 2 and 3, we round to the nearest half number (e.g. 2.5 times); for acceleration factors between 3 and 10, we round to the nearest whole number (e.g. 7 times); and for acceleration factors higher than 10, we note as >10.

REFERENCES

Abramczyk, Marshall, Martha Campbell, Aman Chitkara, Mia Diawara, Aileen Lerch, and James Newcomb. 2017. *Positive Disruption: Limiting Global Temperature Rise to Well Below 2 C°.* Basalt, CO: Rocky Mountain Institute. https://rmi.org/insight/positive_disruption_limiting_global_temperature_rise/.

Arthur, W. Brian. 1989. "Competing Technologies, Increasing Returns, and Lock-In by Historical Events." *Economic Journal* 99 (394): 116. https://doi.org/10.2307/2234208.

Bergek, Anna, Staffan Jacobsson, Bo Carlsson, Sven Lindmark, and Annika Rickne. 2008. "Analyzing the Functional Dynamics of Technological Innovation Systems: A Scheme of Analysis." *Research Policy* 37 (3): 407–29. https://doi.org/10.1016/j.respol.2007.12.003.

Biggs, Reinette, Frances Westley, and Stephen Carpenter. 2010. "Navigating the Back Loop: Fostering Social Innovation and Transformation in Ecosystem Management." *Ecology and Society* 15 (2). https://doi.org/10.5751/ES-03411-150209.

BloombergNEF. 2021. *Electric Vehicle Outlook* 2021. New York: BloombergNEF. https://about.bnef.com/electric-vehicle-outlook/.

Boehm, Sophie, Katie Lebling, Kelly Levin, Hanna Fekete, Joel Jaeger, Richard Waite, Anna Nilsson, et al. 2021. *State of Climate Action 2021: Systems Transformations Required to Limit Global Warming to 1.5°C.* Washington, DC: World Resources Institute. https://www.wri.org/research/state-climate-action-2021.

Boehm, Sophie, Louise Jeffery, Kelly Levin, Judit Hecke, Clea Schumer, Claire Fyson, Aman Majid, and Joel Jaeger. 2022. *State of Climate Action* 2022. Washington, DC: World Resources Institute.

Brandl, Patrick, Mai Bui, Jason P. Hallett, and Niall Mac Dowell. 2021. "Beyond 90% Capture: Possible, but at What Cost?" *International Journal of Greenhouse Gas Control* 105 (February):103239. doi:10.1016/j.ijggc.2020.103239.

Butler-Sloss, Sam, Kingsmill Bond, and Harry Benham. 2021. *Spiralling Disruption: The Feedback Loops of the Energy Transition.* London: Carbon Tracker. https://carbontracker.org/reports/spiralling-disruption/.

Chapin, F. Stuart, Stephen R. Carpenter, Gary P. Kofinas, Carl Folke, Nick Abel, William C. Clark, Per Olsson, et al. 2010. "Ecosystem Stewardship: Sustainability Strategies for a Rapidly Changing Planet." *Trends in Ecology & Evolution* 25 (4): 241–49. https://doi.org/10.1016/j.tree.2009.10.008.

Cherp, Aleh, Vadim Vinichenko, Jale Tosun, Joel Gordon, and Jessica Jewell. 2021. "National Growth Dynamics of Wind and Solar Power Compared to the Growth Required for Global Climate Targets." *Nature Energy* 6: 742–54. https://doi.org/10.1038/s41560-021-00863-0.

Climate Action Tracker. 2020a. *Paris Agreement Compatible Sectoral Benchmarks: Methods Report.* Berlin, Germany: Climate Action Tracker. https://climateactiontracker.org/documents/753/CAT_2020-07-10_ParisAgreementBenchmarks_FullReport.pdf.

Climate Action Tracker. 2020b. *Paris Agreement Compatible Sectoral Benchmarks: Summary Report.* Berlin, Germany: Climate Action Tracker. https://climateactiontracker.org/documents/754/CAT_2020-07-10_ParisAgreementBenchmarks_SummaryReport.pdf.

Climate Action Tracker. 2023. *Methodology for 1.5°C Compatible Sectoral Benchmarks.* Berlin, Germany: Climate Action Tracker. https://climateactiontracker.org/publications/paris-aligned-benchmarks-power-sector/.

