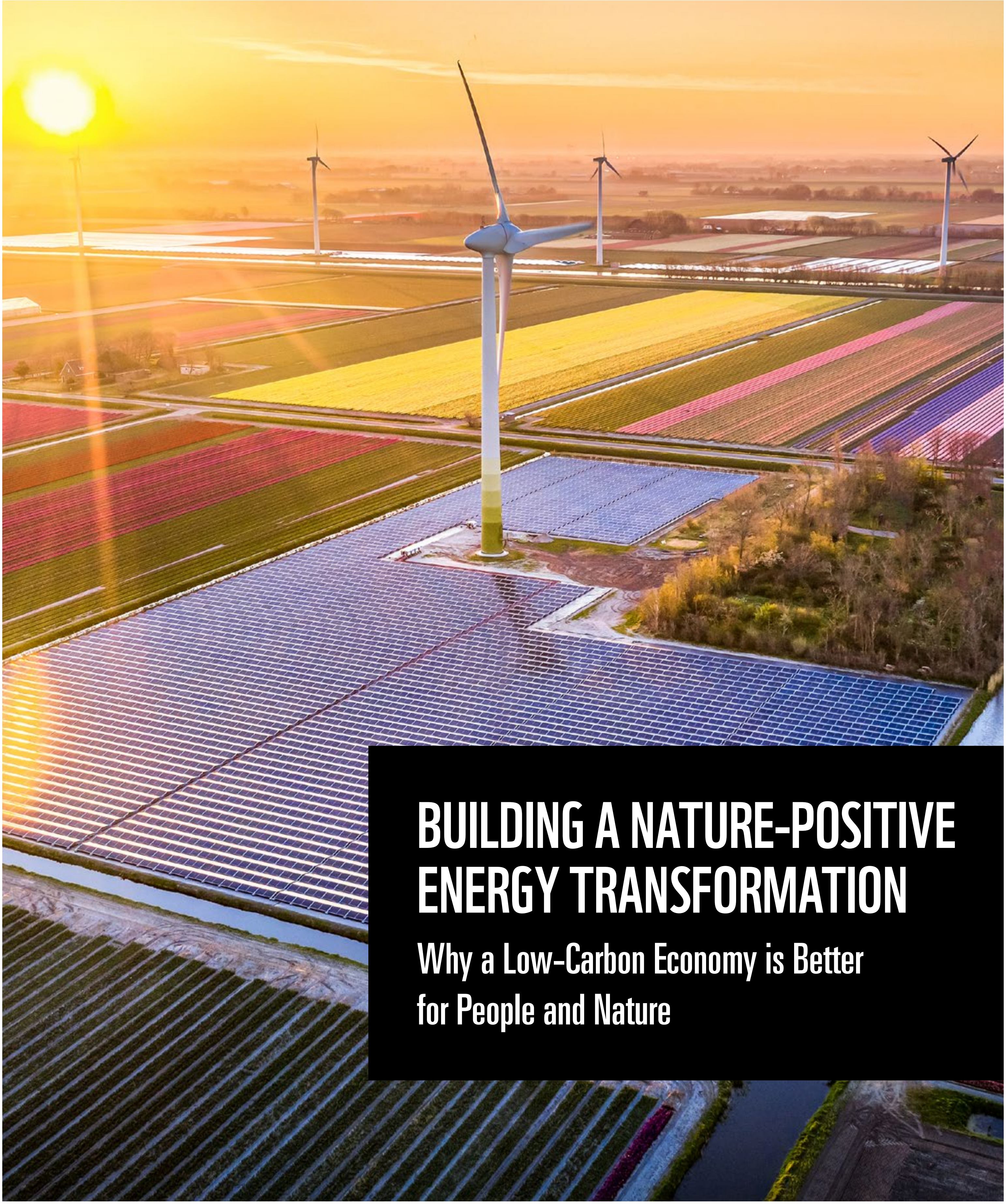

BUILDING A NATURE-POSITIVE ENERGY TRANSFORMATION

Why a Low-Carbon Economy is Better for People and Nature

WWF

BCG

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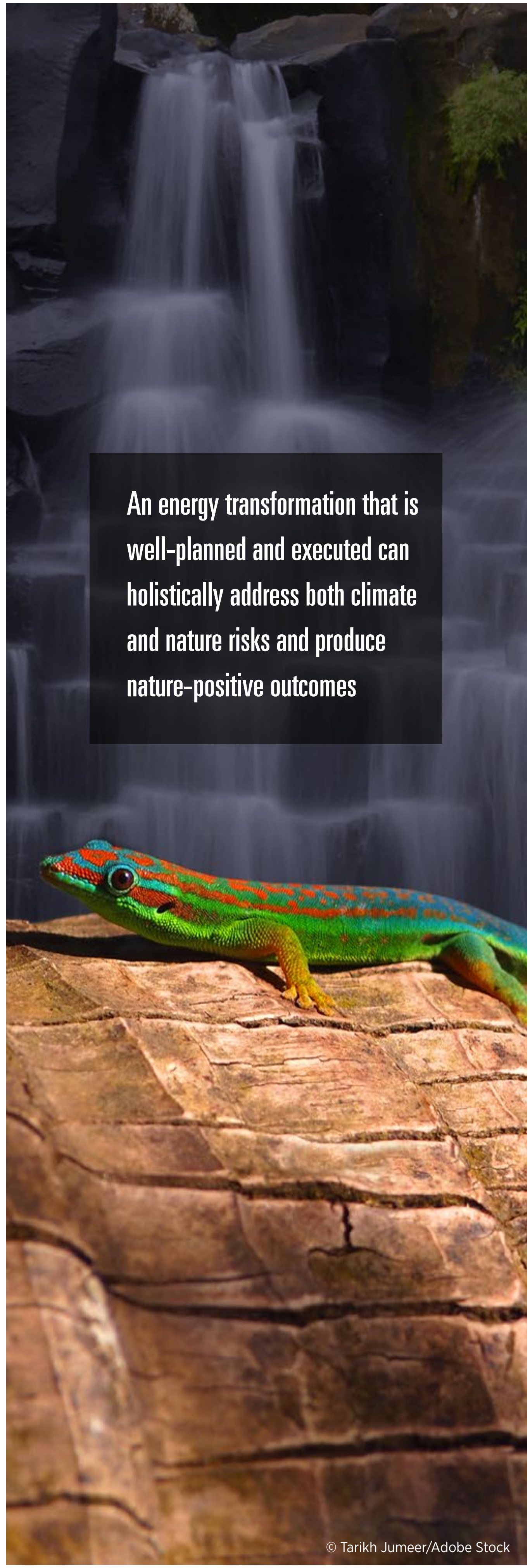

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Executive Summary

Key Messages

1. **The urgent need for a rapid transformation of our global energy system** to mitigate climate change and ensure a livable future cannot be overstated.
2. **An energy system powered by renewables will be far better across a range of metrics** (2-16 times better) for nature and people than a business-as-usual, fossil fuel-dominated energy system, although the transformation will place some demands on natural resources and local communities.
3. **The extent to which the energy transformation is better, and can produce nature-positive outcomes, depends on how well we implement it.** Policymakers, decision-makers, and other stakeholders can avoid or minimize unwanted impacts on some nature and people by deploying laws, incentives, and environmental planning tools and effectively engaging with affected communities.

A major transformation of our global energy system is crucial to ensuring a safer and livable future. This transformation combines local and regional transitions from fossil fuels to renewable energy sources, widespread electrification, improvements in energy efficiency, and deployment in line with sustainable development. Without this transformation, the worsening climate crisis—and the damage it will cause—threatens human wellbeing and the health of the planet.

The *urgency i*n achieving the needed energy transformation has never been greater, and the barriers involved in slowing progress must be addressed. Obstacles for transitioning to renewable energy and electrified transportation include misaligned policies and misdirected economic incentives, but also local concerns related to impacts on people and ecosystems. These have been compounded by growing misinformation on impacts, contributing to now-common media narratives about the environmental and social challenges confronting the renewable transition.

So, it is important that we fully understand the risks and impacts associated with the transition to renewable energy. However, they must be weighed in context to the alternative: the impacts of keeping a fossil-fuel energy system and not achieving the transition.

***How* we implement the transition is also critically important for addressing another global challenge—the worsening nature crisis.** The development needed—including wind and solar infrastructure, transmission lines, and mines for related materials—poses risks to ecosystems and communities that will need to be minimized or avoided to safeguard nature and communities. **In fact, an energy transformation that is well-planned and executed can holistically address both climate and nature risks and produce nature-positive outcomes.**

This report is divided into two parts that explore those themes. Section 1 builds on existing studies and quantifies and compares 30 environmental and socioeconomic impact metrics in two different energy scenarios for the future. The Rapid Transition (RT) scenario limits warming to 1.5°C with limited overshoot through the rapid scale up of renewable energy, electrification (including electric vehicles), and energy efficiency improvements while optimizing delivery of sustainable development outcomes; and the Business-as-Usual (BAU) scenario continues current policies of a fossil fuel-dependent economy. Both scenarios are based on data from the most recent Intergovernmental Panel on Climate Change (IPCC) Working III Report (2022). Section 2 presents a framework for establishing the nature-positive energy transformation that is essential to achieving critical climate and sustainable development goals.

Section 1. Main findings

- **An energy system powered by renewables will be far better for nature and people than a fossil fuel-dominated energy system. Our findings show that the Rapid Transition scenario is 2-16 times better for nature and society than the Business-As-Usual scenario.** These better outcomes occur across 27 of the 30 impact metrics measured.
- **The largest differences are with actively mined areas, air quality impact, water quality impact, biodiversity loss, land lost and degraded from climate impacts, poverty risk, exposure to chronic water scarcity, biome shifts, heat stress, and flooding risk.** These improved outcomes are possible largely due to the decommissioning of coal mines, reduction in fossil fuel combustion, and reduced climate change impacts under the Rapid Transition scenario.
    - **Mining: The mining footprint for critical minerals needed in a Rapid Transition future will be far smaller than the land spared from decommissioned coal mining.** In a Rapid Transition scenario, the demand for critical metals (e.g., lithium, nickel, graphite, neodymium, copper, cobalt, steel, silicon, silver, aluminum) is projected to increase 2-15 times. However, these will only make up about 5% of total global metals production in 2050. Furthermore, by 2050, the Rapid Transition scenario will have 30% less total land area that is actively mined (76,000 km^2) and one third fewer active mines (2,300) compared to Business-As-Usual (at 115,000 km^2 and 3,400 respectively), primarily due to the decommissioning of coal mines. Further, the Rapid Transition scenario will have 25% less mined area than today. For countries with high levels of critical minerals, the report outlines several strategies to minimize the negative impact of additional mining on people and nature.
    - **Air quality: The Rapid Transition scenario involves significantly less burning of fossil fuel, resulting in large air quality and human health improvements.** By 2050, key air pollutants are between 60-90% lower and premature death or disability due to air pollution is 86% lower in a renewable energy future compared to Business-As-Usual. The air quality index in a Rapid Transition future is also 70% better compared to today's air quality index.
    - **Water quality: Pollution from energy development is reduced significantly in the Rapid Transition scenario, with 90% less freshwater eutrophication** compared to Business-As-Usual due to a decrease in coal mining and direct waste-water discharge.

- **Ecosystems and biodiversity: Projected risks are up to 76% lower for biodiversity, natural habitats, and ecosystems in the Rapid Transition scenario compared with Business-As-Usual.** The fossil fuel-dependent global economy in Business-As-Usual will lead to temperature increases to 3.2°C by the end of the century, resulting in four times more species lost and up to three times higher risk of biome shifts on land, as well as significantly increased vegetation loss, permafrost degradation, dryland water scarcity, soil erosion, and wildfire risk and severity—primarily due to climate change-related impacts (sea-level rise and extreme hazards including heatwaves, droughts, fires, and floods).
- **Society and human wellbeing: Across all eight socioeconomic metrics, the Rapid Transition scenario achieves materially greater benefits for people—including improved food security, human health, and livelihoods—compared to Business-As-Usual.** More than twice as many jobs are created (36 million job years in Rapid Transition compared to 14 million in Business-As-Usual) and the cost of electricity access in Sub-Saharan Africa is 30% lower in the Rapid Transition scenario. Furthermore, the costs of infrastructure damage and food supply are 50% lower; poverty risk, heat stress risk, and flooding risk are 65-70% lower; and the number of people that experience chronic water scarcity due to lower climate-change related impacts is up to 80% lower.
- **Area (land and marine) footprints: When considering both the footprint of energy development and that of climate change-related land loss and degradation, the projected total land and ocean area impacted is lower in the Rapid Transition scenario.** The direct footprint of energy development alone in the Rapid Transition is projected to be larger than that of the Business-As-Usual in 2050, primarily due to a 44% higher use of bioenergy (area footprint is 35% larger with bioenergy, though only 8% larger if bioenergy use is limited). However, the land lost and degraded due to climate change (desertification, fire, and coastal flooding) from Business-As-Usual is twice that of the Rapid Transition (15 million km^2 compared to 7.5 million km^2), a larger area than the direct energy development footprint. The report explores a range of options for dramatically reducing the footprint of energy projects in the Rapid Transition scenario, including the potential for considerably lower levels of land needed for bioenergy production and synergistic use of the "spacing" land between wind turbines.
- **Water use: Energy-related water use is somewhat greater in the Rapid Transition, with withdrawal and consumption being 20% and 40% higher than the Business-As-Usual, respectively.** Water use in the Rapid Transition is dominated by irrigation of bioenergy crops. The report reviews several mechanisms that could dramatically reduce water consumption for bioenergy crops; if these occur, water withdrawal in the Rapid Transition would be considerably lower than the Business-as-Usual.
- **Free-flowing rivers: Due to a 60% increase in hydropower in the Rapid Transition scenario, there are larger negative impacts on free-flowing rivers than from the Business-As-Usual** (damming about half of the world's remaining large free-flowing rivers resulting in a 20% increase in fragmented rivers), but this risk can be greatly reduced. For example, other scenarios consistent with meeting climate targets have far lower levels of hydropower expansion.

