

Emerging Technologies and the GEF

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Emerging technologies and the GEF: A STAP Information Note

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Executive summary

Emerging technologies are increasingly shaping how environmental challenges are understood, governed, financed, and addressed. Across the Global Environment Facility (GEF) partnership, such technologies can strengthen project design, improve monitoring and accountability, enable more adaptive and responsive management, and reduce environmental impacts in hard-to-abate sectors.

Rapid technological change, falling costs of digital and clean energy systems, and growing demand for environmental transparency and traceability create an **opportunity for the GEF to engage more strategically with emerging technologies**. In some contexts, these trends enable countries to leapfrog older, less-efficient and more-polluting systems. Across the GEF portfolio, emerging technologies can contribute to environmental outcomes by:

- Strengthening **environmental monitoring, diagnosis and early warning** (e.g. satellite monitoring of deforestation hotspots or fisheries);
- Improving **transparency and compliance** (e.g. digital monitoring, reporting and verification platforms for carbon markets);
- Increasing **resource efficiency** and reducing environmental pressures (e.g. for plastic recovery and recycling);
- Enabling **transitions to less polluting technologies** in hard-to-abate sectors (e.g. industries and transport);
- Supporting **ecosystem restoration, remediation and regeneration** (e.g. treatment of polluted, contaminated or degraded soils);
- Enhancing **climate adaptation, resilience and adaptive management** (e.g. early warnings for disaster preparedness); and
- Catalysing **systems transformation** by reshaping information flows, coordination, governance, decision-making and implementation.

This paper highlights ten case studies that provide practical examples of technologies the GEF could strategically pursue and scale under the ninth GEF replenishment cycle. Some of these are already being deployed in GEF-supported projects. Examples (see Table 1 and Annex 1) include:

- Drones and geospatial tools supporting equitable climate adaptation in Colombia
- Blockchain-enabled crowdfunding and digital platforms for restoration in Cameroon and Kenya
- Clean hydrogen technologies under the Global Clean Hydrogen Programme
- On-board and remote electronic monitoring systems in global tuna fisheries
- Smart grids, battery storage and electric mobility solutions in the Sustainable Cities Integrated Program in Malaysia

- Drones, camera traps, AI-enabled tools and traceability systems in the Wildlife Conservation for Development Integrated Program

Yet, there are significant risks to navigate. **Technologies that are poorly governed, deployed without adequate safeguards or scaled prematurely can accelerate resource use, deepen inequalities, create unintended environmental harm, or lock institutions and markets into unsustainable pathways.** For example, gains achieved through energy efficiency technologies can lead to increased overall consumption, thus diminishing the efficiency gains. Blockchain-based traceability systems may improve transparency but exclude smallholders with limited capacity. AI-enabled systems can strengthen monitoring while increasing energy use, water demand and e-waste. In addition, digital monitoring technologies can strengthen enforcement but may also create risks related to surveillance, data governance and social trust if safeguards are weak.

To assess the opportunities and risks, emerging technologies should not be treated as stand-alone solutions but as components of broader “socio-technical systems” shaped by governance, financing, institutional capacity, infrastructure and social norms. In many cases, the most important gains from using new technology lie less in direct biophysical effects than in improving decision-making, coordination and implementation across systems.

Persistent barriers to the application of emerging technologies include limited institutional capacity, weak data and infrastructure, fragmented governance, lack of sustainable finance, and the absence of long-term ownership, maintenance and scaling pathways. Evidence from the literature, expert consultations and case studies indicates that **successful deployment depends on enabling conditions, including policy alignment, institutional readiness, technical capacity, sustainable financing, safeguards and trust.**

Given the speed and uncertainty of technological change, effective engagement requires anticipatory, evidence-based and adaptive approaches that consider risks vs. benefits, trade-offs and long-term implications. The paper reaches five main conclusions:

- **Emerging technologies are not neutral tools.** Their contribution to global environmental benefits (GEBs) depends on how they are embedded in institutions, governance arrangements, and social contexts.
- **The function of emerging technologies is more important than their novelty.** Their value lies in their ability to improve decision-making, coordination, incentives, and overall system performance.
- **Context determines success or failure.** Without adequate policy alignment, institutional capacity, financing, and governance, emerging technologies are less likely to scale or deliver durable GEBs.
- **Risks and trade-offs must be addressed early.** Poorly governed technologies can create lock-ins, rebound effects, inequality and unintended environmental harm.

- **The GEF’s comparative advantage lies in enabling strategic, responsible deployment and scaling.** The GEF can add the greatest value by creating enabling conditions, supporting piloting and learning, and helping scale technologies that contribute to transformation, adaptation, and resilience. This requires anticipatory, evidence-based, and adaptive engagement, including informed selection, phased deployment, continual monitoring, iterative course correction, and early attention to systemic risks, lock-in, equity, and inclusion.

Delivering on these opportunities will require coordinated but differentiated actions across the GEF partnership:

- **The GEF Secretariat** could help to shape how the partnership engages with emerging technologies, strengthening portfolio-level learning and knowledge exchange, and ensuring alignment with strategic objectives, safeguards, risk appetite and other operational policies.
- **GEF agencies** could translate strategic direction into practice by integrating emerging technologies into project and programme design, bridging internal silos, building partnerships, and facilitating learning and scaling across countries and programmes.
- **Countries** could anchor technology engagement in national priorities and institutional realities by strengthening governance, policy coherence, safeguards, long-term ownership, and capacity for implementation and oversight.

Embracing new technology is not itself a useful goal. By adopting a deliberate, context-sensitive and system-oriented approach, the GEF can better harness such technologies to deliver durable, inclusive and transformational environmental outcomes.

1. Introduction

Emerging technologies are increasingly shaping how environmental challenges are understood, governed, financed, and addressed. Across the Global Environment Facility (GEF) partnership, technologies are creating new possibilities for stronger project and programme design, better monitoring and accountability, and more adaptive management in solving evolving challenges. In some domains, they may also enable new pathways to reduce the environmental footprint of “hard-to-abate sectors”¹ such as heavy industry. For example, digital monitoring, reporting, and verification (MRV) systems can improve the credibility of carbon accounting, while distributed renewable energy systems can help countries expand energy access without locking into more-polluting infrastructure.

Nevertheless, evidence from the scientific and technical literature indicates that technological potential does not automatically translate into durable environmental outcomes. Technologies that are poorly governed, deployed without adequate safeguards or scaled prematurely can reinforce existing problems rather than solve them. They can deepen inequalities, create new environmental pressures or lock institutions and markets into pathways that are difficult and costly to reverse.² For example, technologies that improve efficiency in water or energy use can sometimes reduce costs in ways that encourage greater overall consumption, thus offsetting part of the environmental gains.

For the GEF, this creates significant opportunities and real risks. Emerging technologies can strengthen the delivery of global environmental benefits (GEBs) by improving data, enabling new implementation modalities, and opening new ways to address environmental challenges. At the same time, emerging technologies can introduce uncertainty, unintended consequences, and uneven outcomes.