Climate Analytics. 2023. *2030 Targets Aligned to 1.5°C; Evidence from the Latest Global Pathways.* Berlin: Climate Analytics. https://climateanalytics.org/media/2030_targets_for_1-5.pdf.

Crozier, Constance. 2020. "Forecasting S-Curves Is Hard." Blog. April 16. https://constancecrozier.com/2020/04/16/forecasting-s-curves-is-hard/.

Creutzig, F., K-H. Erb, H. Haberl, C. Hof, C. Hunsberger, and S. Roe. 2021. "Considering Sustainability Thresholds for BECCS in IPCC and Biodiversity Assessments." *GCB Bioenergy* 13 (4): 510–15. https://doi.org/10.1111/gcbb.12798.

Fajardy, M., A. Köberle, N. MacDowell, and A. Fantuzzi. 2019. "BECCS Deployment: A Reality Check." Grantham Institute Briefing Paper No. 28. London: Imperial College London. https://www.imperial.ac.uk/media/imperial-college/grantham-institute/public/publications/briefing-papers/BECCS-deployment---a-reality-check.pdf.

Feola, Giuseppe. 2015. "Societal Transformation in Response to Global Environmental Change: A Review of Emerging Concepts." *Ambio* 44 (5): 376–90. https://doi.org/10.1007/s13280-014-0582-z.

Few, Roger, Daniel Morchain, Dian Spear, Adelina Mensah, and Ramkumar Bendapudi. 2017. "Transformation, Adaptation and Development: Relating Concepts to Practice." *Palgrave Communications* 3 (1): 17092. https://doi.org/10.1057/palcomms.2017.92.

Folke, Carl, Stephen Carpenter, Brian Walker, Marten Scheffer, Terry Chapin, and Johan Rockström. 2010. "Resilience Thinking: Integrating Resilience, Adaptability and Transformability." *Ecology and Society* 15 (4). https://doi.org/10.5751/ES-03610-150420.

Fuss, Sabine, William F. Lamb, Max W. Callaghan, Jerome Hilaire, Felix Creutzig, Thorben Amann, Tim Beringer, et al. 2018. "Negative Emissions—Part 2: Costs, Potentials and Side Effects." *Environmental Research Letters* 13 (6):063002. doi:10.1088/1748-9326/aabf9f.

Geels, Frank W., and Johan Schot. 2007. "Typology of Sociotechnical Transition Pathways." *Research Policy* 36 (3): 399–417. https://doi.org/10.1016/j.respol.2007.01.003.

Geels, Frank W., Benjamin K. Sovacool, Tim Schwanen, and Steve Sorrell. 2017a. "Sociotechnical Transitions for Deep Decarbonization." *Science* 357 (6357): 1242–44. https://doi.org/10.1126/science.aao3760.

Geels, Frank W., Benjamin K. Sovacool, Tim Schwanen, and Steve Sorrell. 2017b. "The Socio-Technical Dynamics of Low-Carbon Transitions." *Joule* 1 (3): 463–79. https://doi.org/10.1016/j.joule.2017.09.018.

Grant, N., A. Hawkes, S. Mittal, and A. Gambhir. 2021. “The Policy Implications of an Uncertain Carbon Dioxide Removal Potential.” *Joule* 5 (10): 2593–2605. https://doi.org/10.1016/j.joule.2021.09.004.

Grin, John, Jan Rotmans, and Johan Schot. 2010. *Transitions to Sustainable Development: New Directions in the Study of Long-Term Transformative Change*. Oxfordshire, UK: Routledge. https://www.routledge.com/Transitions-to-Sustainable-Development-New-Directions-in-the-Study-of-Long/Grin-Rotmans-Schot/p/book/9780415898041.

Griscom, Bronson W., Justin Adams, Peter W. Ellis, Richard A. Houghton, Guy Lomax, Daniela A. Miteva, William H. Schlesinger, et al. 2017. “Natural Climate Solutions.” *Proceedings of the National Academy of Sciences* 114 (44): 11645–50. https://doi.org/10.1073/pnas.1710465114.