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Section 2. Main findings

- **Avoiding or reducing negative impacts and associated conflicts caused by future energy demand is critical to ensure that:**

  (1) the global energy transformation does not exacerbate the global nature crisis or negatively affect communities; and (2) the transformation proceeds as rapidly as needed to meet climate targets and other sustainable development goals.

- **Achieving a nature-positive outcome is essential for delivering a sustainable transformation of our energy system.** Policymakers and other actors can deploy a range of laws, incentives, and practices to accomplish this. We present a framework of mechanisms with high potential to shift energy systems to a nature-positive pathway, which include:

  - **Policies for protecting nature can integrate conservation into decision making early in the planning process.** Mitigating the negative effects of the energy transformation on nature should therefore ideally start with strong overarching nature-preservation policies that protect critically important species, sensitive habitats, and nature's contributions to people.

  - **Planning a national or grid-scale energy mix (portfolio of energy technologies) that optimizes energy, nature, and social objectives can help minimize or avoid the most significant risks and impacts from renewable energy development on land, oceans, and rivers.** Energy planners can use tools such as capacity expansion models to guide their decisions about the mix of power-system investments (e.g., generation, storage, and transmission) needed to meet forecasted demands. These models should be coupled with analyses of the environmental and social performance of different technologies to understand the tradeoffs between different development options (for example, bioenergy and hydropower which pose higher risks for nature and people).

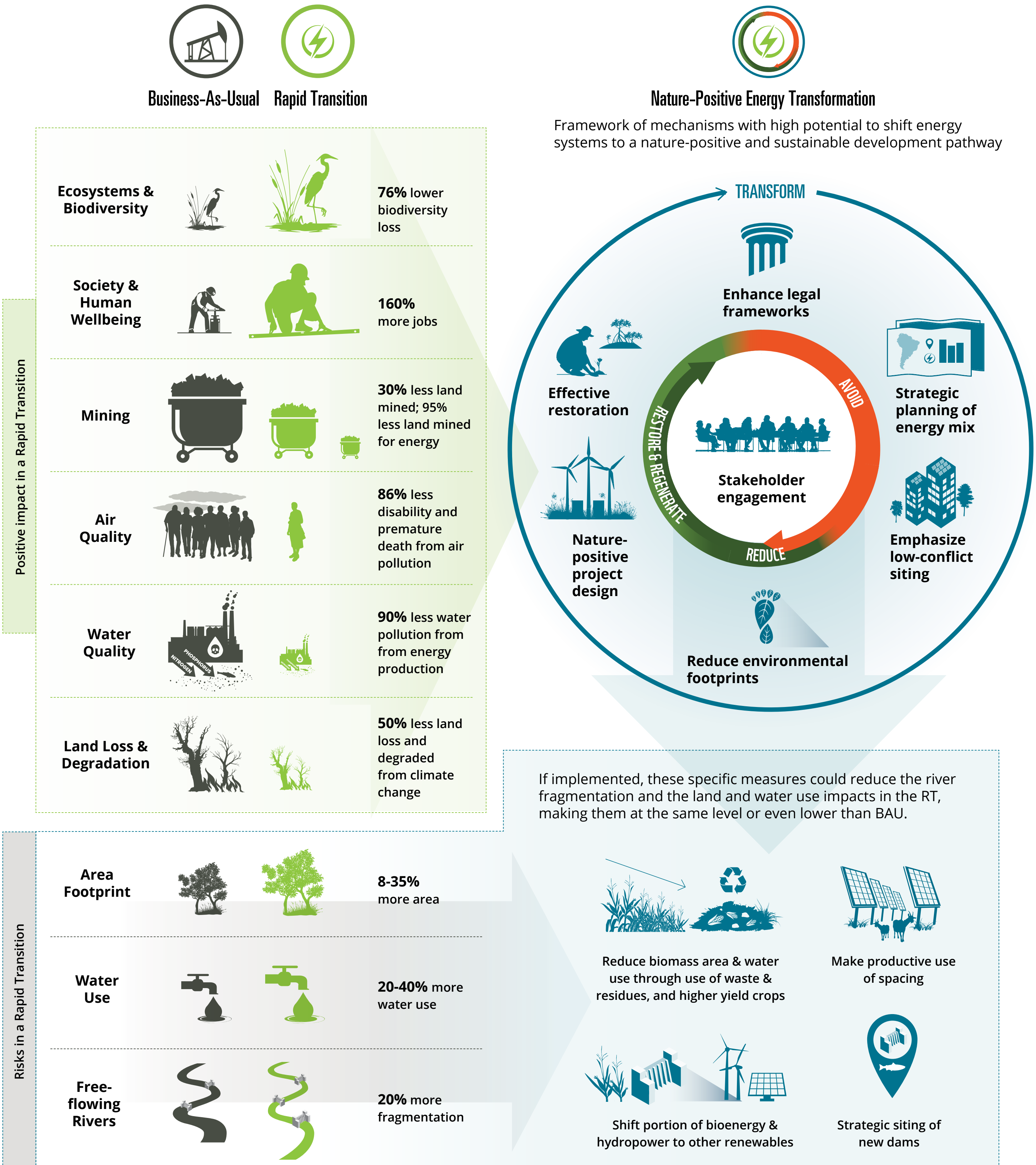
- **Multiple strategies can reduce the footprint of the renewable transition on land, oceans, and rivers.** The direct footprint of energy development—including both the area (land and oceans) and the fragmentation of rivers—are two metrics where the projected impacts of the Rapid Transition are higher than Business-As-Usual. Thus, addressing the land, ocean, and river footprints of the Rapid Transition is one of the most important challenges for delivering a nature-positive energy transformation. There are a number of ways to lessen this footprint, including 1) minimizing the need for additional bioenergy crops by using biomass waste and residues, substitution from other energy sources, and selecting crops and technologies with higher efficiencies and yields; 2) reducing the area footprint of wind and solar through synergistically managing the land between wind turbines and solar arrays (the "spacing" footprint) with agriculture or natural vegetation, which can provide additional services, such as pollinator habitat; and 3) decreasing the impact of hydropower on rivers by substituting other generation technologies for a portion of planned hydropower and then carefully siting new hydropower projects.
- **Siting renewable energy projects in low-conflict areas is vitally important.** Various studies show that most of the needed expansion of renewable energy infrastructure can occur on sites that will have minimal negative impacts on nature and communities. Low-conflict areas that will generally have low negative impacts include rooftops, parking lots, reservoirs, and abandoned mines for solar panels and pastures or other agricultural land for wind turbines. Many countries can meet their 2050 renewable energy requirements using these already converted lands.
- **Impacts from critical minerals mining can be addressed through existing strategies,** including developing circular economies to improve recycling, increasing energy efficiency to reduce demand, following rigorous standards to address environmental and social impacts, and avoiding critical habitats and the deep ocean. Investing in new research and development for alternative materials is also needed to reduce demand for critical minerals.
- **Regional planning can improve outcomes for the environment and communities while increasing the efficiency of permitting, siting, and developing energy projects.** Due to the complexity of permitting for renewable energy projects, advocates for renewable energy often recommend increasing the efficiency of these processes to accelerate project approval and implementation. Regional planning processes have demonstrated that promoting early stakeholder engagement and early integration of energy planning with conservation planning can result in more efficient permitting processes coupled with improved outcomes for ecosystems and communities.
- **Renewable energy projects can be designed, built, and operated in ways that reduce impacts on species and ecosystems.** These include designing the layout of wind farms to minimize interference with bird migration routes, mandating minimum distances between projects and sensitive habitats, promoting habitat features adjacent and within projects, and ensuring that restoration activities (e.g., for mitigation) are based on sound ecological baselines and principles.

Conclusion

A rapid energy transformation is not only better for the planet, but also essential to our well-being. Countries around the globe need to rapidly transition to renewable energy sources to cut emissions and avoid the worst-case scenarios of global warming beyond 1.5°C. **Meeting the scope and scale of the climate and nature crises will require going beyond local, regional, and national transitions and towards a broad transformation of our global energy system that supports net zero, nature-positive and sustainable development outcomes.** That will only be possible if the tools and approaches outlined in Section 2 are part of a more fundamental shift in how energy systems are planned and developed to stabilize the climate, reverse the nature crisis, and deliver development and economic benefits to people around the world.

Executive Summary Figure 1. Projected impacts across key metrics in 2050 in Business-As-Usual and Rapid Transition scenarios and key mechanisms to achieve a nature-positive energy transformation.

A Rapid Transition scenario is dramatically better for nature and society in 27 out of 30 key metrics including: actively mined areas, air quality, water quality, biodiversity, jobs, and land lost and degraded from climate impacts. Additional measures need to be taken to enhance these benefits, and address key risks arising from water use, river fragmentation and the footprint of energy development. These measures, guided by comprehensive stakeholder engagement, can help drive a more fundamental shift towards a nature-positive and sustainable development pathway.



Introduction

Climate change is causing dangerous and widespread disruption in nature and affecting the lives of billions of people. Increasingly frequent and severe climate extremes (e.g., heatwaves, storms, floods, droughts, and fires) and sea-level rise, have destroyed infrastructure and ecosystems, and inflicted damage to people's health, wellbeing, and livelihoods—causing $4.3 trillion in economic losses to date (IPCC AR6 WG2, 2022; WMO, 2023). Every small increase in global temperatures will make impacts worse. Depending on our actions, the threats from climate change could be multiple times higher beyond 2040 than what we experience today.

Compounded by the climate crisis is a worsening nature crisis, with an average 69% decline in wildlife populations since 1970 (WWF, 2022). This crisis threatens not only wildlife but also imperils the many benefits nature provides to people and economies around the world—from food and clean water provision to building materials, fertile soil, and pollination. These benefits, endangered in many areas, are essential in buffering the extremes of a warming planet, protecting coastlines and hillsides from erosion, absorbing floodwaters, and providing cooler temperatures.

To avoid and reverse mounting losses, urgent action is needed. If the world hopes to avoid the worst-case scenarios of global warming beyond 1.5°C, including its pervasive impacts on nature, a major transformation of our global energy system—the main driver of climate change—is vitally important (IPCC AR6 WG3, 2022). Countries around the globe need to rapidly transition to renewable energy sources, expand electrification, improve energy efficiency, and invest heavily in new sustainable infrastructure to achieve critical climate and sustainable development goals. Although there is increasing progress in some countries, with affordability and installed capacity of wind and solar energy growing exponentially in the last decade, the scale and speed of the transition required over the coming decades is many times higher.

Any barriers to progress must therefore be addressed. Misaligned policies and misdirected economic incentives, but also local concerns and conflicts have played a part in delaying the deployment of renewable energy and electrified transportation in many places around the world. These obstacles are compounded by growing misinformation on the potential impacts of the energy transition on local communities and the environment, contributing to increasingly common media narratives about the environmental and social challenges confronting the renewable transition.

So, it is important that we fully understand the risks and impacts associated with the transition to renewable energy. But they must be weighed in context to the alternative: the impacts of keeping a fossil-fuel energy system and *not* achieving the transition.

Box 1. Definitions of Transition and Transformation

While these terms are interchangeable for some audiences, they are important to distinguish for this report.

We use *transition* (e.g., in the Rapid Transition scenario in Section 1) to refer to the local, regional, and national transitions needed to reduce greenhouse gas emissions and address climate change, including moving from fossil fuels to renewable energy, widespread electrification (including electric vehicles), and improved energy efficiency. This term is commonly used in the energy sector.

We refer to *transformation* (e.g., energy system transformation in Section 2) as the global, systemic change in energy production and consumption, combining all the needed local and regional transitions and ensuring the process in which the transitions are implemented deliver a sustainable and nature-positive future that improve human wellbeing and the health of the planet (Figure 10).

In addition, *how* we implement the transition is also critically important. Like any energy and infrastructure development, the transition to renewable energy will significantly impact a range of natural resources. Hydropower dams fragment rivers, and solar- and wind-power generation will require land for photovoltaic panels and turbines. Crop production for biomass to be used as fuel will require additional land and water for irrigation. And minerals to help power electric car batteries and turbine blades will need to be extracted from the earth's surface. We must therefore use approaches that avoid and minimize adverse impacts to safeguard nature and communities, and also defuse the conflicts that could slow down the transition.