Previous Scientific and Technical Advisory Panel (STAP) papers and GEF Independent Evaluation Office (IEO) evaluations have shown that the GEF is increasingly incorporating emerging technologies into its portfolio, although more can be done,³ while also underscoring that technological advances bring new trade-offs that must be explicitly assessed and managed.⁴

This STAP information note, therefore, treats emerging technologies not as stand-alone solutions, but as components of dynamic socio-technical systems.⁵ Technology performance depends on governance arrangements, institutional and technical capacities, safeguards, financing and enabling environments that vary across contexts.⁶ For example, a remote sensing platform may

¹ Hard-to-abate sectors are industries and economic activities where reducing greenhouse gas emissions or environmental impacts is technically, economically or logistically challenging, primarily due to high needs for energy or natural resources (e.g. rare earth minerals or water) and inherent process emissions.

² Florin, 2023a; OECD, 2024b; UNEP, 2025a; UNCTAD, 2025

³ GEF IEO, 2025a, 2025b; STAP, 2025a

⁴ Barra & Leonard, 2018; Bierbaum et al., 2024; STAP, 2025a

⁵ Geels & Schot, 2007

⁶ Geels, 2019

improve land-use planning when institutions can use the data effectively, but it may have limited impact when data systems are fragmented or decision-making authority is weak. The central premise is that **emerging technologies matter for the GEF not because of their novelty, but because of their inherent potential to open or constrain pathways to transformation.**

Against this backdrop, this paper first frames the role of emerging technologies in the GEF context. It then investigates how such technologies are applied to environmental challenges (see the ten case studies in Section 3), how they contribute to durable GEBs, and the factors that influence their effectiveness. Drawing on scientific and technical literature, GEF evaluation evidence, and expert consultations/interviews, the paper then examines the barriers, enabling conditions, and risks associated with emerging technologies. It then outlines considerations and criteria to support more informed, context-sensitive and strategic engagement across the GEF partnership. It ends by outlining the key conclusions and strategic implications for the GEF. The Annexes provide illustrative examples, selection criteria for GEF engagement, guiding considerations for the deployment of emerging technologies, and an analytical synthesis of expert consultations.

2. Framing emerging technologies in the GEF context

2.1 Defining emerging technologies

Despite growing interest, there is no single agreed-upon definition of what constitutes an “emerging technology”. Some definitions focus on the potential socioeconomic impact.⁷ Others emphasize uncertainty and ambiguity in the early stages of development and deployment.⁸ Still others stress characteristics such as novelty, rapid growth, and coherence over time.⁹ Policy and technical literature often uses the term more loosely, referring to technologies that are new, evolving, or potentially transformative, without consistently specifying criteria for qualifying them as emerging.¹⁰ However, across these different strands of literature, there is broad convergence around three recurring features: novelty or rapid evolution; expanding or shifting applications; and uncertainty over trajectories, impacts, and governance requirements.¹¹

For the purposes of this paper, STAP adopts a policy-relevant definition tailored to the GEF operational and strategic context. The emphasis is not on novelty per se, but on conditions under which emerging or increasingly prominent technologies may credibly contribute to the delivery of GEBs and transformational change.¹² Accordingly, emerging technologies are understood here as *novel or rapidly evolving technologies, technology-enabled systems or applications at an early*

⁷ König et al., 2021;

⁸ Boon & Moors, 2014; König et al., 2021

⁹ Rotolo et al., 2015; König et al., 2021

¹⁰ UNEP, 2025a; WEF, 2025

¹¹ Rotolo et al., 2015; Kwon et al., 2019; Florin, 2023a; Florin, 2023b; OECD, 2024b

¹² Rotolo et al., 2015

stage of development, deployment or diffusion, whose impacts, uses and governance still need consideration. The definition recognizes that a technology may be well established in some contexts but still be considered “emerging” in others. For the GEF, these technologies become relevant when they can significantly affect the delivery of GEBs and contribute to broader systems transformation.

2.2 The contextual and dynamic nature of emergence

A key implication of this framing is that the emergent status of a technology is not fixed, but context-dependent. Technologies may be technically mature in one geography, sector or application, while still regarded as emerging in others. This could be because their use is novel, the capacity for adoption is limited, or institutional, governance, and environmental implications are still evolving.¹³

This is particularly important in the GEF context, where technologies that are generally considered established (e.g., remote sensing, digital platforms, or distributed energy systems) may still be novel or emerging in some settings. In some cases, commercially mature technologies can be considered emerging when applied to the delivery of GEBs in low-capacity settings.¹⁴ For example, solar photovoltaic systems are mature and widely deployed globally. Yet, their use in decentralized mini-grids or in arrangements such as agrivoltaics¹⁵ may still be considered emerging in areas where institutional capacity, regulatory frameworks, financing models, and operation and maintenance systems are still developing.¹⁶

Accordingly, the relevance of emerging technologies to the GEF also depends on the specific deployment context, the functions they are intended to serve, and the technical and institutional capacities available. This reinforces the **need for a selective, decision-oriented approach focused not on technological novelty but on fitness for purpose**. In line with this thinking, the paper highlights some technologies relevant to the GEF, with ten case studies of their applications, but does not seek to recommend specific technologies. Instead, it discusses conditions under which their use is most likely to support durable GEBs and transformational change.

2.3 Emerging technologies as socio-technical systems

A defining characteristic of emerging technologies is uncertainty, which is not limited to technical performance. Such uncertainty also concerns system-level impacts, deployment pathways, and longer-term environmental and social consequences. It is compounded by the speed at which

¹³ Rotolo et al., 2015; OECD, 2024b; Andersson et al., 2023

¹⁴ Byrne & Ockwell, 2013; GEF IEO, 2025a, 2025b

¹⁵ Chirinda et al., 2024

¹⁶ Byrne & Ockwell, 2013;

such technologies can scale, often outpacing the ability of governance, regulatory, and financing systems to respond effectively.¹⁷

Since the impacts of adopting emerging technologies may be uncertain and driven by myriad factors, they should not be viewed as stand-alone tools or technical fixes. They should be understood as components of broader socio-technical systems shaped by governance, institutional capacity, financing, and user practices¹⁸ (Figure 1). Their environmental impacts depend not only on their technical design but also on how they are deployed and integrated into wider social contexts.¹⁹ Evidence shows that outcomes are ultimately determined by the interaction between technologies and these surrounding systems, including incentive structures, infrastructures, and governance arrangements.²⁰

In practice, the same technology may improve environmental performance in one context while generating unintended consequences in another. For example: energy efficiency technologies can trigger rebound effects that increase overall consumption; blockchain-based traceability systems may improve transparency but exclude smallholders with weak capacity; and artificial intelligence (AI)-enabled systems can strengthen monitoring while increasing energy use, water demand, and e-waste.²¹ Equally, conservation monitoring tools may strengthen ecological oversight in one setting while undermining trust or creating surveillance concerns in another. Therefore, **what matters is not just the technology itself but also how it is used, by whom and under what conditions, including the presence of effective oversight, safeguards, and accountability.**²²

¹⁷ Barra & Leonard, 2018; OECD, 2024b; Florin 2023b

¹⁸ Geels & Schot, 2007; Geels, 2019

¹⁹ Florin, 2023a; Florin, 2023a; OECD, 2024b; UNEP, 2025a

²⁰ Byrne & Ockwell, 2013; Andersson et al., 2023; OECD, 2024b, 2025a; UNCTAD, 2025

²¹ Gillingham et al., 2016; Luccioni et al., 2025; STAP, 2025a; UNEP, 2024b; Chittipaka et al., 2023; Deloitte, 2023