Hanssen, S.V., Z.J.N. Steinmann, V. Daioglou, M. Čengić, D.P. Van Vuuren, and M.A.J. Huijbregts. 2022. “Global Implications of Crop-Based Bioenergy with Carbon Capture and Storage for Terrestrial Vertebrate Biodiversity.” *Global Change Biology—Bioenergy* 14 (3): 307–21. https://doi.org/10.1111/gcbb.12911.

Heffron, Raphael J., and Darren McCauley. 2017. “The Concept of Energy Justice across the Disciplines.” *Energy Policy* 105 (June): 658–67. https://doi.org/10.1016/j.enpol.2017.03.018.

Heffron, Raphael J., and Darren McCauley. 2022. “The ‘Just Transition’ Threat to Our Energy and Climate 2030 Targets.” *Energy Policy* 165 (June): 112949. https://doi.org/10.1016/j.enpol.2022.112949.

Hekkert, Marko P., R.A.A. Suurs, S.O. Negro, S. Kuhlmann, and R.E.H.M. Smits. 2007. “Functions of Innovation Systems: A New Approach for Analysing Technological Change.” *Technological Forecasting and Social Change* 74 (4): 413–32. https://doi.org/10.1016/j.techfore.2006.03.002.

Holland, John H. 2000. *Emergence: From Chaos to Order*. Oxford, UK: Oxford University Press. https://books.google.com/books/about/Emergence.html?id=JINlW1XziBUC.

Hölscher, Katharina, Julia M. Wittmayer, and Derk Loorbach. 2018. “Transition versus Transformation: What’s the Difference?” *Environmental Innovation and Societal Transitions* 27 (June): 1–3. https://doi.org/10.1016/j.eist.2017.10.007.

ICAT (Initiative for Climate Action Transparency). 2020. *Transformational Change Methodology: Assessing the Transformational Impacts of Policies and Actions*. Copenhagen and Washington, DC: ICAT, United Nations Environment Programme DTU Partnership, and World Resources Institute. https://climateactiontransparency.org/wp-content/uploads/2020/04/Transformational-Change-Assessment-Guide.pdf.

IEA (International Energy Agency). 2021a. *Net Zero by 2050: A Roadmap for the Global Energy Sector*. Paris: IEA. https://www.iea.org/reports/net-zero-by-2050. Accessed January 2024.

IEA. 2022. *World Energy Outlook 2022*. Paris: IEA. https://www.iea.org/reports/world-energy-outlook-2022.

IEA. 2023. *Global EV Data Explorer*. Paris: IEA. https://www.iea.org/data-and-statistics/data-tools/global-ev-data-explorer. Accessed August 2023.

IIASA (International Institute for Applied Systems Analysis). n.d. (Database.) *AR6 Scenario Explorer and Database*. https://iiasa.ac.at/models-tools-data/ar6-scenario-explorer-and-database. Accessed June 27, 2023.

ILO (International Labour Organization). 2015. *Guidelines for a Just Transition towards Environmentally Sustainable Economies and Societies for All*. Geneva: International Labour Organization. https://www.ilo.org/global/topics/green-jobs/publications/WCMS_432859/lang—en/index.htm. Accessed January 2024.

IPBES (Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services). 2019. *Global Assessment Report on Biodiversity and Ecosystem Services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services,* edited by Eduardo Brondizio, Josef Settele, Sandra Díaz, and Hien Ngo. Bonn, Germany: IPBES secretariat. https://doi.org/10.5281/zenodo.3831673.

IPCC (Intergovernmental Panel on Climate Change). 2018. *Global Warming of 1.5°C. An IPCC Special Report on the Impacts of Global Warming of 1.5°C above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty,* edited by Valérie Masson-Delmotte, Panmao Zhai, Hans-Otto Pörtner, Debra Roberts, Jim Skea, Priyadarshi R. Shukla, Anna Pirani, et al. Geneva, Switzerland: IPCC. https://www.ipcc.ch/site/assets/uploads/sites/2/2019/06/SR15_Full_Report_High_Res.pdf.

IPCC. 2022. *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change,* edited by P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, et al. Cambridge, UK, and New York: Cambridge University Press. https://www.ipcc.ch/report/ar6/wg3/.