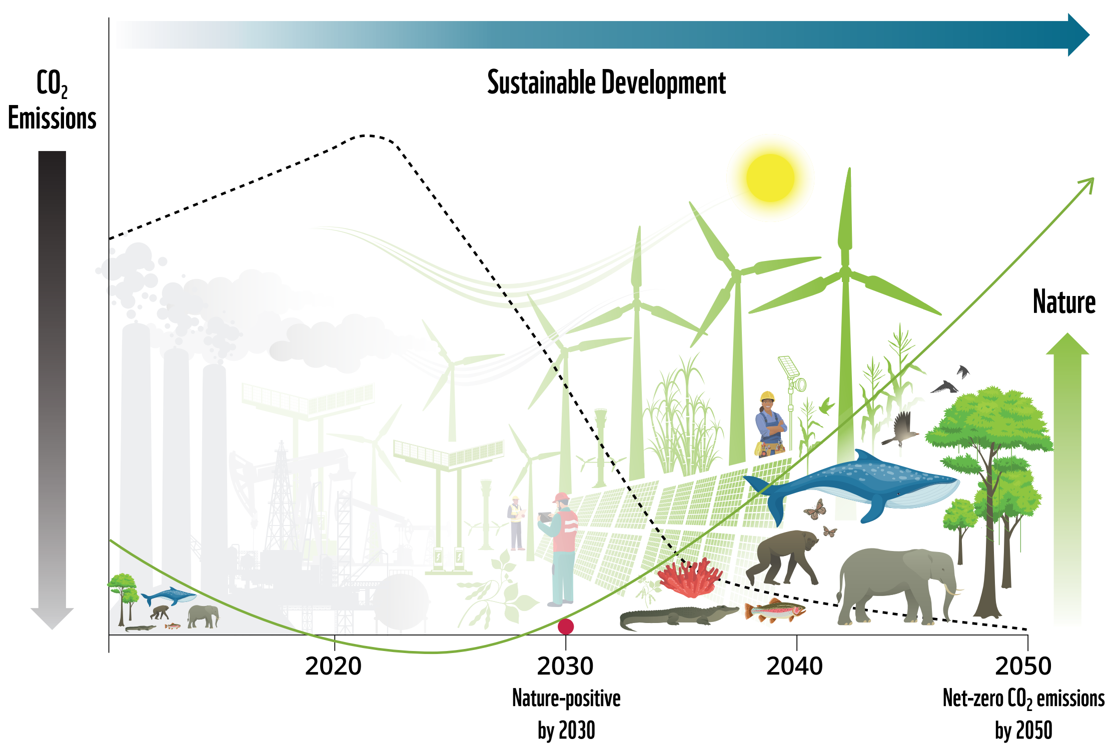
Effectively addressing the climate and nature crises will require going beyond local, regional, and national transitions and towards a systemic transformation of our global energy system—including a fundamental shift in how energy systems are planned and built—that supports net zero, nature positive and sustainable development outcomes (Figure 1; Box 1). Net zero is the 2050 goal for limiting warming to 1.5ºC, nature-positive is the 2030 goal for halting and reversing nature loss, and the sustainable development goals are 2030 targets for improving the health and wellbeing of people and the planet.

Recently, CLEANaction (2023) reviewed key impacts and mitigation measures for different energy types, and the Energy Transitions Commission (2023) assessed the material and resource requirements of the renewable energy transition. This report builds on these studies by providing a quantitative comparative analysis of two energy futures and their impacts, and a set of approaches for achieving a nature-positive pathway.

In the first section of this report, we use a scenario-based approach to quantitatively assess 30 key environmental and socioeconomic impact metrics associated with the renewable transition needed to limit warming to 1.5ºC and compare those to impacts from a Business-As-Usual trajectory in which fossil fuels persist as major contributors to the global energy mix. We did not explicitly assess the full financial or capital costs for the transition or the full costs from climate change impacts.

The second section of the report offers a framework for policy makers to achieve an energy transition that avoids and minimizes impacts on communities and nature and facilitates a nature-positive future. Through early engagement with stakeholders, this approach can also minimize the types of conflict that risk slowing investment and implementation needed to achieve the energy transition.

Figure 1. A transformation of our energy system that supports net zero, nature-positive and sustainable development pathways by 2050. (adapted from CLEANaction, 2023)



Section 1. Assessing the Impact of Two Futures on Nature and Society

To analyze the impact of climate actions on nature and people, we compare two scenarios. The first, Rapid Transition (RT), involves large-scale decarbonization and a massive scale-up of low carbon energy technologies and efficiency measures by 2050, including renewables (accounting for more than 85% of primary energy supply), updated energy grids, and electric vehicles. The RT scenario limits warming to 1.5ºC, in line with net zero ambitions of the Paris Agreement. The second scenario, Business-As-Usual (BAU), involves a limited transition with countries continuing current policies that largely retain fossil-dependent economies and fail to deliver on global climate ambitions (more detail on scenarios is provided in Box 2).

We quantified and compared the effects of these two scenarios in 2050, across 30 key environmental and social metrics within eight main impact areas: mining; ecosystems and biodiversity; air quality; water quality; water use; area footprints (land, and marine); free-flowing rivers; and society.

Overall, our findings show that the Rapid Transition scenario is approximately 2-16x better for nature and society than the Business-As-Usual scenario. This result occurs across 27 of the 30 metrics measured across the impact areas (Figure 2). Actively mined areas, air quality impact, human health impacts from air pollution, water quality impact, biodiversity loss, land lost and degraded from climate impacts, poverty risk, and exposure to chronic water scarcity show the largest difference. These improved outcomes are possible largely due to the decommissioning of coal mines, reduction in fossil fuel combustion, and mitigated climate change impacts that occur under the RT.

The RT scenario has a higher area footprint from energy production and generation and somewhat higher water use (primarily due to an increase in bioenergy) as well as higher impact on free-flowing rivers (due to an increase in hydropower dams).

The sub-sections below detail the findings for each impact area and are listed in order of the magnitude of impact. The Figure captions provides information on the methods and the Technical Annex provides additional data, analyses and results.

Figure 2. Summary of projected impacts across eight categories and 30 metrics in a Business-As-Usual and Rapid Transition scenario.

	Mining	Air Quality	Water Quality	Ecosystems & Biodiversity	Society & Human Wellbeing	Area Footprint	Water Use	Free-flowing Rivers
Business-as-Usual	HIGHER IMPACT	HIGHER IMPACT	HIGHER IMPACT	HIGHER IMPACT	HIGHER IMPACT	HIGHER IMPACT	LOWER IMPACT	LOWER IMPACT
Rapid Transition	LOWER IMPACT	LOWER IMPACT	LOWER IMPACT	LOWER IMPACT	LOWER IMPACT	LOWER IMPACT	HIGHER IMPACT	HIGHER IMPACT
Magnitude of difference	1.4-16.4X	2.5-11.7X	3.5-10X	2-4X	1.3-5X	-1.3-2X	1-1.4X	1.2X
30 Metrics	▪ Total land area for active mining ▪ Land area for active mining attributable to primary energy production ▪ Number of active mines worldwide	▪ Carbon monoxide ▪ Nitrogen oxides ▪ Sulfur oxides ▪ Volatile organic compounds ▪ Particulate matter ▪ Disability-adjusted life years	▪ Freshwater eutrophication ▪ Marine eutrophication	▪ Biodiversity loss ▪ Biome shifts (% of global land) ▪ Vegetation loss ▪ Dryland water scarcity ▪ Soil erosion ▪ Wildfire Risk ▪ Permafrost degradation	▪ Net employment ▪ Cost of electricity access in SA ▪ Disruptions to food supply ▪ Poverty risk ▪ Infrastructure damage ▪ Flooding risk ▪ Heat stress ▪ Exposure to chronic water scarcity	▪ Energy Area Footprint ▪ Land loss and degradation from climate change	▪ Water consumption	▪ Free-flowing rivers

Notes: Categories are ordered in order according to the magnitude of impact. The metrics were chosen according to their relevance to the category and based on publicly available data to compare the two scenarios.

Box 2. Two scenarios used in the impact assessment

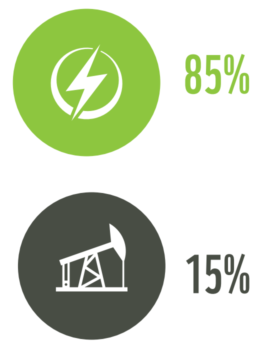
Business-As-Usual (BAU) scenario

This scenario assumes that countries continue current policies and climate commitments outlined in their nationally determined contributions (policies implemented, and pledges made through 2020). These current policies are projected to increase greenhouse gas emissions (GHG), leading to a rise in the Earth's temperature of about 3.2°C (2.2°C-3.5°C) by the end of this century. We chose this publicly available scenario as it reflects a future based on existing policies (from 2020), and not just the most up-to-date country pledges. Under this scenario, by 2050, fossil fuels still make up about 80% of global primary energy supplies while renewable energy accounts for about 20%, and global GHG emissions increase to 64 gigatons per annum of CO_2-eq. This scenario is based on the "Current Policies" illustrative mitigation pathway, C7 scenario from the IPCC (IPCC AR6 WG3 Ch4, 2022, Byers et al., 2022).

Rapid Transition (RT) scenario

This scenario limits global warming to 1.5°C (with no or limited overshoot[1]) above preindustrial levels by the end of this century through accelerated growth in renewable energy, electrification including electric vehicles, and energy efficiency measures. We chose this scenario as it not only limits warming to 1.5ºC with limited overshoot to avoid the worst impacts of climate change, but it also couples deep cuts in greenhouse gas emissions with sustainable development outcomes, including a reduction in poverty, enhanced food security, and increased protection and restoration of nature. Under this scenario, by 2050, renewable energy sources make up about 85% of global primary energy supplies while fossil fuels account for about 15%, and greenhouse gas emissions are reduced to 11 gigatons of CO2-eq (carbon dioxide equivalent) per year. This RT scenario is based on the "Shifting Development pathway" C1 scenario, one of the illustrative mitigation pathways in the United Nations' Intergovernmental Panel on Climate Change's (IPCC's) Sixth Assessment Report on Mitigating Climate Change (IPCC AR6 WG3 Ch4, 2022, Byers et al., 2022) to map possible climate futures.

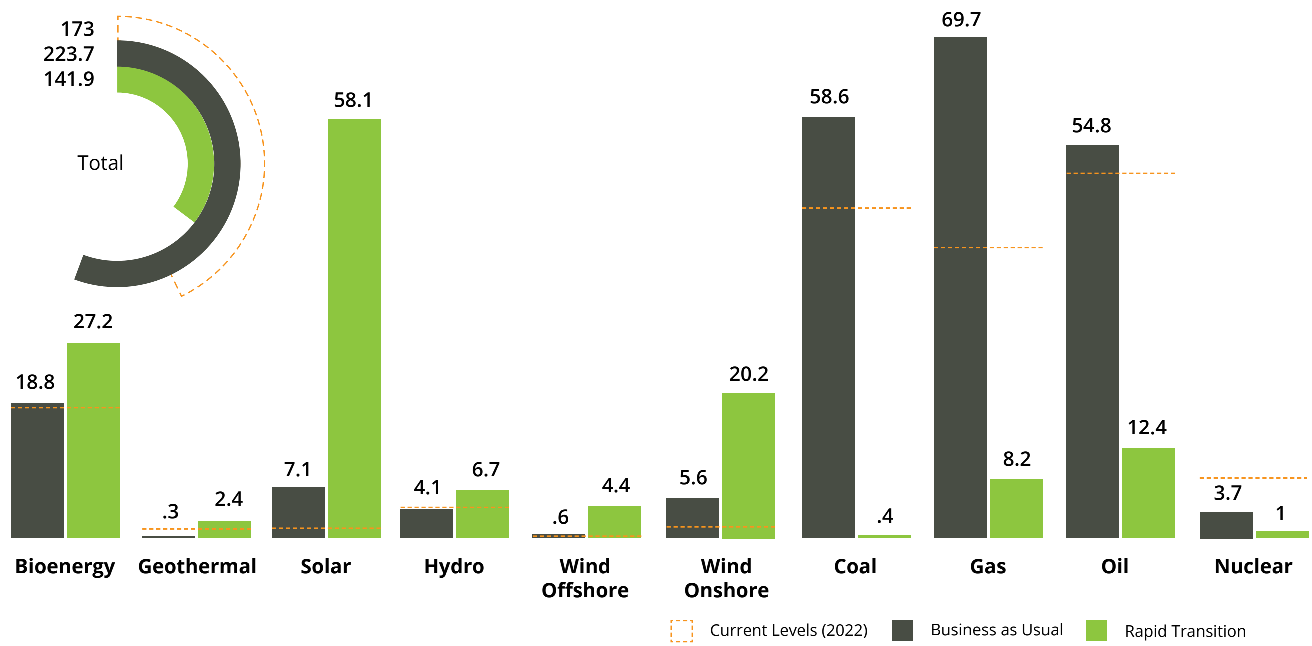
Percent of renewables in 2050



Current percent of renewable energy is 15%

Energy mix and demand in 2050 in two scenarios

Thousand TWh/year



[1] Overshoot refers to the exceedance of a specified global warming level, followed by a decline to or below that level during a specified period (e.g., before 2100). Limited overshoot refers to exceeding 1.5°C by up to about 0.1°C and for up to several decades (Riahi et al. 2021)

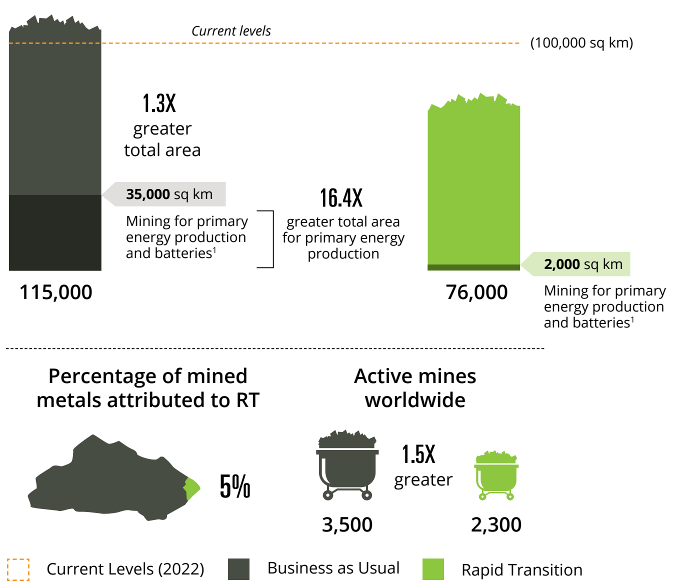
Mining

Mining can cause considerable damage to nature through toxic discharge and the destruction or degradation of important ecosystems. About one-third of the world's forest ecosystems, which cover 31% of global land area, are currently negatively affected by mining—both from extraction processes and mining infrastructure—leading to water and soil contamination and deforestation (WWF, 2023). Poor mining practices can also lead to negative social impacts and human rights violations.