²² Florin, 2023a; GEF IEO, 2025b

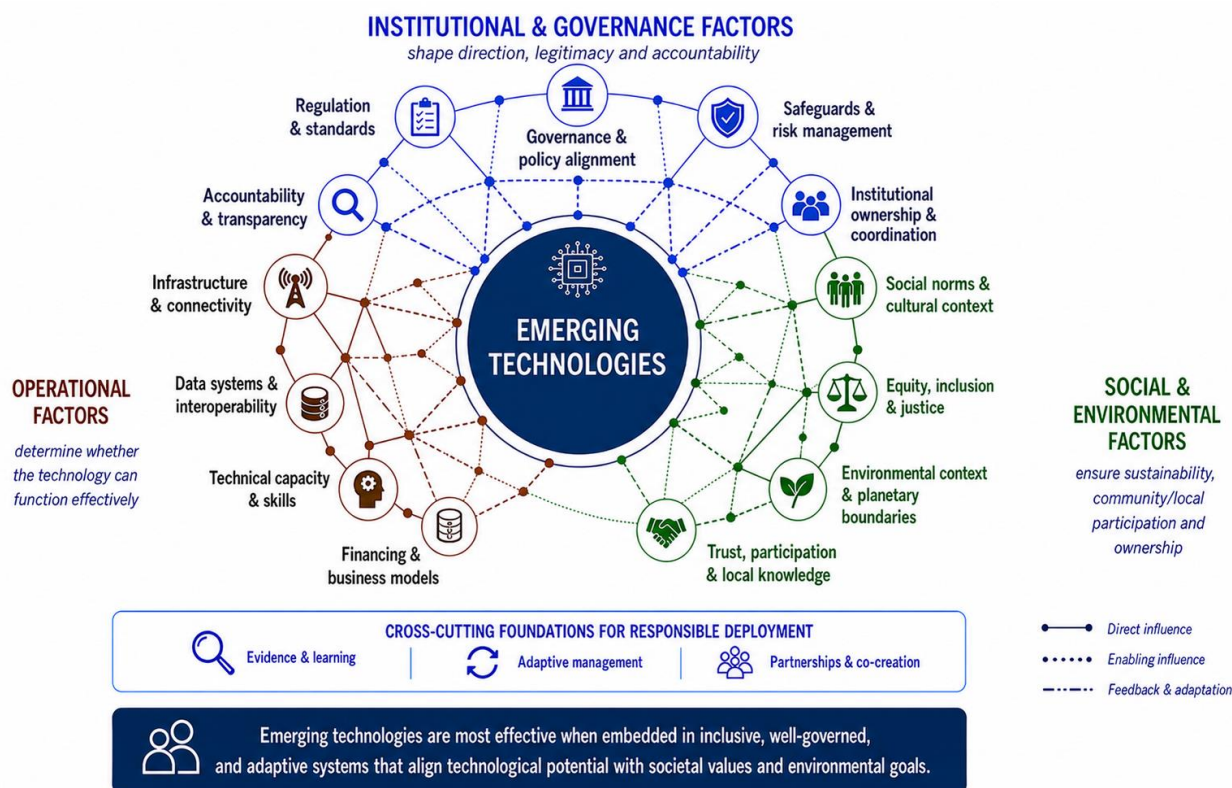


Figure 1: Emerging technologies as socio-technical systems. Emerging technologies do not produce outcomes independently. Their impacts are shaped by the broader systems in which they are embedded, including governance arrangements, operational readiness, financing, institutional coordination, and social legitimacy. This systems perspective emphasizes that technological potential translates into environmental outcomes only when enabling conditions, safeguards, and local ownership are present. Section 4 further discusses the enabling conditions. Source: STAP, 2026.

In the GEF context, emerging technologies should be assessed and deployed as part of broader transformation pathways rather than as stand-alone solutions. **Their value lies not in novelty, but in their ability to enhance the effectiveness, durability, and scalability of interventions,** including by improving how environmental information is generated, shared and used. Realizing these benefits depends on integrating governance frameworks, institutional and technical capacity, financing pathways, safeguards, and broader country readiness into project and programme design from the outset. Embedding technologies within system-based interventions that address these enabling conditions and long-term sustainability considerations is therefore essential to ensure technological applications translate into durable GEBs.

3. Relevance of emerging technologies to the GEF

3.1 How emerging technologies deliver GEBs and catalyse transformation

Across the GEF portfolio, emerging technologies contribute to GEBs through interrelated pathways that affect how environmental systems are understood, governed and transformed.²³ This section discusses and presents examples of these pathways.

Emerging technologies can **improve environmental visibility, diagnosis and early warning** by making environmental change more visible, timely and actionable. Earth observation, remote sensing, geospatial analytics, sensors, environmental DNA (eDNA) and AI-enabled tools can help detect ecosystem change, identify pressures and hotspots, and support earlier intervention. For example, satellite imagery can reveal deforestation hotspots in near real time, while sensor networks can help detect changes in water quality before damage becomes more severe. This is particularly relevant to biodiversity conservation, land and ecosystem restoration, freshwater and marine management, and adaptation planning (case study 1).

Another pathway is through **stronger MRV, transparency and compliance**. This helps reduce information asymmetries, improve oversight, and support more credible governance and enforcement. Digital MRV systems, environmental data infrastructure, traceability tools, vessel-tracking systems and digital product passports can support more credible governance and enforcement in areas such as deforestation-free supply chains and fisheries monitoring (case study 2). They can also support the management of chemicals, waste and the plastic value chain, as well as broader transparency agendas.

A further is **greater resource efficiency and lower environmental pressure in production and consumption systems**. Through better design, optimization, and circularity, emerging technologies can reduce material, energy and water use, as well as emissions across value chains. They can also reduce waste and leakage and support shifts towards more circular and less polluting systems. For example, smart production systems can optimize energy and material use in manufacturing (case study 3), while digital tools can improve sorting, recovery and reuse in plastics and other waste streams (case study 4).

Emerging technologies can also help enable the **substitution of polluting technologies and transition to greener alternatives in hard-to-abate systems**, particularly in energy, transport, industry, and some chemical supply chains. Technologies such as advanced energy storage, low-emissions fuels, electric mobility and low-carbon industrial processes can help shift entrenched systems towards lower-emission and lower-pollution pathways, especially when combined with enabling policies, finance and infrastructure (case study 5).

²³ Florin, 2023a; UNEP, 2024a; 2025a

A further pathway to impact is **stronger restoration, remediation, and regenerative capacity** in degraded or polluted systems. Emerging technologies can improve the targeting, implementation, and follow-up of interventions in these settings. This includes technologies that support ecosystem restoration, ecological engineering, and bioremediation, with relevance to land restoration, biodiversity, freshwater systems, and chemical, waste and pollution challenges (case studies 6 and 7).

Emerging technologies to support **environmental intelligence applications and early warning systems** have also been applied to deliver **improved climate adaptation, resilience, and adaptive management under uncertainty**. Novel technology-based applications can help institutions and communities respond more dynamically to changing and uncertain risks. Environmental intelligence, scenario tools, digital twins,²⁴ predictive analytics, distributed sensing, and decision-support systems can strengthen planning, targeting, and iterative management, while enabling decision makers to test different adaptation options before investing in them. In this way, these technologies can improve the durability of outcomes under conditions of climate variability, ecological change, and institutional fragility (case study 8).