Kucharavy, Dmitry, and Roland De Guio. 2011. “Logistic Substitution Model and Technological Forecasting.” *Procedia Engineering*, Proceeding of the ETRIA World TRIZ Future Conference, 9 (January): 402–16. https://doi.org/10.1016/j.proeng.2011.03.129.

Lenton, Timothy M., Hermann Held, Elmar Kriegler, Jim W. Hall, Wolfgang Lucht, Stefan Rahmstorf, and Hans Joachim Schellnhuber. 2008. “Tipping Elements in the Earth’s Climate System.” *Proceedings of the National Academy of Sciences* 105 (6): 1786–93. https://doi.org/10.1073/pnas.0705414105.

Lenton, Timothy M. 2020. “Tipping Positive Change.” *Philosophical Transactions of the Royal Society B: Biological Sciences* 375 (1794): 20190123. https://doi.org/10.1098/rstb.2019.0123.

Levin, Kelly, Benjamin Cashore, Steven Bernstein, and Graeme Auld. 2012. “Overcoming the Tragedy of Super Wicked Problems: Constraining Our Future Selves to Ameliorate Global Climate Change.” *Policy Sciences* 45 (2): 123–52. https://doi.org/10.1007/s11077-012-9151-0.

Levin, Kelly, Sophie Boehm, Neelam Singh, Anne Maassen, Madeleine Galvin, Fiona McRaith, Renilde Becqué, et al. 2020. *Safeguarding Our Global Commons: A Systems Change Lab to Monitor, Learn From, and Advance Transformational Change*. Washington, DC: World Resources Institute. https://globalcommonsalliance.org/wp-content/uploads/2020/12/Systems-Change-Paper.pdf.

Meadows, Donella H. 2008. *Thinking in Systems: A Primer*. Hartford, VT: Chelsea Green Publishing. https://books.google.com/books/about/Thinking_in_Systems.html?id=CpbLAgAAQBAJ&source=kp_book_description.

Mersmann, Florian, Timon Wehnert, Maja Göpel, Sophie Arens, and Orsolya Ujj. 2014. *Shifting Paradigms: Unpacking Transformation for Climate Action; a Guidebook for Climate Finance & Development Practitioners*. Wuppertal Institute for Climate, Environment and Energy. https://epub.wupperinst.org/frontdoor/index/index/docId/5518. Accessed January 2024.

Moore, Frances C., Katherine Lacasse, Katharine J. Mach, Yoon Ah Shin, Louis J. Gross, and Brian Beckage. 2022. "Determinants of Emissions Pathways in the Coupled Climate–Social System." *Nature* 603 (7899): 103–11. https://doi.org/10.1038/s41586-022-04423-8.

Moore, Michele-Lee, Ola Tjornbo, Elin Enfors, Corrie Knapp, Jennifer Hodbod, Jacopo A. Baggio, Albert Norström, et al. 2014. "Studying the Complexity of Change: Toward an Analytical Framework for Understanding Deliberate Social-Ecological Transformations." *Ecology and Society* 19 (4): art54. https://doi.org/10.5751/ES-06966-190454.

Muñoz Cabré, Miquel, and José Antonio Vega Araújo. 2022. "Considerations for a Just and Equitable Energy Transition - Stockholm+50 Background Paper Series." Stockholm, Sweden: Stockholm Environment Institute. https://www.sei.org/publications/just-equitable-energy-transition/. Accessed January 2024.

O'Brien, Karen, and Linda Sygna. 2013. "Responding to Climate Change: The Three Spheres of Transformation." In *Proceedings Transformation in a Changing Climate*, International Conference in Oslo, June 19–21, 2013., 16–23. Oslo, Norway: University of Oslo. https://www.sv.uio.no/iss/english/research/projects/adaptation/publications/1-responding-to-climate-change---three-spheres-of-transformation_obrien-and-sygna_webversion_final.pdf.

Okereke, Chukwumerije. 2018. "Equity and Justice in Polycentric Climate Governance." In *Governing Climate Change*, edited by Andrew Jordan, Dave Huitema, Harro van Asselt, and Johanna Forster, 1st ed., 320–37. Cambridge, United Kingdom: Cambridge University Press. https://doi.org/10.1017/9781108284646.019.