In the two scenarios, mining continues to play a major role in supporting energy provision, however their footprints are very different. In a Rapid Transition future, demand and mining for certain metals (e.g., lithium, nickel, graphite, neodymium, copper, cobalt, steel, silicon, silver, aluminum) are projected to increase 2-15 times (ETC, 2023a). **However, by 2050, the RT scenario will have 30% less total land area that is actively mined (76,000 km2) and one third less active mines (2,300) compared to BAU (at 108,000 km^2 and 3,400 respectively), primarily due to the decommissioning of coal mines** (Figure 3). Compared to today's actively mined global area (approximately 100,000 km^2), the RT scenario will be 25% lower and the BAU scenario will be 15% higher, primarily due to changes in coal demand. The comparison is even more stark when comparing the actively mined land area for primary energy production only, which is 16.4 times higher in a BAU (34,400 km^2) than the RT scenario (2100 km^2). **So, the extent of land spared from decommissioned coal mines will be far greater than the land needed for mining critical minerals for the energy transition.** Mining's impact on water quality will also be lower, due to fewer active mines compared with a BAU scenario.

Although mining for critical minerals will increase in a RT scenario, the metals for the energy transition will only make up about 5% of total global metals production in 2050. Impacts from mining activities of these metals will be concentrated, therefore countries with high levels of critical minerals will need to take steps to minimize the negative impact of additional mining on people and nature (strategies are outlined in Section 2 of this report).

Figure 3. Projected mining impacts by 2050.

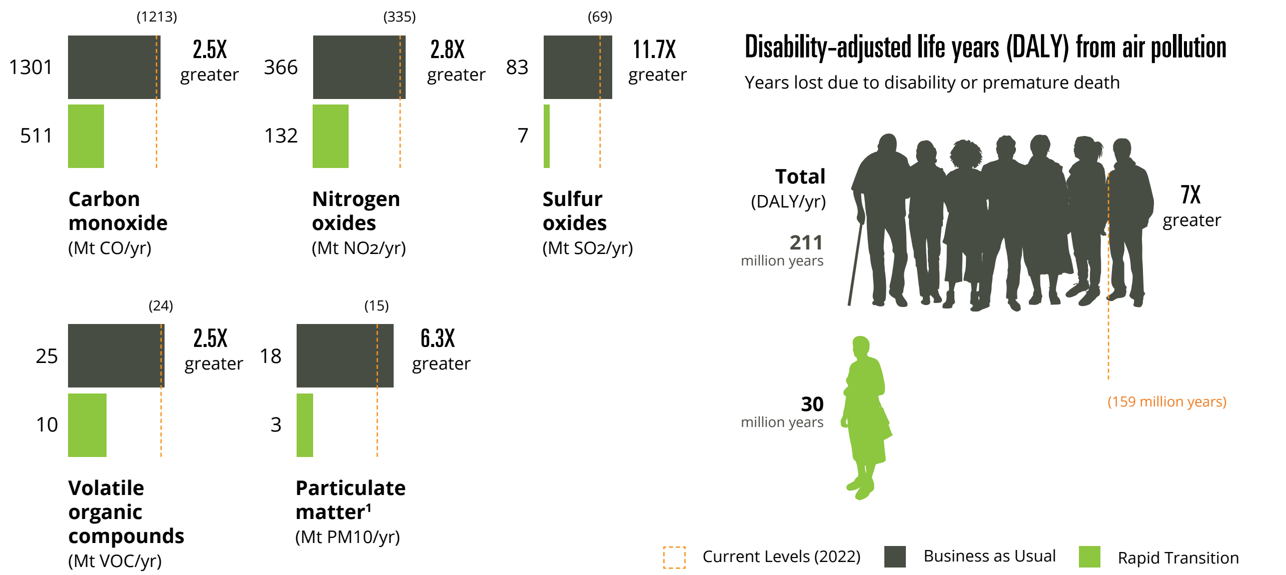


Notes: Total area used for mining includes all actively mined global land areas, representing demand across all sectors. The mining for primary energy production and batteries include coal mining for fossil fuels, and all metals and minerals needed for wind, solar and grid infrastructure as well as power and transportation battery storage. Calculations are based on mining land footprint data from Jasansky et al., 2023, Maus et al., 2022, and Murguía and Bringezu, 2016, and metal and mineral requirements from IEA, IPCC (Byers et al., 2022), Tesla Master Plan Part 3, and BCG analysis.

Air quality

Air pollution caused by burning fossil fuels is currently responsible for one in five deaths worldwide, making it one of the leading causes of global mortality (Vohra et al., 2021). Because the RT scenario involves significantly less burning of fossil fuels, it will dramatically improve air quality compared to that of today, while the BAU would lead to worse air quality across a range of pollutants. **Emissions of carbon monoxide (CO), nitrogen oxides (NOx), sulfur oxides (Sox), volatile organic compounds (VOCs), and particulate matter (PM) are between 60-90% lower in the RT scenario compared to BAU by 2050** (Figure 4). The air quality in a RT future is also 70% better compared to today. Improved air quality improvements will also significantly improve health outcomes. **The risk of global premature death or disability (disability-adjusted life years – DALY) due to air pollution is 86% lower in a renewable energy future.**

Figure 4. Projected impacts on air quality by 2050.



Notes: Emissions for CO were taken from the IPCC scenarios (Byers et al., 2022), and the other four pollutants were modeled using the EPA AP-42 database and the NREL emission factors according to the energy sources for the scenarios. PM10 refers to particulate matter that is 10 micrometers or less in diameter. The Disability-adjusted life years (DALY) is calculated for each energy source, using data from Gibon et al., 2017. In this figure, DALY represents the sum of years lost due to disability or premature death due to air pollution, where one DALY equals one lost year of healthy life. The energy mix for current levels (2022) are based on estimates from the IEA Energy Outlook 2022.

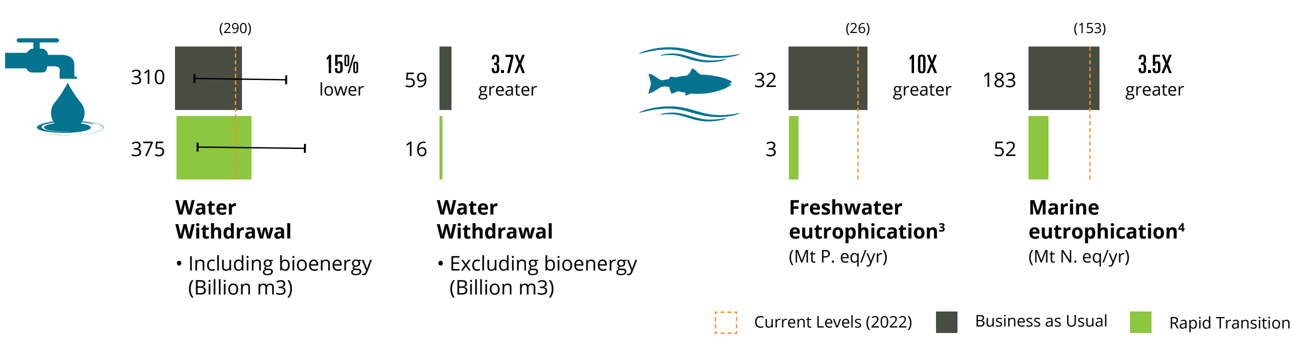
Water use and quality

Freshwater is a vital natural resource for all life on Earth. Energy systems can affect both water quantity and quality (as well as the health and integrity of rivers and other aquatic ecosystems, discussed in subsequent sections). Energy affects water quantity through extraction (e.g., for cooling water) and consumption (e.g., through irrigation of biomass), while affecting water quality through pollution (e.g., from emissions and mining runoff).

Pollution from energy development is reduced significantly in the RT scenario compared to BAU. In 2050, energy-driven eutrophication (accumulation of nutrients that leads to dead zones) of freshwater is more than 10 times higher in the BAU scenario due to more coal mining and an increase in direct waste-water discharge (Figure 5). In marine ecosystems, energy-related eutrophication is about 3.5 times higher in BAU, primarily driven by increased discharge of nutrient-rich wastewater and runoff to marine environments (Figure 5). Other water-quality metrics, such as pH, temperature, and toxicity levels are also likely to be improved with a renewable energy transition given reduced mining activity and less wastewater (including effluent discharge and leakage of tailings, which can lead to high concentrations of heavy metals and toxic reagents that pollute local waterways); however, these changes are harder to quantify for future scenarios and the actual impacts depend on the regulatory environment and control measures implemented at mining sites.

Water use is somewhat greater in the RT: the RT (375 billion cubic meters (bcm)) has 22% greater volume of withdrawal than the BAU (307 bcm) and the RT's consumption (73 bcm) is 43% greater than the BAU (51 bcm). These values are less than 10% of global water withdrawal and less than 5% of global consumption. The per-technology estimates of water use intensity have considerable range, and so the scenarios' interquartile ranges are broadly overlapping (e.g.,110 – 670 bcm for the RT and 105 – 540 bcm for the BAU for withdrawal). Irrigation for bioenergy crops represents 96% of the RT's withdrawals and, without bioenergy, the BAU's withdrawals would be four times greater than those of the RT (Figure 5). With even a 20% decline in the share of bioenergy (as examined in Section 2), the BAU would have greater withdrawals. Bioenergy also represents more than 97% of consumption in both scenarios. By limiting bioenergy crops, consumption would be comparable between the two (approximately 1.5 bcm). The Energy Transition Commission (2023) reported similar findings with their clean energy scenario having 56% greater consumption than a fossil-fuel scenario. Generation from fossil fuels and nuclear requires substantial withdrawal of water for cooling, although only a small portion of that is actually consumed. Wind and solar don't require water for operation; however, solar panels require water for cleaning to improve sunlight penetration. The water consumption for energy production may lead to trade-offs with other water demands, including for agriculture and freshwater ecosystems, and will need to be managed regionally. **There are various measures to reduce water consumption, including through fuel switching from bioenergy to renewables or green hydrogen, using waste and residue biomass for bioenergy, and technology innovations. If bioenergy (and its related water use) can be limited, the water withdrawal in RT would be one quarter of BAU.**

Figure 5. Projected impact on water use and water quality by 2050.



Notes: Water withdrawal estimates are calculated by multiplying the average water intensity values per energy source from Jin et al., 2019 with the energy source TWh estimates from the IPCC scenarios (Byers et al., 2022) and Current levels (IEA Energy Outlook 2022). Freshwater and marine eutrophication is estimated by using the nutrient values per GWh from the Ecoinvent LCA database for each energy source.

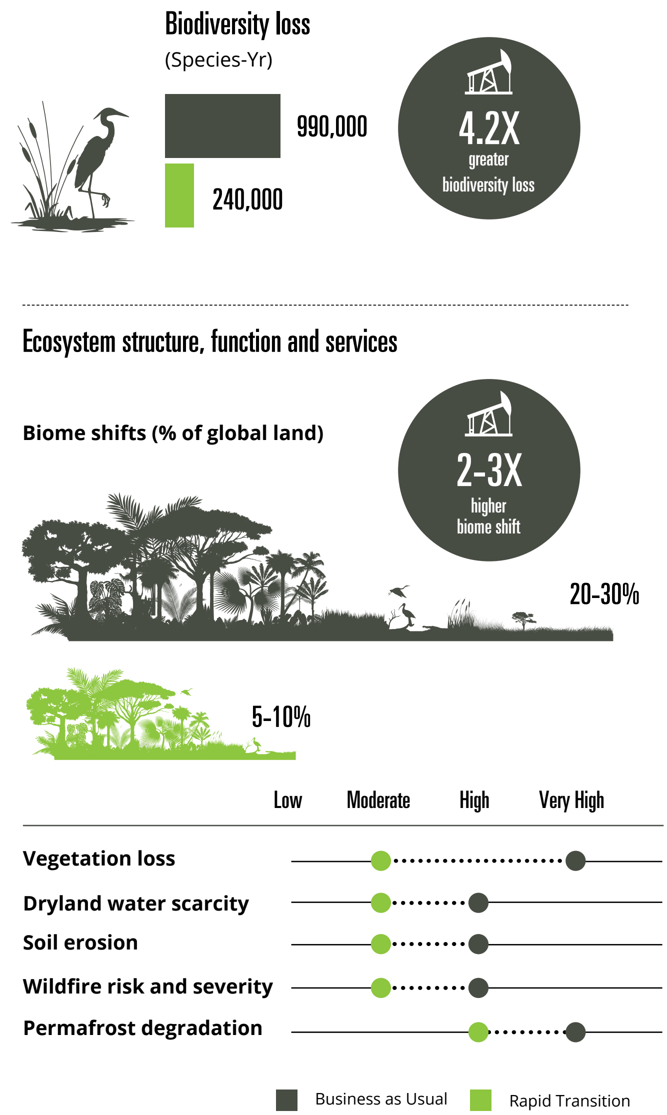
Ecosystems and biodiversity

Forest, grassland, wetland, freshwater, and marine ecosystems not only provide habitats for the planet's plants and animals, they also support critical ecosystem services including air and water filtration, pollination, nutrient cycling, and climate regulation—valued to be greater than the annual Gross Domestic Product ($125 trillion) (Costanza et al., 2014). Human prosperity relies on the sustained supply of nature's goods and services as most are irreplaceable with technology. Biodiversity, essential for supporting healthy and resilient ecosystems, has been declining at an alarming speed—reflected in the approximate 69% decline in wildlife populations since 1970 (WWF, 2022). Although renewable energy development will need careful management to minimize impacts on ecosystems and biodiversity from conversion and fragmentation, this report, and others (e.g., IPCC AR6 WG2 Ch2, 2022) finds that a much larger risk comes from climate change caused by fossil energy.