More broadly, emerging technologies such as **MRV, traceability, and digital registries** can **catalyse systems transformation** by changing how decisions, coordination, and finance work. Their most important contribution is often not direct biophysical impact, but their ability to reshape information flows, alter incentives, reduce transaction costs, facilitate novel finance and business models, improve coordination across scales, and enable new forms of governance, verification and investment. This is especially important in the GEF context, where transformational change depends on linking multiple actors, sectors and policy domains rather than deploying single technologies in isolation (case study 9).

A diverse and evolving set of technologies enable the pathways described above. These can be grouped into five functional categories: (i) environmental sensing, monitoring and intelligence technologies; (ii) traceability, verification and environmental governance infrastructure; (iii) clean energy, storage, transport and industrial transition technologies; (iv) circular materials, pollution prevention and waste systems technologies; and (v) biotechnologies, ecological engineering, and frontier technologies (Figure 2).

²⁴ A “digital twin” is a dynamic, virtual replica of a physical object, process or system that uses real-time Internet of Things (IoT) sensor data, machine learning and AI to simulate behaviour and performance.

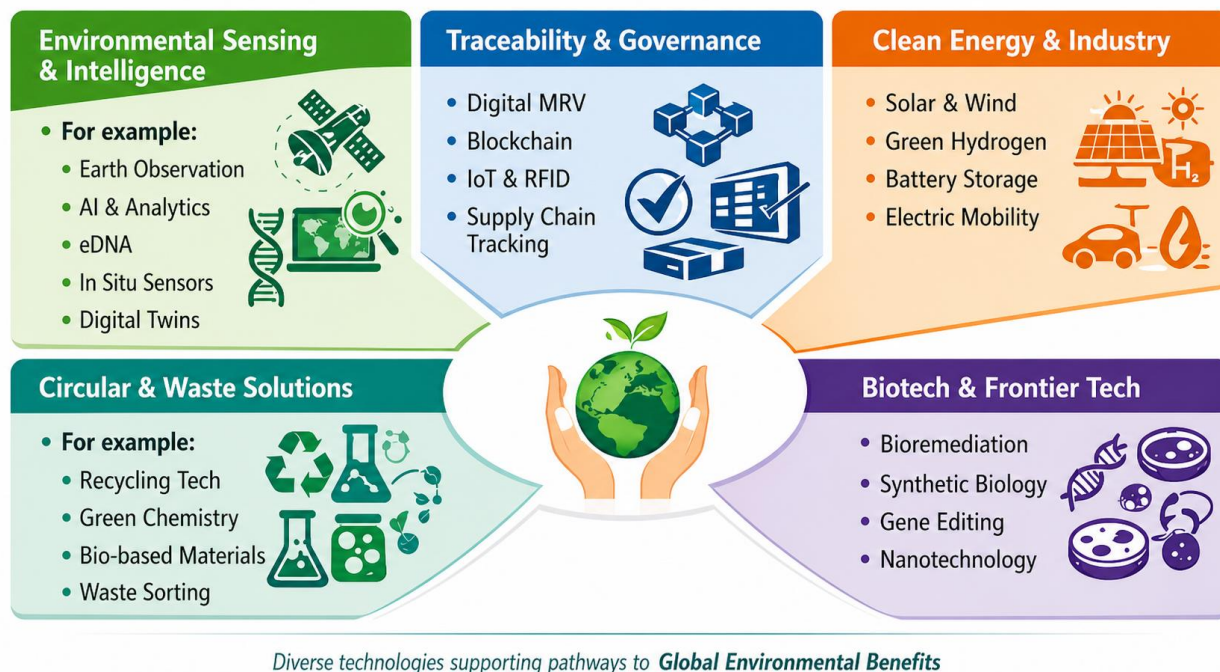


Figure 2: Illustrative typology of emerging technologies. A non-exhaustive typology of emerging technologies (clustered around functional areas) that can be deployed to support pathways to deliver GEBs and catalyse transformational change. **Source:** STAP 2026

These categories are neither exhaustive nor mutually exclusive. They illustrate the diversity of technologies that may be suitable for application within the GEF portfolio. The most impactful applications often arise from combinations across categories rather than isolated solutions, and their relevance ultimately depends on how they are adapted to and embedded within specific institutional, environmental and socioeconomic contexts

Transformational impacts of emerging technologies arise not simply when technologies improve efficiency, but when they alter how systems function, by changing who can access information, who can act on it, how incentives are structured, or how infrastructure, markets, and governance systems are organized. For example, digital monitoring systems may become transformational when they move beyond isolated data collection to integrated systems that support policy design, enforcement, and adaptive management. Likewise, distributed energy systems may transform access, autonomy, and the political economy of energy, rather than merely adding generation capacity. At the same time, not all technology-enabled gains need to be transformational; incremental improvements can also deliver important environmental benefits.

3.2 Case studies of emerging technologies applications in GEF work areas

Case study 1: Integrating geospatial intelligence for systems-based environmental management – the World Bank’s GeoLab and Livable Planet Observatory²⁵

The World Bank’s [GeoLab](#) and the [Livable Planet Observatory \(LPO\)](#) provide practical examples of how emerging technologies can be deployed within a broader socio-technical system to support integrated environmental decision-making. The LPO combines global Earth observation data with advanced analytics to generate insights across domains such as biodiversity, climate, water, agriculture and disaster risk. GeoLab complements this by offering a cloud-based platform for processing and analysing geospatial data, including satellite imagery, drone-based inputs, and AI-enabled tools for land-use mapping, environmental risk screening and scenario analysis.²⁶

A key strength of this approach lies in the integration of top-down and bottom-up data systems. Global data sets are combined with locally generated information (e.g. from field sensors and crowdsourced data), enabling more granular, context-specific analysis. This enables near-real-time monitoring of environmental change, improved baseline assessments, and modelling of potential future scenarios. The platforms also support collaboration and knowledge-sharing through interoperable systems that are accessible to a wide range of users, from governments to researchers.

By enhancing access to integrated, high-quality data and analytical tools, such platforms can strengthen project design, improve monitoring and adaptive management, and support the identification of leverage points across interconnected systems. They also offer opportunities to improve transparency and accountability in tracking GEBs. However, the effectiveness of these technologies depends on enabling conditions, including institutional and technical capacity, data governance frameworks and country readiness, highlighting that their value lies not in the technology itself, but in how it is embedded within broader governance and decision-making systems.