Olsson, Per, Carl Folke, and Thomas Hahn. 2004. "Social-Ecological Transformation for Ecosystem Management: The Development of Adaptive Co-Management of a Wetland Landscape in Southern Sweden." *Ecology and Society* 9 (4). https://doi.org/10.5751/ES-00683-090402.

Olsson, Per, Lance H. Gunderson, Steve R. Carpenter, Paul Ryan, Louis Lebel, Carl Folke, and C.S. Holling. 2006. "Shooting the Rapids: Navigating Transitions to Adaptive Governance of Social-Ecological Systems." *Ecology and Society* 11 (1): art18. https://doi.org/10.5751/ES-01595-110118.

Otto, Ilona M., Jonathan F. Donges, Roger Cremades, Avit Bhowmik, Richard J. Hewitt, Wolfgang Lucht, Johan Rockström, et al. 2020. "Social Tipping Dynamics for Stabilizing Earth's Climate by 2050." *Proceedings of the National Academy of Sciences* 117 (5): 2354–65. https://doi.org/10.1073/pnas.1900577117.

Patterson, James, Karsten Schulz, Joost Vervoort, Sandra van der Hel, Oscar Widerberg, Carolina Adler, Margot Hurlbert, Karen Anderton, Mahendra Sethi, and Aliyu Barau. 2017. "Exploring the Governance and Politics of Transformations towards Sustainability." *Environmental Innovation and Societal Transitions* 24 (September): 1–16. https://doi.org/10.1016/j.eist.2016.09.001.

Puri, Jyotsna. 2018. "Transformational Change: The Challenge of a Brave New World." Incheon, Republic of Korea: Green Climate Fund Independent Evaluation Unit. https://www.cbd.int/doc/presentations/tc-imrr/Learning-Paper-1.pdf.

Putnam-Walkerly, Kris, and Elizabeth Russell. 2016. "The Road to Achieving Equity: Findings and Lessons from a Field Scan of Foundations That Are Embracing Equity as a Primary Focus." Putnam Consulting Group. http://putnam-consulting.com/wp-content/uploads/Equity-Field-Scan_Layout_FINAL.pdf.

Reyers, Belinda, Carl Folke, Michele-Lee Moore, Reinette Biggs, and Victor Galaz. 2018. "Social-Ecological Systems Insights for Navigating the Dynamics of the Anthropocene." *Annual Review of Environment and Resources* 43 (1): 267–89. https://doi.org/10.1146/annurev-environ-110615-085349.

Robertson, B., and M. Mousavian. 2022. *The Carbon Capture Crux: Lessons Learned*. Lakewood, OH: Institute for Energy Economics and Financial Analysis. https://ieefa.org/resources/carbon-capture-crux-lessons-learned.

Roe, Stephanie, Charlotte Streck, Robert Beach, Jonah Busch, Melissa Chapman, Vassilis Daioglou, Andre Deppermann, et al. 2021. "Land-Based Measures to Mitigate Climate Change: Potential and Feasibility by Country." *Global Change Biology* 27 (23): 6025–58. https://doi.org/10.1111/gcb.15873.

Rotmans, Jan, and Derk Loorbach. 2009. "Complexity and Transition Management." *Journal of Industrial Ecology* 13 (2): 184–96. https://doi.org/10.1111/j.1530-9290.2009.00116.x.

Sachs, Jeffrey D., Guido Schmidt-Traub, Mariana Mazzucato, Dirk Messner, Nebojsa Nakicenovic, and Johan Rockström. 2019. "Six Transformations to Achieve the Sustainable Development Goals." *Nature Sustainability* 2 (9): 805–14. https://doi.org/10.1038/s41893-019-0352-9.

Schumer, Clea, Joel Jaeger, Sophie Boehm, Louise Jeffery, Kelly Levin, Judit Hecke, and Claire Fyson. 2022. *Methodology Underpinning the State of Climate Action Series*. Washington, DC: World Resources Institute.

Searchinger, Tim, Richard Waite, Craig Hanson, Janet Ranganathan, Patrice Dumas, and Emily Matthews. 2019. *World Resources Report: Creating a Sustainable Food Future—A Menu of Solutions to Feed Nearly 10 Billion People by 2050*. Washington, D.C.: World Resources Institute. www.sustainablefoodfuture.org.