In the Rapid Transition scenario, projected risks are up to 75% lower for biodiversity, natural habitats, and ecosystems than with BAU (Figure 6). With a continued fossil fuel-dependent global economy, declines in biodiversity (loss of species richness and potential species extinction) are expected to increase by approximately 400% compared to RT. These declines are due to eutrophication, acidification, ecotoxicity, and climate change impacts (habitat and food web disruptions and mass mortality events from sea-level rise and extreme events including heatwaves, droughts, fires, and floods). According to the IPCC, the risk of species extinction increases 10 times for endemic species (IPCC AR6 WG2 Ch2, 2022).

In a BAU scenario, climate change will fundamentally alter all ecosystems, their structure, function, and the ecosystem services they provide. Beyond 2°C, the risks of ecosystem collapse escalate rapidly (IPCC AR6 WG2 Ch2, 2022). **A temperature increase trajectory to 3.2ºC in the BAU is projected to result in up to three times higher risk of biome shifts on land (changes in the major vegetation form of an ecosystem), as well as significantly increased vegetation loss, permafrost degradation, dryland water scarcity, soil erosion, and wildfire risk and severity** (Figure 6). These impacts are significantly higher compared to the 1.5ºC warming levels in the RT scenario. In coastal and ocean ecosystems, the BAU warming levels will lead to increases in intensity, recurrence, and duration of marine heatwaves, increasing the risk of habitat collapse and exceeding ecological tipping points (IPCC AR6 WG2 Ch3, 2022). When climate change risks combine with other pressures (increased pollution, habitat fragmentation, and land-use changes), the impacts will be compounded and increasingly difficult to manage and adapt to.

Figure 6. Projected impacts on ecosystems and biodiversity.



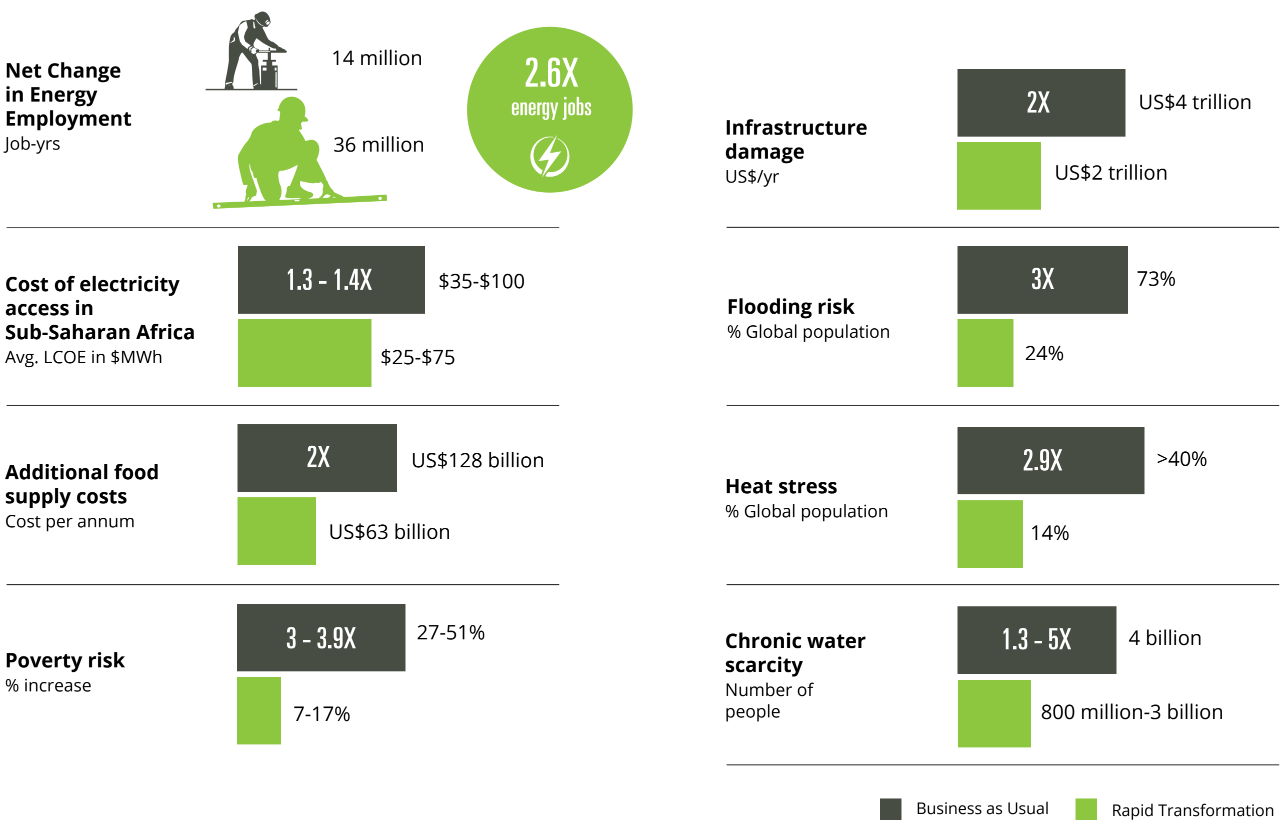
Notes: The impacts on biodiversity, based on data from Gibon et al. 2017, represent the aggregated species diversity effects from freshwater eutrophication, terrestrial acidification, freshwater, terrestrial and marine ecotoxicity and climate change from the two scenarios, expressed in terms of species-years of biodiversity loss. Species-years is derived from the potentially disappeared fraction (PDF) approach which quantifies the fraction of today's present species that will potentially become extinct, and therefore is a measure for loss of species richness and potential species extinction. The impacts on ecosystems are based on data from IPCC AR6 WG2 Ch2, 2022.

Society and human wellbeing

More than 100 years of industrial development based largely on fossil energy sources have significantly raised the quality of life and socioeconomic wellbeing across the globe. This development, however, has come at an increasingly significant cost. Emissions from fossil fuel combustion and land-use change are responsible for increasing global temperatures to over 1.2ºC above preindustrial times, making extreme events like heatwaves, floods, droughts, fires, and storms more frequent and severe—causing more than $4 trillion in damages (WMO, 2023). Estimated costs globally of adapting to these new extremes are as high as $340 billion by 2030 and more than half a trillion by 2050 (UNEP, 2022).

We find that across key metrics, including direct economic benefits and reduced impacts from climate change, the Rapid Transition scenario is significantly better for society and human wellbeing than a fossil fuel-dependent economy under BAU (Figure 7). **More than twice as many jobs are created (36 million job years in RT compared to 14 million in BAU) and the cost of electricity access in Sub-Saharan Africa is 30% lower in the RT scenario.** This is especially critical in developing economies where millions of people still lack basic energy security and have high levels of poverty and human health challenges.

Figure 7. Projected socioeconomic impacts by 2050.



Notes: Net change in energy employment represents jobs created minus jobs lost, where 1 job-year = 1 full time position employed for a 1-year duration. Jobs include direct employment (construction, manufacturing, installation, operations and maintenance) and indirect employment. Estimates are based on IEA World Energy Employment Report 2022 and Wei et al 2010. Cost of electricity access was calculated for Sub-Saharan Africa as ~90% of people without electricity access after 2030 will be in this region. Cost estimates, expressed in terms of LCOE (Levelized cost of electricity) in US$/MWh, are based on IEA 2022, IEA 2021, and IEA 2017. Food supply costs are the annual (undiscounted) expenditures in US$ of adaptation and residual damage to sustain major crop yields, based on Iizumi et al 2020. Poverty risk is the change in populations vulnerable to poverty (income <$10/day), based on Byers et al 2018. Infrastructure damage is the present discounted value-at-risk (VaR) of global physical infrastructure in 2050 (in 2015 US$), based on The Economist Intelligence Unit 2015. Flooding risk is the percent of the global population that will experience increased flood risks with high likelihood, according to Alfieri et al 2016. Heat stress is the percent of the global population exposed to severe heat waves at least once every 5 years, based on Dosio et al 2018. Exposure to chronic water scarcity is the number of people globally who experience severe water scarcity for at least one month per year, based on IPCC AR6 WG2 Ch4, 2022.

The socioeconomic impacts from climate change-related extreme events are also significantly less in an RT scenario (1.5ºC warming levels) compared with the BAU scenario (3.2ºC warming levels). **The costs of infrastructure damage are 50% lower ($2 trillion compared to $4 trillion); food supply costs are also 50% lower; poverty risk, heat stress risk, and flooding risk are 65-70% lower; and the number of people that experience chronic water scarcity is up to 80% lower (Figure 7).** These statistics, largely based on the most recent IPCC findings (AR6 WG2, 2022), highlight that a renewable energy future improves food security, human health and livelihoods, and is cheaper and more socioeconomically beneficial, especially for developing economies.

Although the RT scenario generates more jobs overall, policymakers still need to consider the broader societal implications of changing employment trends to ensure an equitable energy transition. For example, legacy workers may struggle to access clean energy jobs because of where they live. In addition, some new employment opportunities may pay less well than traditional energy-related jobs (IEA 2021). Ensuring that the renewable energy transition is more economically equitable and environmentally just is critical to creating community ownership and overcoming potential conflicts around new renewable energy infrastructure.

Area footprints (land and marine)

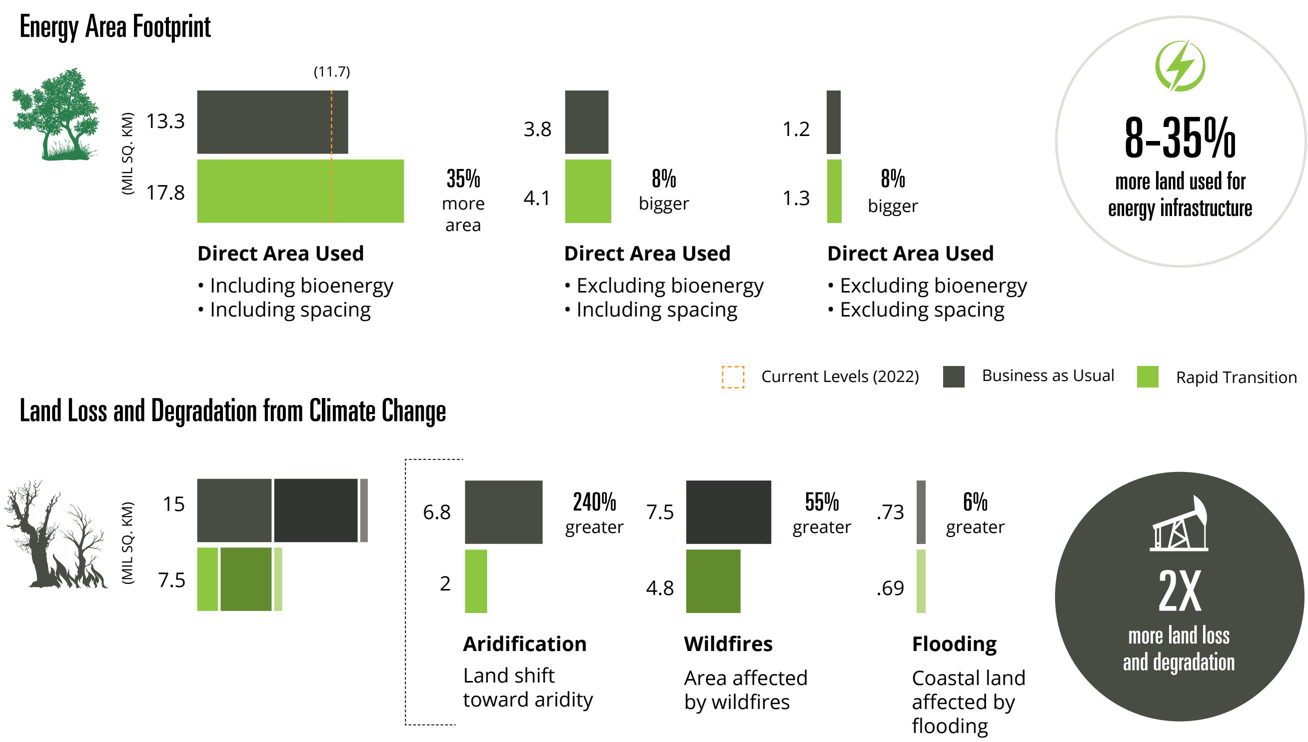
Land is a finite resource with various competing demands (including food and water supply, habitat and ecosystem service provision, development, and resource extraction). Most arable land is currently in use; so future land use and its sustainability will require balancing a wide range of priorities, including energy. Similarly, the increasing pressures on our oceans from toxic spills, eutrophication, marine debris, overfishing, extractive activities, and shoreline development will need to be carefully managed to maintain the resilience of, and provision of services from, marine habitats.

Today, the energy system covers 11.7 million kilometers square (km^2) on land and 36,000 km^2 in the ocean. **The RT scenario has a 35% larger energy area footprint (17.8 million km^2) compared to the BAU scenario (13.2 million km^2), with offshore (marine) area making up less than 5% of the total in both scenarios (Figure 8).** A majority (~80%) of the energy area footprint in RT is due to bioenergy crops (including for bioenergy with carbon capture and storage) which is 44% higher compared to BAU, followed by wind and hydropower. However, most of the wind energy footprint is in the area known as “spacing,” the unused areas of land and sea between wind turbines (note that this spacing is also relevant for the footprint of oil and gas facilities). Additional transmission and distribution (T&D) lines have a far smaller area footprint (0.03 million km^2), but because of their linear nature will still need to be carefully addressed.