Case study 2: Digital fisheries monitoring²⁷

Digital technologies, including satellite monitoring, AI-enabled analytics, and integrated data platforms, are transforming how fisheries are governed by improving transparency, coordination, and enforcement. Sector-specific applications such as automatic identification systems (AIS), vessel monitoring systems (VMS), and satellite-based remote sensing enable near-real-time tracking of vessel activity and the detection of illegal, unreported, and unregulated (IUU) fishing.²⁸ The Organisation for Economic Co-operation and Development (OECD) notes that improved data systems and monitoring technologies enhance transparency and enforcement, which are critical for sustainable fisheries governance.²⁹

In practice, technology-enabled platforms such as [Global Fishing Watch](#) integrate satellite AIS data, machine learning and cloud computing to create publicly accessible maps of global fishing activity. These systems process data from hundreds of thousands of vessels to track movements, identify suspicious behaviour, and support marine protection and enforcement. Evidence shows that such technologies enable authorities to detect illegal

²⁵ Sources: World Bank Group, 2025, n.d.a; World Bank Group GeoLab, 2026

²⁶ World Bank Group, 2025

²⁷ Sources: Arthur-Mensah, 2023; FAO, 2019; Fujita et al., 2018; Global Fishing Watch, n.d.a; n.d.b; n.d.c; Holland, 2026; Hutniczak et al., 2019; Scalia-Bruce, 2023; Schneider, 2025

²⁸ STAP has developed a paper on IUU fishing, which will be presented to the GEF 71st GEF council meetings along this one.

²⁹ OECD, 2019

fishing in near real time and improve enforcement effectiveness by directing patrols and resources more efficiently. This represents a shift from reactive enforcement to data-driven, pre-emptive surveillance and interventions that focus on prevention, fundamentally altering how decisions are made and coordinated across jurisdictions.

One example of country-level implementation is from Peru, where authorities have combined VMS with electronic monitoring (EM) and data systems to manage one of the world's largest fisheries, thus improving compliance and sustainability outcomes.³⁰ Another is from Ghana, where the use of VMS and EM has strengthened oversight of industrial trawl fleets and supported efforts to address IUU fishing. However, challenges remain in enforcement and governance capacity, highlighting that technology alone is insufficient without enabling conditions.

These technological solutions help reduce information asymmetries, lower monitoring and enforcement costs, and enable coordination among governments, regional fisheries bodies and private actors, thus supporting more effective management of shared marine resources. Their transformative potential lies in enabling continuous, transparent and scalable oversight, which is essential for addressing transboundary challenges such as IUU fishing and for delivering durable GEBs.

Case study 3: Green ammonia and green concrete – emerging technologies for resource-efficient production systems³¹

The World Economic Forum's report on 10 emerging technology solutions for planetary health identifies green ammonia and green concrete as promising innovations to reduce the environmental footprint of two resource- and emissions-intensive sectors: fertilizers and construction. Green ammonia replaces fossil-based hydrogen with hydrogen produced from renewable energy, lowering greenhouse gas emissions and enabling more sustainable fertilizer production. Green concrete uses alternatives, such as limestone calcined clay cement (LC3), binders derived from industrial byproducts or construction and demolition waste, and carbon-capture-based processes to reduce the carbon and material intensity of cement production while enabling more circular use of resources.

These technologies are already being implemented in developed and developing countries. In the Global North, projects such as Yara's renewable ammonia plant in Norway and Heidelberg Materials' carbon capture-enabled cement production at Brevik demonstrate industrial-scale deployment. In the Global South, the OCP Group in Morocco is also investing in a green ammonia flagship project and distributed green ammonia systems are being piloted in Kenya to localize fertilizer production. India is scaling up large green ammonia projects and the use of LC3 in major infrastructure developments, such as Noida International Airport. These examples highlight the opportunities presented by emerging technologies to improve resource efficiency, reduce emissions and material use, and support more resilient and less polluting production systems.

³⁰ OECD, 2019

³¹ Sources: WEF, 2025; Allee et al., 2025; Aluri, 2026; Heidelberg Materials, 2025; Yara International, 2024; OCP, 2024

Case study 4: Digital tools for circular plastics systems – enabling conditions matter³²

Plastics pollution in Southeast Asia is driven by rising consumption and fragmented waste management systems, involving households, informal waste workers, intermediaries, recyclers, and public authorities, which are often poorly connected and weakly coordinated. Emerging digital technologies are transforming how plastics are collected, monitored, traded and managed by improving coordination, transparency, and information flows across the value chain. Applications include waste-collection and recycling apps, digital marketplace platforms, AI-based litter-detection systems using closed-circuit television and drone footage, and digital outreach tools to support awareness and behaviour change.

In practice, these technologies are already being piloted in countries such as Indonesia and Viet Nam. In Indonesia, platforms such as [Duitin](#) connect households and businesses with waste collectors, facilitate pickups, and improve record-keeping and waste traceability. In Viet Nam, digital marketplace tools such as VECA³³ improve price transparency and link informal collectors and junk shops with buyers, reportedly increasing trading volumes by 15 percent in some pilots. AI-enabled monitoring tools have also been used to identify hotspots of plastic leakage and pollution sources, improving targeting and decision-making.

These technologies can reduce transaction costs, improve market access for recyclables, strengthen monitoring of plastic leakage, and support more inclusive participation in the plastics value chain, including for women and informal workers. Their broader transformative potential lies in helping shift waste systems towards more circular and evidence-based management by improving traceability, coordination, and accountability across actors and stages of the plastics value chain.

However, evidence from these pilots also shows that technology alone is insufficient. Their effectiveness depends heavily on enabling conditions such as user-centred design, training, local-language support, community engagement, financial viability, and alignment with public systems and policy frameworks. The pilots found that combining digital tools with “social infrastructure”, including community meetings, local champions and in-person engagement, was often more effective than relying on digital tools alone. These examples highlight the opportunities and the limits of digital technologies in supporting more circular, inclusive and scalable plastics management systems.

³² Sources: ADB, 2025a, 2025b; Development Asia, 2025; Southeast Asia Development Solutions, 2025

³³ VECA is a pioneering mobile application in Vietnam that digitizes the waste management supply chain, connecting households with waste pickers and recyclers to improve recycling rates and formalize the informal sector

Case study 5: Electric mobility and green hydrogen – enabling transitions in hard-to-abate systems³⁴

Energy transition assessments by the International Energy Agency identify electric mobility, energy storage and low-emissions fuels, including hydrogen, as key technologies for decarbonizing transport and industry, particularly where direct electrification alone is insufficient.³⁵ These technologies enable substitution away from fossil-fuel-based systems by improving energy efficiency and reducing emissions intensity across value chains. For example, electrification of transport can significantly reduce life-cycle emissions when paired with cleaner electricity, while hydrogen-based fuels offer pathways for decarbonizing heavy-duty transport and industrial processes where direct electrification is difficult.³⁶

These transitions are already happening in some countries. In Chile, Santiago has deployed one of the world's largest electric bus fleets outside China, with over 2,700 electric buses in operation. Evidence shows that electric buses in the city reduce carbon dioxide emissions per bus by more than 25 per cent and particulate matter by about 60 per cent compared to diesel alternatives, while also lowering operating costs and improving urban air quality.³⁷ In India, national programmes have supported the deployment of over 10,000 electric buses, with plans to scale to tens of thousands more through aggregated procurement and innovative financing mechanisms, demonstrating how policy and finance can accelerate substitution in public transport systems.

At the same time, emerging low-emissions fuel systems are being explored to address segments that are harder to electrify. Countries such as Brazil, Chile, India, and South Africa are assessing the role of green hydrogen and fuel-cell technologies for buses, freight, and industrial applications. World Bank modelling shows that while costs remain high, hydrogen-based systems, particularly for heavy-duty vehicles, can offer energy efficiency and emissions advantages over internal combustion technologies, especially as renewable energy costs decline and infrastructure develops.³⁸

These examples demonstrate how emerging technologies can enable substitution in entrenched, high-emitting systems by improving energy efficiency, reducing pollution, and shifting production and consumption towards lower-emissions pathways. However, their success depends on enabling conditions, such as supportive policy frameworks, financing models, infrastructure development, and institutional capacity, which are critical for scaling these transitions across diverse country contexts.