Searchinger, Tim, Jessica Zionts, Stefan Wirsenius, Liqing Peng, Tim Beringer, and Patrice Dumas. 2021. *A Pathway to Carbon Neutral Agriculture in Denmark*. Washington, DC: World Resources Institute. https://www.wri.org/research/pathway-carbon-neutral-agriculture-denmark.

Seto, Karen C., Steven J. Davis, Ronald B. Mitchell, Eleanor C. Stokes, Gregory Unruh, and Diana Ürge-Vorsatz. 2016. "Carbon Lock-In: Types, Causes, and Policy Implications." *Annual Review of Environment and Resources* 41 (1): 425–52. https://doi.org/10.1146/annurev-environ-110615-085934.

Sharpe, Simon, and Timothy M. Lenton. 2021. "Upward-Scaling Tipping Cascades to Meet Climate Goals: Plausible Grounds for Hope." *Climate Policy* 21 (4): 421–33. https://doi.org/10.1080/14693062.2020.1870097.

Steffen, Will, Johan Rockström, Katherine Richardson, Timothy M. Lenton, Carl Folke, Diana Liverman, Colin P. Summerhayes, et al. 2018. "Trajectories of the Earth System in the Anthropocene." *Proceedings of the National Academy of Sciences* 115 (33): 8252–59. https://doi.org/10.1073/pnas.1810141115.

Sterl, Sebastian, Markus Hagemann, Hanna Fekete, Niklas Höhne, Karlien Wouters, Yvonne Deng, Kornelis Blok, et al. 2017. *Kick-Starting Global Decarbonization: It Only Takes a Few Actors to Get the Ball Rolling*. Berlin, Germany: NewClimate Institute, Ecofys, Climate Analytics, and ClimateWorks Foundation. https://climateactiontracker.org/documents/354/CAT_2017-04-20_Faster-Cleaner-2_Technical-Report.pdf.

Termeer, Catrien J.A.M., Art Dewulf, and G. Robbert Biesbroek. 2017. "Transformational Change: Governance Interventions for Climate Change Adaptation from a Continuous Change Perspective." *Journal of Environmental Planning and Management* 60 (4): 558–76. https://doi.org/10.1080/09640568.2016.1168288.

Trancik, Jessika E. 2014. "Renewable Energy: Back the Renewables Boom." *Nature* 507 (7492): 300–302. https://doi.org/10.1038/507300a.

UNFCCC (United Nations Framework Convention on Climate Change) Secretariat. 2021. *Transforming Our Systems Together: A Global Challenge to Accelerate Sector Breakthroughs for COP26—and Beyond*. Bonn, Germany: UNFCCC Secretariat. https://racetozero.unfccc.int/wp-content/uploads/2021/02/Race-to-Zero-Breakthroughs-Transforming-Our-Systems-Together.pdf.

United Nations. 2019. *Global Sustainable Development Report 2019: The Future Is Now – Science for Achieving Sustainable Development*. New York: United Nations. https://sustainabledevelopment.un.org/content/documents/24797GSDR_report_2019.pdf.

Victor, David G., Frank W. Geels, and Simon Sharpe. 2019. *Accelerating the Low Carbon Transition: The Case for Stronger, More Targeted and Coordinated International Action*. Washington, DC: Brookings Institution. https://www.brookings.edu/wp-content/uploads/2019/12/Coordinatedactionreport.pdf.

Waddell, Steve, Sandra Waddock, Sarah Cornell, Domenico Dentoni, Milla McLachlan, and Greta Meszoely. 2015. "Large Systems Change: An Emerging Field of Transformation and Transitions." *Journal of Corporate Citizenship* 2015 (58): 5–30. https://doi.org/10.9774/GLEAF.4700.2015.ju.00003.

Walker, Brian, C. S. Holling, Stephen R. Carpenter, and Ann P. Kinzig. 2004. "Resilience, Adaptability and Transformability in Social-Ecological Systems." *Ecology and Society* 9 (2): art5. https://doi.org/10.5751/ES-00650-090205.

WBCSD (World Business Council for Sustainable Development). 2021. *Vision 2050: Time to Transform*. Geneva, Switzerland: WBCSD. https://www.wbcsd.org/Overview/About-us/Vision-2050-Time-to-Transform/Resources/Time-to-Transform.