The footprint of bioenergy can be substantially reduced by using biomass residues and waste to avoid using additional land for energy crops. The Energy Transitions Commission (2023a) estimates nearly all additional biomass needs for the clean energy transition can come from secondary products like agricultural waste and residues. In addition, fuel switching to renewables or green hydrogen to lower demand for biofuels, along with increasing bioenergy crop yields, could further reduce the bioenergy footprint. Impacts on habitats from wind and solar can also be reduced by co-locating them on agricultural land and urban areas, which is challenging or impossible to do with fossil fuel infrastructure due to their negative impacts (e.g., pollution and waste-water discharge from coal mines and oil refineries). In the case of wind, the “spacing” area is still there, but is maintained in productive agriculture or other services like pollinator fields, reducing the “loss” of land in the wind footprint. Solar can also be sited in places with nearly no impact on ecosystems, including on rooftops and parking lots, or floating on reservoirs. Indeed, in 2021, over 40% of solar PV installations were on rooftops (IEA, 2021). **If the additional land for bioenergy can be limited, and only the direct footprint of energy development is calculated** (i.e., the area occupied by the turbines and/or gas or oil facilities, not the area represented by the spacing between them), **then the area footprints are far smaller and comparable in both the RT and BAU scenarios (1.3 million and 1.2 million km^2, respectively)** (Figure 8).

Although the direct area footprint of energy development is important for assessing land and marine use tradeoffs, it provides an incomplete story. Impacts from climate change will also affect the amount and quality of habitable and arable land. Our analysis shows that in a BAU scenario, the total land lost and degraded due to climate change-related impacts, including aridity, wildfires, and coastal flooding is to up to 15 million km^2 of land globally by 2050, two times greater than in an RT scenario (Figure 8). **When considering both the footprint of energy development and that of climate change-related land loss and degradation, the projected total impact on land-use change is considerably greater with the BAU scenario.**

Figure 8. Projected impacts on area (land and marine) footprint from energy development and land lost and degraded from climate change impacts in 2050.



Notes: For the area footprint from energy development, land and marine area intensity values were estimated per TWh for each energy source in the scenarios, according to the following: Solar: UNEC 2021, EPRI, Industry interviews; Wind onshore: UNEC 2021, EPRI, Industry interviews; Wind offshore: UNEC 2021, EPRI, Industry interviews; Geothermal: EPRI, Jordaan et al., 2017; Nuclear: UNEC 2021, Lovering et al., 2022; Biomass, Oil, Gas, Coal, Hydropower: CLEANaction, 2023. 'Excluding spacing' means that the land between equipment within oil, gas, and wind facilities are leveraged for synergistic land use, and vice versa for 'including spacing.' The estimates for land lost and degraded from climate change were calculated as the sum of land area affected by increased aridity and desertification (Spinoni et al., 2021, Global Land Outlook, 2022), wildfire (Jones et al., 2022), and flooding (Brown et al., 2018, Kulp & Strauss 2019).

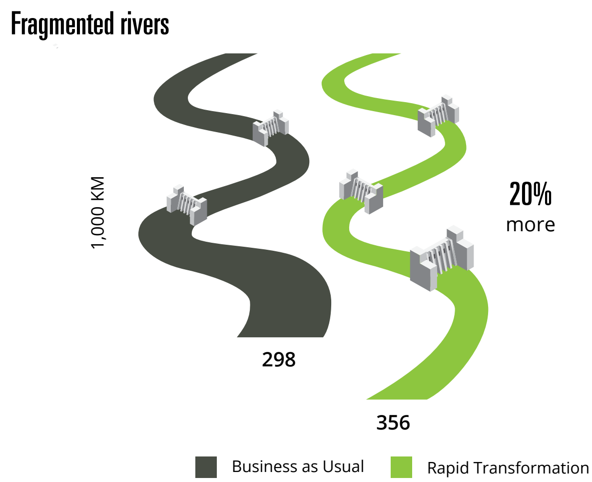
Free-flowing rivers

Free-flowing rivers provide a range of benefits to people, including habitat for fish and the delivery of sediment that maintains deltas. Hydropower dams have been a primary contributor to dramatic global declines of migratory fish (76% since 1970), which are often among the most important contributors to freshwater fisheries (Deinet et al., 2020). Further, the reservoirs behind dams now capture approximately one quarter of the global annual flux of sediment—silt and sand that would otherwise help maintain deltas in the face of erosion and sea level rise (Syvitski et al., 2005). Deltas are home to 500 million people and are some of the most important agricultural regions on the planet. Some key deltas, such as the Nile, have lost more than 90% of their sediment supply and are now sinking and shrinking (Syvitski et al., 2009).

Most energy transition scenarios consistent with the 1.5° C climate target, such as those from the International Energy Agency (IEA) and the International Renewable Energy Agency (IRENA), feature a doubling of global hydropower capacity. **Hydropower in the RT scenario is over 60% higher compared to the BAU.** While that amount of hydropower is a far smaller proportional increase than other renewables such as wind and solar PV, a 50-100% increase of global hydropower capacity nonetheless represents a dramatic expansion of major infrastructure that will affect the world's rivers—and the diverse benefits they provide to societies and economies from freshwater fisheries that feed hundreds of millions to flood mitigation and stable deltas.

The RT has larger negative impacts on the world's free-flowing rivers compared to the BAU. Only one-third of the world's longest (>1,000 km) rivers remain free flowing today (Grill et al., 2019). **The RT includes a level of hydropower development that would result in the damming of about half of those that remain (about a 20% increase in fragmented rivers relative to BAU),** while generating less than 1% of the needed renewable generation in 2050; Figure 9). As discussed in Section 2, there are a variety of ways to reduce this level of impact. Several other scenarios consistent with holding warming to 1.5° C include considerably lower levels of new hydropower. **Development at those levels, along with careful planning of dams that are developed, could reduce negative impacts from hydropower on the world's rivers by 90%** (Opperman et al. 2019).

Figure 9. Projected impacts on long free-flowing rivers in 2050.



Notes: Impacts from different levels of hydropower development on free-flowing rivers were calculated using data on free-flowing rivers from Grill et al. (2019) and planned hydropower dams from Zarfl et al. (2015). To estimate the impact on free-flowing rivers from the level of development in the RT we added all the dams in the Zarfl database (totaling about 10% less new capacity than what is in the RT) to a global hydrography database and recalculated connectivity statistics as described in Grill et al. (2019). This analysis is described in Thieme et al. (2021). Although many of the scenarios used the IPCC include an increase in hydropower, the one we selected for the BAU did not include additional hydropower (or, just enough new hydropower to offset decommissioning of older plants). Recent studies, such as Chowdhury et al. (in press) have found that ambitious climate policies are likely to increase hydropower expansion considerably compared to status quo trajectories.

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Section 2. A Framework for Achieving a Nature-Positive Energy Transformation

Though our findings confirm that a RT future is significantly better for nature and people than a BAU future, the transition will still exert considerable demands on a range of resources. Avoiding or reducing negative impacts and associated conflicts is critical to ensure that (1) the needed energy transition does not exacerbate the global nature crisis or negatively affect communities in other ways; and (2) by addressing these conflicts, the transition proceeds as rapidly as needed to meet climate targets and other sustainable development goals.

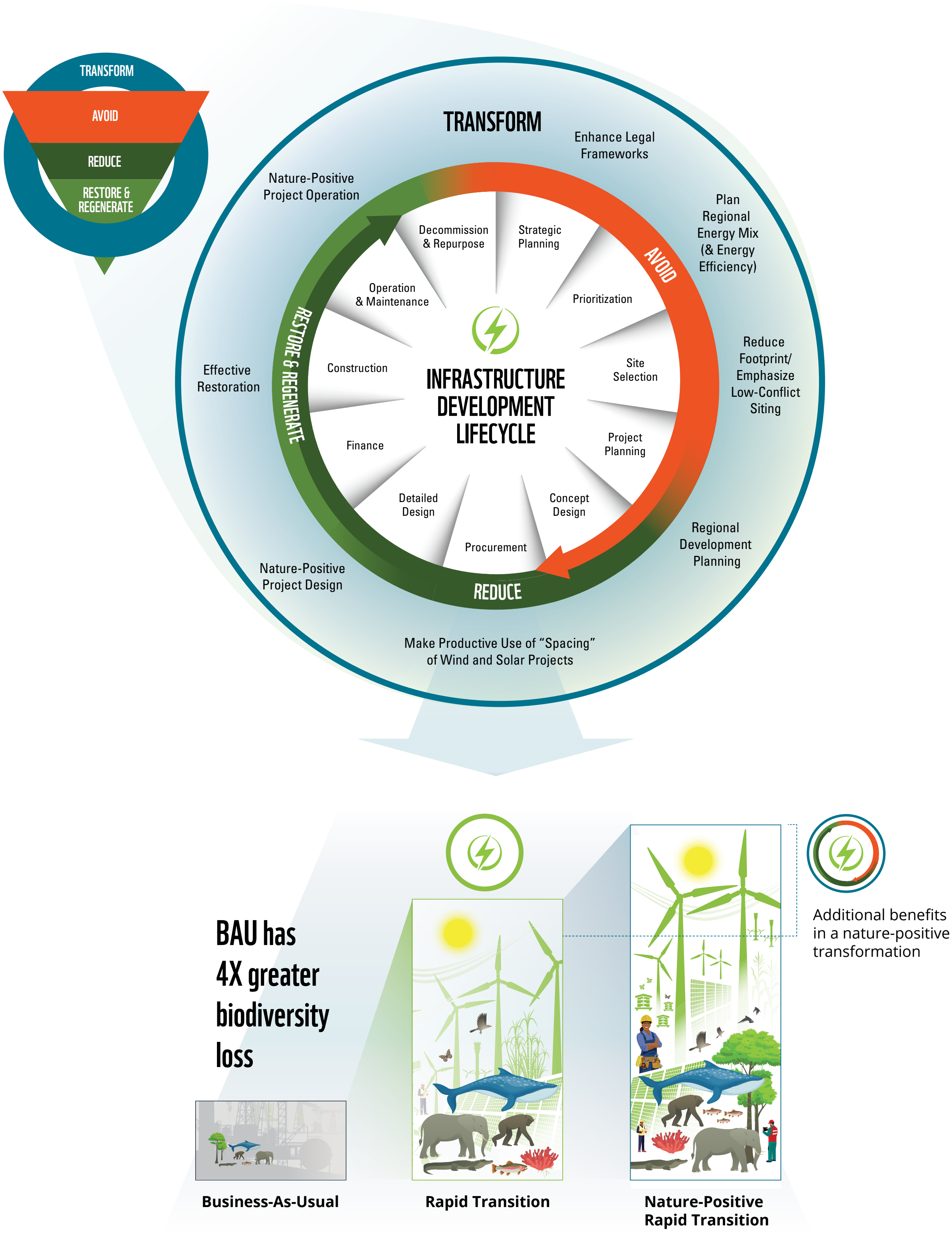
A nature-positive approach is therefore central to achieving the needed sustainable transformation of our energy system. Policymakers and other actors can deploy a range of laws, incentives, and practices to achieve this.

In this section we present a framework of seven mechanisms with high potential to shift energy systems to a nature-positive pathway. These mechanisms span different steps in the mitigation hierarchy, a widely accepted framework for addressing the impacts of development on nature that prioritizes avoidance and reduction—which offer the greatest potential for improving environmental outcomes—followed by the restoration and regeneration of degraded natural environments (Figure 10). We present them in a logical sequence that follows the infrastructure development lifecycle: from national-scale policies, to planning an overall energy mix, to siting of new projects, to nature-friendly designs and operations (Figure 10). These strategies are not exhaustive and there are a range of other legislative, regulatory, and best practices that can be applied toward these same goals (e.g., CLEANaction, 2023, ETC, 2023a, ETC, 2023b).

Key in this framework is the need for early and frequent stakeholder engagement to reduce conflicts and maximize benefits for people and nature. If done well, such engagement can ultimately accelerate energy projects by creating buy-in from potentially resistant stakeholders and securing agreement on how best to manage tradeoffs between development and environmental objectives. A transparent and inclusive stakeholder approach is also essential for a just energy transition by including marginalized communities as early as possible in the planning process.

To transition from fossil fuels to renewable energy at the speed and scale needed, and to do so in a sustainable and nature-positive way, these mechanisms can't be applied piecemeal, one project or company or region at a time. These approaches need to be directly embedded in a larger energy system-wide transformation, through levels of coordination that do not yet exist, including the broader process of how we build infrastructure and produce and use energy, as well as how we support and manage economic activities at larger spatial scales and longer time horizons (Figure 10). The report closes by outlining ways to catalyze this critical transformation.

Figure 10. The framework of mechanisms with high potential to shift energy systems to a nature-positive pathway.



Notes: The mechanisms span different steps in the mitigation hierarchy (adapted from SBTN) and are sequenced following the infrastructure development life cycle (adapted from UNEP and GIZ). To be successful, these approaches need to be directly embedded in the broader process of how we build infrastructure and produce and use energy and applied globally as part of a transformation of our energy system.

A Framework for Achieving a Nature-Positive Energy Transformation

Enhance legal frameworks for protecting nature

Avoidance is often the least costly and most effective way of reducing adverse impacts on nature and people. However, it requires including considerations about the natural environment in decision-making early in the planning process. Mitigating the negative effects of the energy transition on nature should therefore ideally start with strong overarching nature-preservation policies that protect critically important species and sensitive habitats.