³⁴ Sources: IEA, 2025; Bacovsky, 2020; Qiao et al., 2025; REN21, 2025; Global Commercial Vehicle Drive to Zero, n.d.; Jaeger, 2025

³⁵ ; IEA, 2025

³⁶ REN21, 2025; World Bank Group, 2025

³⁷ Global Commercial Vehicle Drive to Zero, n.d.;

³⁸ World Bank Group, 2025

Case study 6: Soil health technology convergence – restoring soils with sensors, microbes, and AI³⁹

Soil health technology convergence solutions are an emerging pathway that combines sensors, microbial engineering, and AI to restore degraded soils and improve the sustainability of land-use systems. Academic and practitioner literature suggests that this convergence is becoming increasingly relevant not only to precision agriculture but also to soil remediation and regeneration. Advances include bioaugmentation,⁴⁰ phytoremediation,⁴¹ engineered or selected microbial consortia,⁴² AI-enabled pollutant detection, and sensor-based monitoring systems that can improve the targeting of interventions, track soil recovery in real time, and adapt management as conditions change. Literature shows that biological approaches are effective at removing or transforming pollutants while preserving soil quality and supporting longer-term ecological recovery, and that combining beneficial microbes with sensors and data systems can reduce input use while improving resilience and resource efficiency.

These approaches are already moving into implementation. In Europe, the [AI4SoilHealth](#) project, funded by the European Union, is building an open-access, AI-based Soil Digital Twin, along with a rapid soil health assessment toolbox, a Europe-wide data cube, and monitoring services to support continual soil health assessment and tracking of degradation. In China, a 2025 field study in the country's southwest applied compound microbial agents to a severely degraded former quarry slope and found that the treatment improved soil conditions, supported vegetation establishment and promoted microbial community development. In a more explicit contamination remediation context, a 2025 field-simulated pilot used compost plus microbial enhancement to treat explosives-contaminated soil and reported that [RDX](#) and [TNT](#) (two types of explosives commonly used for military and industrial applications) declined to or near non-detectable levels by day 85, informing the design of a planned large-scale cleanup.

These examples show how converging biological and digital technologies can expand restoration and remediation capacity by making interventions more targeted, adaptive and scalable across degraded and polluted systems, and could be relevant to GEF work on land degradation, chemical pollution and food systems.

³⁹ Sources: Badding, 2020; Ben Laish et al., 2025; European Commission, n.d.; WEF, 2025; Dinesh, 2024; Lv et al., 2025; Malik et al., 2025; Popescu et al., 2024; Santos et al., 2025; Rezaee Danesh, 2025

⁴⁰ “Bioaugmentation” is the addition of specific, cultured microorganisms (bacteria or fungi) to contaminated environments or wastewater systems to accelerate the degradation of target pollutants.

⁴¹ “Phytoremediation” is an in-situ technology that uses plants to remove, transfer, stabilize or destroy contaminants in soil and groundwater. It leverages natural plant processes, such as uptake, accumulation and degradation, to “remediate” sites contaminated with heavy metals, organic solvents or petroleum.

⁴² “Microbial consortia” are complex communities of diverse microorganisms that coexist and cooperate within an ecological network. They enable biological processes required for the degradation of complex materials, increased biomass conversion, improved bioremediation and enhanced stability against environmental perturbations.

Case study 7: Nanomaterials for removing persistent organic pollutants and treating wastewater.⁴³

Persistent organic pollutants (POPs) are toxic chemicals that persist in the environment, bioaccumulate, travel over long distances, and cause serious harm to human health and ecosystems. Their production, use, import, and export are regulated under the Stockholm Convention on Persistent Organic Pollutants, for which the GEF serves as a financial mechanism. One emerging technological response to POP contamination is the use of nanomaterials for water treatment and remediation. Research highlights several relevant pathways, including nano-adsorption, nano-filtration and nano-catalysis, using materials such as metal oxides, graphene-based composites, iron-based nanoparticles and other engineered nanomaterials to capture, degrade or filter POPs from contaminated water.

These technologies improve the removal of hard-to-treat pollutants from wastewater and polluted water systems in two main ways. Nanomaterials can adsorb or filter contaminants that conventional systems often struggle to remove efficiently, while some can act as photocatalysts, accelerating chemical reactions that break down pollutants under light exposure.

Reported outcomes are promising, although still mostly at laboratory or pilot scale. Some studies have found that magnetic, reusable nanocomposite material achieved highly efficient photocatalytic removal of chlorinated pesticides from wastewater under visible light. They also catalysed reactions that support hydrogen generation in the presence of pollutants, suggesting potential multiple benefits through pollutant degradation, cleaner water and energy co-benefits.

While nanotechnology shows promise for restoration and remediation, its application remains constrained by cost, scale-up challenges, uncertainty about long-term environmental fate and toxicity, and the difficulty of replicating laboratory performance under real-world conditions. In the GEF context, its relevance will depend on careful assessment of ecological risks, life-cycle impacts, regulatory and institutional readiness, and the capacity to deploy and govern such technologies safely and effectively.

Case study 8: Strengthening adaptive management and resilience through environmental intelligence and early warning systems.⁴⁴

Emerging technologies that combine environmental intelligence, predictive analytics, and distributed sensing are increasingly enabling more dynamic and adaptive responses to climate and ecological risks. The World Meteorological Organization has documented how modern multi-hazard early warning systems integrate satellite observations, ground-based sensors, climate models, and data platforms to provide timely, actionable information for decision-making.⁴⁵

The case of Bangladesh illustrates how such systems can strengthen resilience when embedded within broader risk-management measures. The Government invested in early warning systems that combine satellite data, river gauges and communications tools, alongside cyclone shelters, evacuation plans, coastal embankments, reforestation and public awareness. Together, these measures have dramatically reduced cyclone-related

⁴³ Sources: Boulkhessaim et al., 2022; Hainer et al., 2018; Ismael et al., 2020; Stockholm Convention, n.d.

⁴⁴ Sources: Haque et al., 2012; International Centre for Humanitarian Affairs - Kenya Red Cross, 2021; Salzenstein & Montu, 2021; UNDRR, n.d.; World Food Programme Africa, 2025; WMO, 2018

⁴⁵ WMO, 2018

mortality, from hundreds of thousands of deaths in past decades to fewer than 100 in comparable recent events. This illustrates the value of integrated forecasting and response systems.

Another example comes from the Horn of Africa. There, forecast-based financing systems supported by predictive climate analytics have been used to trigger early action, such as cash transfers and livelihood support, before drought impacts fully materialize. This has helped improve resilience and reduce humanitarian costs. These approaches rely on predefined triggers linked to forecasts, illustrating how data-driven systems can operationalize anticipatory action.

More advanced applications are emerging through digital twin and scenario modeling. For example, the European Commission's [Destination Earth initiative](#) uses high-resolution Earth system models and digital twins to simulate climate impacts and support decision-making for adaptation and disaster risk reduction. These tools enable policymakers to explore future scenarios, test interventions, and adjust strategies iteratively as conditions change.