Westley, Frances, Per Olsson, Carl Folke, Thomas Homer-Dixon, Harrie Vredenburg, Derk Loorbach, John Thompson, et al. 2011. "Tipping Toward Sustainability: Emerging Pathways of Transformation." *AMBIO* 40 (7): 762–80. https://doi.org/10.1007/s13280-011-0186-9.

Yellen, David. 2020. "Carbon Capture and the Allam Cycle: The Future of Electricity or a Carbon Pipe(Line) Dream?" (Atlantic Council blog). May 21. https://www.atlanticcouncil.org/blogs/energysource/carbon-capture-and-the-allam-cycle-the-future-of-electricity-or-a-carbon-pipeline-dream/.

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ABOUT OUR PARTNERS AND FUNDERS

UN Climate Change High-Level Champions

The United Nations High-Level Champions for Climate Action for COP26 and COP27— Mahmoud Mohieldin and Nigel Topping—build on the legacy of their predecessors to engage with nonstate actors and activate the "ambition loop" with national governments. Their work is fundamentally designed to encourage a collaborative shift across all of society toward a decarbonized economy, so that we can all thrive in a healthy, resilient, zero-carbon world. Gonzalo and Nigel have convened a team to help them deliver on this work through flagship campaigns, targeted stakeholder engagement, and leadership in systems transformation.

Climate Action Tracker

The Climate Action Tracker (CAT) is an independent scientific analysis that tracks government climate action and measures it against the globally agreed Paris Agreement aim of "holding warming well below 2°C, and pursuing efforts to limit warming to 1.5°C." A collaboration of two organizations, Climate Analytics and NewClimate Institute, CAT has been providing this independent analysis to policymakers since 2009. CAT quantifies and evaluates climate change mitigation targets, policies and action. It then aggregates country action to the global level, determining likely temperature increase by the end of the century under different scenarios. CAT also develops sectoral analysis to illustrate required pathways for meeting the global temperature goals.

Bezos Earth Fund

The Bezos Earth Fund is Jeff Bezos's $10 billion commitment to fund scientists, activists, NGOs, and other actors that will drive climate and nature solutions. By allocating funds creatively, wisely, and boldly, the Bezos Earth Fund has the potential for transformative influence in this decisive decade. Funds will be fully allocated by 2030, the date by which the United Nations' Sustainable Development Goals must be achieved.

ClimateWorks Foundation

ClimateWorks Foundation is a global platform for philanthropy to innovate and accelerate climate solutions that scale. We deliver global programs and services that equip philanthropy with the knowledge, networks, and solutions to drive climate progress. Since 2008, ClimateWorks Foundation has granted over $1.3 billion to more than 600 grantees in over 50 countries.

World Resources Institute

World Resources Institute is a global research organization that turns big ideas into action at the nexus of environment, economic opportunity, and human well-being.

Our Challenge

Natural resources are at the foundation of economic opportunity and human well-being. But today, we are depleting Earth's resources at rates that are not sustainable, endangering economies and people's lives. People depend on clean water, fertile land, healthy forests, and a stable climate. Livable cities and clean energy are essential for a sustainable planet. We must address these urgent, global challenges this decade.

Our Vision

We envision an equitable and prosperous planet driven by the wise management of natural resources. We aspire to create a world where the actions of government, business, and communities combine to eliminate poverty and sustain the natural environment for all people.

Our Approach

COUNT IT: We start with data. We conduct independent research and draw on the latest technology to develop new insights and recommendations. Our rigorous analysis identifies risks, unveils opportunities, and informs smart strategies. We focus our efforts on influential and emerging economies where the future of sustainability will be determined.

CHANGE IT: We use our research to influence government policies, business strategies, and civil society action. We test projects with communities, companies, and government agencies to build a strong evidence base. Then we work with partners to deliver change on the ground that alleviates poverty and strengthens society. We hold ourselves accountable to ensure that our outcomes will be bold and enduring.

SCALE IT: We don't think small. Once tested, we work with partners to adopt and expand our efforts regionally and globally. We engage with decision-makers to carry out our ideas and elevate our impact. We measure success through government and business actions that improve people's lives and sustain a healthy environment.

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