The US Endangered Species Act and Australia's Environment Protection and Biodiversity Conservation Act are good examples of national policies that guide governments, landowners and others in the management and protection of each country's plants, animals, and ecosystems. Particularly when applied early in planning processes, and/or at regional scales, such policies can guide development choices in ways that both protect nature and support transparent and efficient regulatory processes. The absence of a strong policy framework, however, should not prevent relevant actors from using alternative approaches and following good practice in implementing the mitigation hierarchy (IFC, 2012).

In addition, habitats for endangered species should not be the only focus for planners looking to inform the avoid stage. Many important lands exist outside these critical areas that provide essential benefits to people, and these often lack the same level of protected status. Especially in a world of rapidly increasing climate extremes—even under the RT scenario—it is critical to take a comprehensive approach in planning major infrastructure investments to integrate and accurately assess trade-offs among climate risks, ecosystem services, community needs (including their dependence on critical ecosystem benefits), and biodiversity. Draft guidance from the US Biden Administration, for example, describes how government agencies should evaluate ecosystem services in federal investment decisions (White House 2023).

Plan the national or regional energy mix to manage tradeoffs between different options

Planning an energy mix (the type and amount of primary energy sources consumed by a country or region) to optimize energy, nature, and social objectives can help avoid some or most of the impacts from renewable energy development on land, oceans, and rivers. Because the impacts of an energy system vary according to the technology used (e.g., wind vs. hydropower) and the location where those technologies are built and operated, strategic planning of the mix of technologies in a given energy system provides the best opportunity to reduce and minimize impacts. For example, both hydropower and biomass can have relatively high impacts on environmental and social resources. Therefore, planning that considers options for different levels and combinations of technologies can compare and ultimately manage the tradeoffs associated with those options.

Planning energy sources requires forecasting target levels of needed generation, storage, and transmission. Reducing energy consumption can often be the most cost-effective way to avoid or reduce energy-related impacts and, therefore, such planning should also include a focus on options for energy efficiency and grid management (e.g., "smart grids") to reduce energy demand.

Energy planners can use tools such as capacity expansion models to guide their decisions about the mix of power-system investments (e.g., generation, storage, and transmission) needed to meet forecasted demands. These models should be coupled with analyses of the environmental and social performance of different technologies to understand the tradeoffs of different development options (Opperman et al., 2023). The Energy Policy Simulator, an open-source model for estimating the environmental, economic, and human health effects of climate and energy policies developed by RMI, is one such tool. A summary table containing examples of the different tools and databases currently available to policymakers is provided in the Technical Annex.

Governments can use Integrated Resource Plans (IRPs), or similar long-range energy planning processes, to develop blueprints for power-system expansion. While these processes have typically proposed a mix of generation technologies to achieve least-cost objectives, they can also compare the performance of different options (e.g., different combinations of generation technologies) in terms of how they perform for climate, environmental, and social objectives. The IRP process can be adapted so it allows governments to identify energy development pathways that are low carbon, low cost, and as low conflict (both in terms of social and environmental aspects) as possible (LowCx3).

Reduce the footprint of energy development with high impacts

The overall footprint of energy development—including both the area (land and oceans) and the fragmentation of rivers—is one of the few categories where the projected impacts of the RT are potentially higher than those of the BAU. Addressing the land, ocean and river footprints of the RT is thus one of the most important challenges for achieving a nature-positive energy transition. In this section we explore how these footprints can be reduced.

Energy mix planning (described above), when coupled with an assessment of tradeoffs of alternatives, can inform decision makers about where the footprints of specific renewable energy choices pose risks to other resources and help identify substitutes or management options to avoid and reduce impacts. Because biomass and hydropower are two of the main reasons for the projected higher footprint impacts from the RT, here we explore options to reduce or substitute for those choices. We also explore how to reduce the footprint of energy development through synergistic management of "spacing" land in wind farms.

Reduce the land and marine area footprint

Many 1.5°C scenarios include a significant contribution from biomass because of its assumed low cost and potential ability to remove carbon through carbon capture and storage. For example, the IPCC scenario we used for the RT projects that by 2050, biomass will contribute 39% of the primary energy mix in Latin America and 26% in Africa. However, this production could displace other agricultural crops or promote conversion of forests and other ecosystems while affecting water resources through consumption and pollution.

This extent of land dedicated to renewable energy can be reduced through several interventions. First, the area required for biomass crops can be reduced if a portion of the biomass energy demand (e.g., that used for electricity generation) is replaced by wind and solar. Second, advanced agricultural technology and policies to promote appropriate crop types can increase the yield from biomass, reducing land requirements for the same energy output. Third, using agricultural and forestry waste products and residues would reduce the amount of dedicated bioenergy crops and related land, water and nutrients needed. The Energy Transition Commission finds that nearly all additional biomass needed for the renewable transition can come from agricultural waste products, requiring essentially no additional land for biomass (ETC 2023a). And fourth, the area footprint of the renewable transition can also be reduced by synergistically managing the land between wind turbines with agriculture or natural vegetation, which can provide additional services, such as pollinator habitat. Similarly, with offshore wind, pilot projects have explored aquaculture "co-location" with offshore wind turbines, with the potential additional benefit of water filtration (from bivalve aquaculture). Note that these areas would still be part of the spacing of wind turbines, but because the areas would be producing food or ecosystem services, they could be considered no longer part of the footprint as defined as a negative impact. We estimate that these four interventions could reduce the direct area footprint of an RT scenario by 35%. (Figure 11).

Reduce the footprint of hydropower

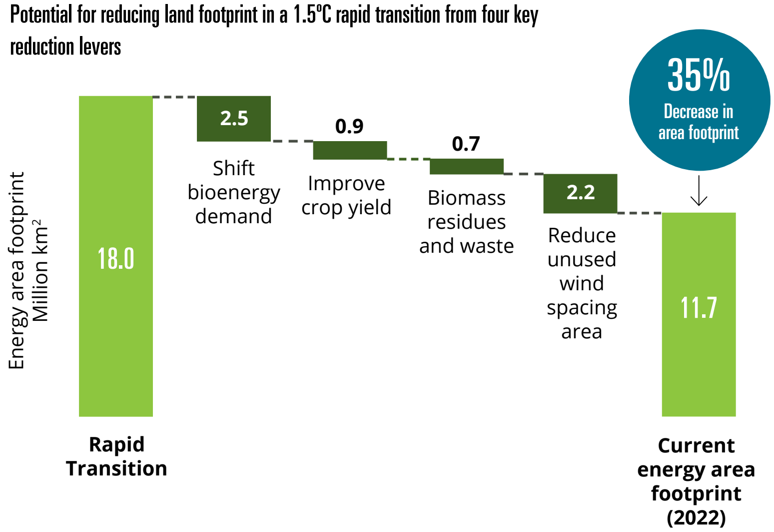
Although hydropower's contribution to the energy mix in a 1.5°C RT scenario is 5% of the global energy mix by 2050—far lower than that of wind, solar, or biomass—that level would still represent a 60% increase in installed hydropower capacity between now and then, and many other climate mitigation projections project a doubling of current capacity (IEA, 2021; IPCC AR6 WG3 Ch 6, 2022). Despite its relatively small share of global electricity generation by 2050 in the RT scenario, this level of development would have dramatic negative effects on the world's remaining free-flowing rivers and the services they provide to people, with particularly high impacts on free-flowing large tropical rivers in Asia, Africa and Latin America that support the greatest level of ecosystem services and biodiversity (Opperman et al., 2019; Thieme et al., 2021; Chowdhury et al., 2023)

Due to the potential for significant environmental and social impacts, decision-makers should assess hydropower in the context of broader power-system planning and consider the costs and benefits of different technology options, including lower-impact alternatives. Substituting other generation technologies for a portion of planned hydropower and then carefully siting new hydropower projects could reduce the impact from hydropower on free-flowing rivers in an RT scenario by nearly 90% (Figure 11; Opperman et al., 2019). Grid-scale studies have demonstrated that alternatives to hydropower with large negative impacts can generally be found, often with little or no difference in system cost (Opperman et al., 2023). Further, existing and new dams can also be designed or retrofitted to lessen their impacts on ecosystem extent and function (Thieme et al. 2023).

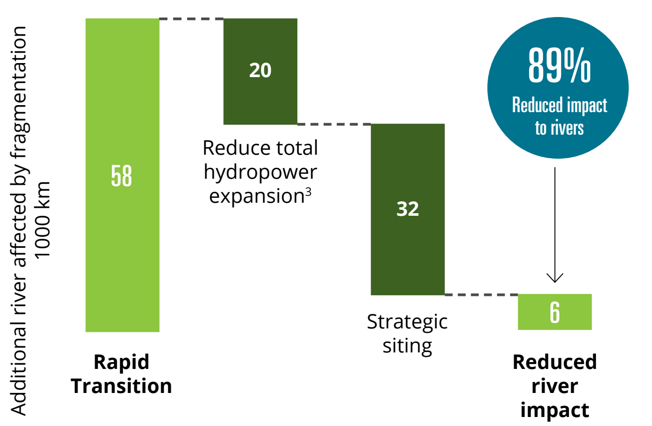
Markets for exporting electricity can drive additional hydropower development, with a potentially negative impact on rivers. For example, Laos has plans to build hydropower dams on the Mekong River primarily for export to neighboring countries. However, such cross-border trade can also promote a greater proportion of wind and solar within power systems by integrating larger and more diverse areas of both supply and demand. For example, Europe's interconnected power grid allows national electricity markets to trade power to balance differences between consumption and generation in individual countries, smoothing out the generation coming from variable renewables (European Council, 2017). This large-scale integration also increases the potential for many countries to find development sites for new generations in low-impact areas (see next section).

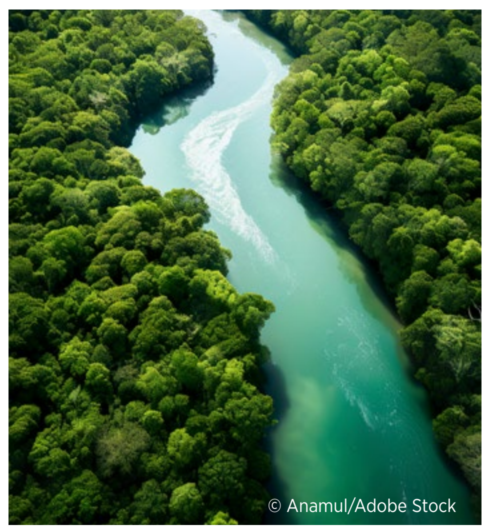
Figure 11. Strategies and estimates for reducing land footprints and hydropower impacts on flowing rivers.

Potential for reducing land footprint in a 1.5°C rapid transition from four key reduction levers



Potential for maintaining free-flowing rivers in a 1.5 °C rapid transition scenario from two key reduction levers





Notes: Interventions like shifting demand for bioenergy, improving crop yields, reducing unused space between wind turbines, and using agricultural and forestry waste and residues instead of dedicated energy crops can reduce the direct area footprint of an RT scenario by about 35%—making the area footprint about equivalent to the current amount of land used by our energy system today (11.7 million km²). The lower demand for bioenergy represents the difference between the percent of bioenergy use in the Rapid Transition scenario (19%) to the 5th percentile of all IPCC 1.5°C scenarios (Byers et al., 2022). Crop yield increases represent efficiency gains by switching to more productive energy crops (see Technical Annex). A large portion of future bioenergy demand (11-21 EJ/year) could be met using agricultural residues (5-12 EJ/yr) and municipal and industrial waste (6-9 EJ/yr), freeing up approximately 0.6-1.1 million km² of energy crop biomass needed (ETC, 2021). The estimate for reducing the wind turbine spacing area, or the unused area between equipment that can be potentially leveraged for synergistic land use, assumes that up to ~80% can be co-located with other productive activities. The impact on rivers can be diminished by about 90% by limiting hydropower expansion and carefully planning new projects (analysis described in Opperman et al. (2019)).

Site energy and mining projects in low-conflict areas

Global-scale mapping studies have found that much of the needed expansion of renewable energy infrastructure can occur on sites that will have minimal disruption on nature and communities (CLEANaction, 2023). Areas that will generally have very low negative impacts include rooftops, parking lots, reservoirs, and abandoned mines for solar PV and pastures or other agricultural land for wind turbines. Using available roof space alone would generate 26,800 TWh, comparable to global electricity demand in 2021 (Joshi et al., 2021).

Many countries can meet 2050 renewable energy targets using these already converted lands. However, 68 countries—including leading emitters such as China, Japan, India, and Indonesia—may not have sufficient converted land (Baruch-Mordo et al., 2019). This lack highlights the importance of strong regulations governing the siting of projects on greenfield land and free-flowing rivers, and of cross-border trading.

As an example of directing new development toward areas with lower negative impacts, regulators in Montgomery County (Maryland, US) developed codes that directed development away from the most valuable agricultural areas. The codes allowed solar installations in the county's Agricultural Reserve, a protected rural area, provided they are not located on fertile soils. In addition, the land underneath the installations must be used synergistically with nature and agriculture, such as for pasture or for "agrivoltaic" crops (plants grown in spacing between panels) (Montgomery County Code, 2023).

Mapping can identify the overlay between resource availability and areas of low-conflict—and can also identify "no go" zones where new development should be avoided (such as protected areas and Key Biodiversity Areas (KBAs)). Regional planning can guide the siting of wind and solar projects toward these low-impact or already converted sites. This is the focus of the next section. Box 3 provides a deep dive on mining, including siting to avoid conflicts and measures to reduce the footprint of mining, including through recycling to reduce the need for new materials.