Case study 9: Digital MRV, traceability, and registries as catalysts of systems transformation.⁴⁶

The emergence of digital MRV, interoperable registries, and geospatial traceability platforms exemplifies the catalytic role of emerging technologies. World Bank guidance argues that digital MRV can reduce the cost of generating and verifying environmental assets, improve transparency and transaction integrity, and strengthen the infrastructure needed for credible carbon markets and results-based finance. The same body of work emphasizes that the value of these technologies lies less in direct biophysical effects than in their ability to reshape information flows, verification, coordination and investment decisions across multiple actors and institutions. Similar evidence from OECD flagship technical reports shows that digital technologies can accelerate green transformation by improving coordination, data use and system efficiency across sectors.

These dynamics are already visible in practice. In Kenya, the launch of the [National Carbon Registry](#) as a centralized digital platform for registering projects, tracking emissions reductions, and authorizing transactions represents an important step towards strengthening transparency, avoiding double counting, and improving the credibility of carbon markets. Early uptake, with numerous project submissions at launch, highlights how digital governance infrastructure can help unlock climate finance by reducing transaction costs and increasing investor confidence.

In Brazil, national and subnational systems that integrate satellite-based monitoring (e.g. [Prodes and Deter](#)) with supply chain and enforcement data have significantly strengthened the country's capacity to detect and respond to deforestation in near real time. These systems are improving transparency, supporting regulatory enforcement and enabling compliance with emerging international requirements such as the European Union [Deforestation Regulation](#), illustrating how digital infrastructure can reshape governance and accountability across complex land-use systems. Similarly, in Indonesia, the Government has been developing a digital commodity dashboard and related traceability systems for commodities such as palm oil, coffee, and rubber to support compliance with deforestation-free supply chain requirements. Independent analysis notes that these

⁴⁶ Sources: Carbon Markets Infrastructure Working Group & World Bank, 2025a, 2025b, 2025c; European Forest Institute, 2025; Faiz, 2026; FAO, n.d.; Malleret, 2026; Munda, 2026; OECD, 2024a; Reuters, 2024

systems could reduce duplication, improve transparency, and help include smallholders in legal and deforestation-free value chains.

In Costa Rica, long-standing integration of satellite monitoring, land registries and payment for ecosystem services schemes has strengthened the credibility and effectiveness of conservation finance by enabling transparent tracking of forest outcomes and aligning incentives across actors. Similarly, in the European Union, the development of interoperable digital systems such as the European Union [Deforestation Regulation Information System](#) to support compliance with the Deforestation Regulation is driving the integration of geospatial monitoring, supply chain traceability and regulatory oversight, reshaping how producers, traders, and regulators coordinate across jurisdictions.

These examples reinforce the notion that the transformative potential of emerging technologies lies not only in their technical capabilities but also in their ability to enable new forms of governance and verification, and improved accountability and coordination across actors and scales. These can all increase the likelihood of nudging systems towards transformative change, when combined with appropriate policy measures.

3.3 Existing use of emerging technologies in the GEF portfolio

Evidence from the GEF IEO shows that technological innovation has long been part of the GEF's mandate and operations. This has included not only new technologies, but also new approaches, financial instruments, and institutional arrangements tailored to different countries and sector contexts.⁴⁷ Over successive replenishment periods, the use of technology within the GEF portfolio has expanded significantly, with many projects incorporating a technological component.⁴⁸ From the sixth replenishment cycle (GEF-6) through to GEF-8, the IEO identified around 120 technologies across the portfolio and found that about 63 percent of projects included technology-related elements, although only around 10 percent featured more advanced or emerging innovations.⁴⁹

Across the portfolio, technologies are already being applied in ways that align closely with the pathways described in section 3.1. In many cases, globally mature technologies continue to play an emerging role in specific country contexts where institutional capacity, enabling policies, or infrastructure are still developing. Table 1 provides illustrative examples of how emerging technologies and applications are being used in the GEF portfolio. Annex 1 provides a more detailed description of each.

⁴⁷ GEF IEO, 2021, 2025b

⁴⁸ GEF IEO, 2021, 2025b

⁴⁹ GEF IEO, 2025b

Table 1: Illustrative examples of emerging technologies in GEF-supported projects

GEF programme/project	Technology/application	Approach / lesson illustrated
Mocoa, Colombia (GEF ID 10438) Uncrewed aerial vehicles (UAVs)/drones for equitable climate adaptation	Drones, light detection and ranging (LiDAR), Global Navigation Satellite System (GNSS) stations, geospatial processing, machine learning	Shows how technology packages can strengthen climate risk monitoring and anticipatory action. Also highlights that impact depends on local capacity, maintenance, participatory governance and sustained technical support.
Cameroon and Kenya (GEF ID 10637) Restoration Challenge Grant Platform with blockchain-enabled crowdfunding	Mobile applications, blockchain-enabled traceability, digital payments, crowdfunding	Illustrates how digital systems can make restoration more verifiable, coordinated and financeable. Also shows that digital infrastructure, user access and community support are essential for uptake.
Global Clean Hydrogen Programme (GEF ID 11437)	Clean/green hydrogen technologies, readiness assessments, financing mechanisms, policy and regulatory support	Shows that emerging industrial technologies require enabling systems, not just hardware. The main lesson is that regulation, standards, finance and institutional readiness are critical for deployment in hard-to-abate sectors.
Electronic Monitoring in Tuna Fisheries (GEF ID 11996)	On-board cameras, sensors, global positioning systems (GPS), digital transmission, edge AI	Illustrates how digital monitoring can improve transparency, compliance and fisheries governance. Also underscores the need for legal frameworks, technical capacity, financing and stakeholder acceptance.
Wildlife Conservation for Development Integrated Program (GEF ID 11148)	SMART , eCITES , drones, camera traps, AI-enabled tools, traceability systems	Demonstrates how digital tools can strengthen monitoring, enforcement and protected-area management when embedded in broader conservation systems. Also points to continuing challenges around safeguards, coordination and inclusive engagement.
Sustainable Cities Integrated Program, Melaka (GEF ID 11287)	Smart grid, renewable energy, battery storage, electric vehicle charging, smart meters, energy dashboard	Shows how combining technologies within integrated urban planning can support wider low-carbon transition. The lesson is that technology works best when linked to planning, finance, governance and public-private partnerships.

The application of more advanced technologies, such as AI-enabled analytics, blockchain-based systems and emerging industrial technologies, remains relatively limited in current GEF projects and is often concentrated in pilot or demonstration activities. The IEO's 2025 *Evaluation of GEF support for technological innovation* found that such technologies are under-represented in the GEF portfolio relative to their growing global relevance, reflecting constraints in technical and institutional capacity, data availability, regulatory readiness, and the pace of technological innovation in relation to project cycles.⁵⁰

This evidence indicates that the GEF partnership already has substantial experience in applying technology and supporting innovation, including where technologies are new or emerging at the country level. However, this experience remains uneven and has not yet been systematically leveraged across the portfolio. The opportunity for the GEF is therefore to **engage with emerging technologies more strategically, building on existing experience to scale effective applications, address enabling constraints, and align technology use more explicitly with pathways to durable GEBs and broader systems transformation.**

4. Barriers, enabling condition, risks and opportunities associated with emerging technologies

This section draws primarily on insights from expert interviews, complemented by a review of the scientific and technical literature and lessons from IEO evaluations of past projects and programmes. Together, these sources point not only to the barriers, enabling conditions and risks associated with emerging technologies, but also to a set of timely strategic opportunities for the GEF.