BOX 3: Reducing the impacts of mining for critical minerals

Although the renewable transition will require less mining than a BAU future, increased extraction of critical minerals and materials will be required. Such mining can result in considerable damage to the natural environment through toxic discharge or disruption to sensitive habitats. **Permitting processes should avoid mines near fragile habitats and protected areas.** Regulators can use geospatial tools to help them determine the degree of biodiversity risk in specific areas. For example, the Key Biodiversity Area (KBA) dashboard currently has over 16,000 KBAs, locations considered highly important for species and their habitats. Of these, about 300 KBAs are at risk of high or extremely high impact due to mining and other extraction activities (KBA, 2023). Regulators can block projects that pose unacceptable environmental or social risks, including disruption to heritage sites and Indigenous land.

Mining certification standards can help policymakers create transparency and foster trust in the sourcing of mined products. For example, the Initiative for Responsible Mining Assurance (IRMA) provides a global standard for responsible mining with an independent, third-party assessment of industrial-scale mine sites (IRMA, 2018). International organizations, such as the Intergovernmental Forum on Mining, Minerals, Metals and Sustainable Development, also promote responsible mining practices.

Deep seabed mining—the extraction of valuable mineral deposits from the seafloor—currently poses considerable uncertainty and risk. Early studies indicate that deep sea mining can result in sediment plumes and light and noise pollution, posing significant risk of harm to deep-sea ecosystems (Miller et al., 2018). While there are no commercial operations yet, interest in deep seabed mining is growing. **Countries should consider prohibiting further mining activity until all the risks have been assessed and they are sure that all potential negative effects can be successfully managed.**

Finally, just as energy efficiency can replace the need for some proportion of new energy projects—and thus avoid their impacts— circular economies (recycling) for materials can replace the need for some proportion of mining and thus avoid associated impacts. Increasing recycling rates and reducing the need for new materials can thus avoid some impacts to nature. About 250,000 tons of electric car batteries will be discarded each year over the next decade. Many valuable materials in these batteries, such as lithium and cobalt, can be recovered using current technologies. However, only about 3% of lithium-ion batteries are recycled today (Swain, 2016). Policymakers have an important role to play in boosting recycling rates through mandates, rebates, and tax credits that encourage various actors to recycle and develop effective collection and sorting programs. The EU's new battery directive, for example, sets minimum levels of recovered metals that must be reused in new batteries (EU, 2022). Furthermore, investing in new research and development for alternative materials is also needed and can reduce demand for critical minerals.

Implement regional planning to improve outcomes for energy, the environment, and communities

Permitting a renewable energy project can be complex and time consuming. In the US, for example, developers typically must deal with federal, state, and local regulators, with federal agencies taking an average of 4.5 years to complete an environmental impact statement (EIS) for a proposed development (White House CEQ, 2020). Similarly, in the European Union, an estimated 80% of wind and solar projects are delayed during the permitting phase (GlobalData, 2022). As a result, advocates for renewable energy often recommend increasing the efficiency of permitting processes to accelerate the implementation of projects.

Regional planning processes have demonstrated that promoting early stakeholder engagement and integration of energy planning with conservation planning can result in more efficient and faster permitting processes, while also facilitating improved outcomes for ecosystems and communities. They can help regulators clarify rules, improve interagency coordination, centralize the recording of permit approval and review decisions, establish and strengthen stakeholder consultation and engagement processes, and ensure that agencies have sufficient technical resources for their reviews.

These processes integrate the typical criteria for selecting energy sites (level of the resource, distance to roads and transmission lines, etc.) with conservation planning (distribution of species and ecosystem services, objectives for conservation areas, etc.). This integration results in the selection of sites with low conflicts–and thus lower potential for legal or other challenges–along with more strategic gains for conservation than is typically achieved through project-level, and thus generally piecemeal, mitigation. Existing mechanisms, such as Strategic Environmental Assessments (SEAs), can be adapted to facilitate regional approaches to permitting and review.

Examples of regional planning for renewables have demonstrated its potential to both streamline permitting and generate significant funding directed toward achieving regional conservation goals:

- Under the Renewable Energy Directive, European Union officials set deadlines for granting permits (including a three-month review period for solar projects) and lowered the requirements for so-called "go-to" areas that have high renewables potential and pose few risks to the natural environment (European Commission, 2023).
- Through a planning process that featured extensive stakeholder participation (including conservation organizations, state and local governments, and Tribal Nations), the US Bureau of Land Management (BLM) created 17 zones in the southwestern US that are ideally suited for utility-scale solar production based on factors including solar potential, topography, and minimal overlap with critical habitats, areas of environmental concern, and areas with important cultural and archeological resources (U.S. Department of the Interior, 2019). Permitting times were reduced by more than half for projects within these zones, from an average of two years to about ten months. This process also created "no go" areas to protect the most important habitats, contributing to the conservation of large blocks of high-quality habitat.
- In the Philippines, regulators established 25 Competitive Renewable Energy Zones (CREZ). These areas have high resource potential and low development costs and pose minimal risks to nature (Lee et al., 2020).

While it is up to policymakers to create rules governing the planning, siting, and permitting of renewable energy projects, other stakeholders have a role to play. Non-governmental organizations have worked to promote regional planning for renewables, including WWF-Canada's Renewables for Nature and The Nature Conservancy's Site Renewables Right Program, which identified 300,000 km^2 in the central U.S. with the potential for low-conflict renewable siting. Developers can work with these NGOs and use geospatial tools to identify low-conflict sites based on factors including energy potential, topographical suitability, and proximity to habitats (TNC, 2022).

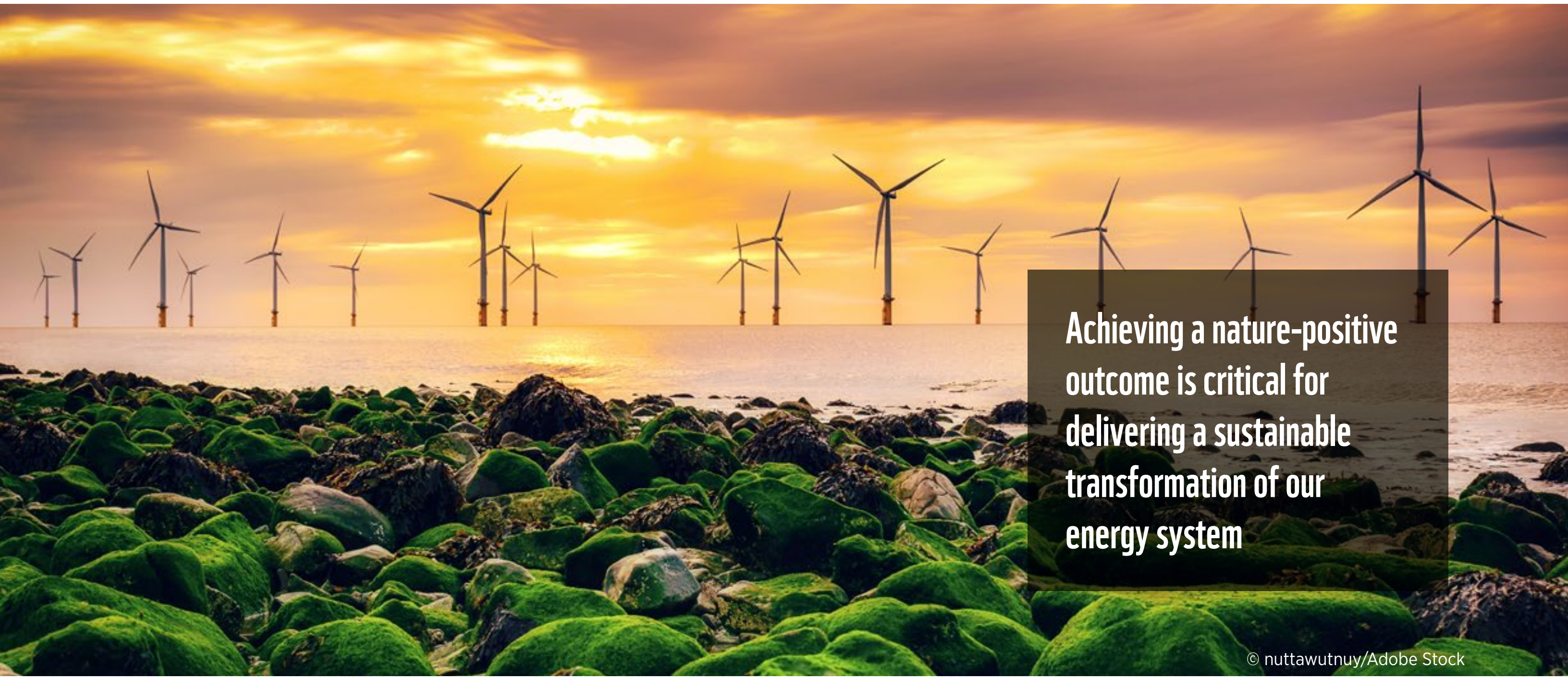
Use nature-friendly project designs, operations, and effective restoration

Renewable energy projects can be designed and built in ways that reduce impacts on species and ecosystems. Nature-friendly design solutions can be used with solar and wind farms. For example, at its Hollandse Kust West offshore wind farm in the Netherlands, developer Vattenfall has incorporated openings in turbine foundations to allow fish movement and added rocks that serve as habitat and promote marine biodiversity (Vattenfall, 2022). In the Netherlands, researchers are experimenting with painting wind turbine blades black to reduce bird collisions (Vattenfall, 2022). The layout for offshore wind turbines can be designed to reduce impacts on bird migration routes. Turbines can be built in clusters and include corridors allowing birds to pass between the clusters (IUCN, 2021).

Mandating minimum distances between projects and nesting sites or migration routes can reduce damaging impact on habitats. In Alberta, Canada, policymakers established setback requirements ranging between 50 meters and 3,200 meters via the Wildlife Directive for Alberta Solar Energy Projects (Alberta Environment and Parks, 2017).

The linear infrastructure needed for energy projects—including roads, railways, and transmission lines—should also be planned and designed through processes that fully integrate requirements for minimizing negative impacts on wildlife and ecosystems and their services, including those important for reducing climate risks (Bartlett, 2020). In Spain's Sevilla region, native shrubs and seedlings were planted near transmission lines to improve local habitat conditions. As a result, the region has enjoyed enhanced ecological connectivity and greater diversity of invertebrates, small mammals, and bird species (Ferrer et al., 2020).

Operations can also be adjusted to reduce impacts on nature or restore ecosystems. For example, wind turbines can be shut down during key periods of bird migration when risks of bird strike are greatest. Hydropower dams can release environmental flows to maintain or restore habitat conditions in rivers. Finally, restoration is increasingly required for any major infrastructure project with a significant impact on intact habitats, as regulators and civil society continue to move the private sector toward "nature-positive" approaches (Locke et al., 2021). Restoration success can be improved through the development of ecological baselines, built by collecting data on pre-impact conditions of affected habitats. They can use collection guidelines, such as the Cross Sector Biodiversity Initiative's "Good Practices for the Collection of Biodiversity Baseline Data" (Gullison et al., 2015) and biodiversity databases, such as the IUCN's red list of threatened species.



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Catalyze a nature-positive energy transformation

The various mechanisms reviewed above are essential for reducing conflicts between needed renewable energy systems, communities, and ecosystems. In short, they can help the renewable transition to be both rapid and careful. But to fully address both the climate and nature crises, these mechanisms will need to be part of a broader set of transformations in how economies operate.

None of these mechanisms are entirely new. There is a long history of strengthening environmental, social, and governance (ESG) standards for major infrastructure development projects, to the extent that ESG is now a minimum basic requirement for all major projects, including renewable energy and mining infrastructure. As is now clear, however, existing regulatory and ESG frameworks have not yet been sufficiently robust to meaningfully address the simultaneous and growing climate and biodiversity crises. Implementation and oversight remain a challenge in many countries, especially those with urgent development needs and limited institutional and governance capacity. But more fundamentally, negative impacts on nature and climate have been viewed as the unfortunate, but necessary, externalities of development rather than truly internalized in project evaluations.

Due to this framing, many decision-makers, financers, and developers have generally overlooked the "avoid" stage of the mitigation hierarchy, instead relying on smaller changes at later stages once projects are largely designed and financed. And stakeholders, including communities most directly affected, have also often been consulted only when projects are already approved, greatly limiting opportunities to fundamentally change plans or designs because the costs for changes are too steep.

But the gravity of current global crises underscores the need to move beyond incremental progress. Climate-driven extremes, with tragic impacts on people and ecosystems, are becoming more frequent and severe (**IPCC AR6 WG2, 2022**). Meanwhile, global wildlife populations have declined by a staggering average of 69% since 1970 (**WWF, 2022**). **It is clear we need a profound shift in how we plan, design, develop, and ultimately either repurpose or decommission infrastructure.**

There are signs that this shift is underway. New initiatives like the Science Based Targets for Nature (SBTN) and the Task Force for Nature Related Disclosures (TNFD) are creating novel, rigorous frameworks for the private sector to better integrate nature into their business models.

To achieve the necessary speed and scale of the Rapid Transition scenario, however, a more fundamental *transformation* in the energy sector and of our global energy system is needed. It cannot be done one project or company at a time or through simply scaling up the ESG approaches of the past. Systems and projects need to be planned at larger spatial scales and on longer time horizons, based on clear cost-benefit analyses of not just how they impact people and nature, but how they depend on the ecosystem services nature provides—especially those that reduce climate hazards and support community needs. A circular economic model will also be key for reducing the need for primary materials and additional extraction and lessening the impacts from disposal of materials. And the only way to effectively address local concerns and pushback is through genuine, comprehensive stakeholder engagement that creates ownership over shared outcomes early in the development process.

These transformations in planning, engagement, and the integration of nature's costs and benefits into all phases of the project development cycle are essential for both reversing the decline of nature and creating a more resilient, equitable, and prosperous future.

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