Several experts highlighted that current technological and policy developments create **opportunities for countries to leapfrog older, less-efficient systems and adopt more adaptive, decentralized and inclusive approaches.** Such developments include: rapid convergence of digital, data and environmental monitoring systems; falling costs of distributed and modular technologies; growing demand for traceability and environmental transparency; and stronger international focus on climate information, early warning, and resilient infrastructure.

For some GEF-recipient countries, this may include distributed renewable energy in weak-grid settings, lower-cost biodiversity and environmental monitoring tools, open-source or adaptable digital platforms, and South–South pathways for technology diffusion and adaptation.

However, the evidence is equally clear that leapfrogging is not automatic. It depends on enabling conditions such as institutional capacity, interoperability, financing, governance and local innovation ecosystems. Against this backdrop, the following sections examine the main barriers,

⁵⁰ GEF IEO 2025b

enabling conditions, and risks (Figure 3) that will shape whether emerging technologies deliver durable GEBs across the GEF portfolio.

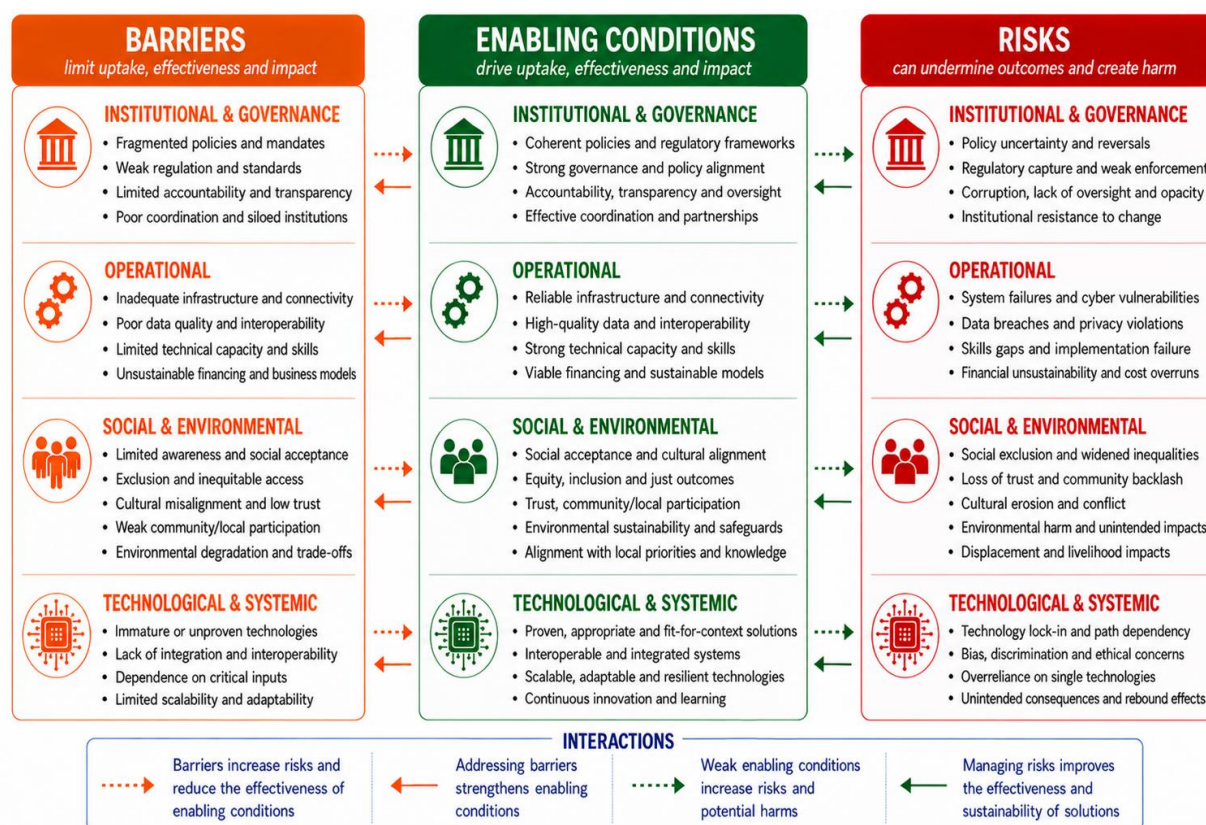


Figure 3: Barriers, enabling conditions and risks for emerging technology deployment. When barriers are reduced, enabling conditions are strengthened, risks are managed, and emerging technologies are more likely to deliver inclusive, equitable and sustainable outcomes. **Source:** STAP 2026

4.1 Barriers and enabling conditions

Several barriers constrain the application and scaling of emerging technologies, particularly in lower-capacity settings where institutional, financial, technical, and governance constraints often overlap and reinforce one another. Evidence from the literature, GEF evaluations, STAP analysis, and expert consultations suggests that successful deployment depends on establishing the enabling conditions.

Technical feasibility, data infrastructure, and life-cycle sustainability. Emerging technologies, particularly digital and data-intensive systems, depend on reliable infrastructure, connectivity, interoperable data systems, skilled personnel, and long-term operation and maintenance. IEO evaluations show that these requirements are often underestimated, especially local capacity for

maintenance and system management, leading to performance gaps and weak sustainability.⁵¹ Digital monitoring systems, AI-enabled analytics, and traceability platforms are especially affected by persistent digital divides and fragmented environmental data systems, which constrain equitable access, system integration, credible monitoring, transparency, and decision-support.⁵² Effective deployment, therefore, requires investments in environmental data systems, digital public infrastructure, interoperable platforms, and data-sharing standards, alongside clearly assigned institutional responsibilities, trained personnel, long-term hosting arrangements, and budgets for operation, maintenance, and upgrades.⁵³ This shifts the focus from short-term installation to life-cycle sustainability.

Institutional fragmentation, weak coordination, and limited technology stewardship. Fragmented mandates, weak cross-sector coordination, and limited knowledge-sharing can result in technologies accelerating existing processes without addressing underlying institutional failures. As several experts noted, automation should not be conflated with transformation: AI-enabled tools may improve speed or scale while entrenching inefficiencies or inequities if deployed in weak systems. Addressing this requires stronger institutional coordination, knowledge sharing, and strategic partnerships among governments, private sector entities, research institutions, and civil society.⁵⁴ Such ecosystems of support can facilitate knowledge transfer, reduce costs, accelerate market development, and support innovation, adaptation, and diffusion. This aligns with prior STAP guidance that transformational change depends on coordinated action across institutions and sectors.⁵⁵

Financial, market, and pilot-to-scale barriers. While the GEF has supported numerous pilot applications of innovative technologies, these often fail to scale because of weak enabling environments, insufficient policy alignment, and limited follow-through beyond demonstration phases. For many environmental applications, emerging technologies require complementary financial mechanisms, such as blended finance, risk-sharing instruments, guarantees, innovation windows, and market creation, to achieve system-level impact.⁵⁶ IEO findings highlight the gap between pilot demonstration and wider deployment.⁵⁷ Bridging the gap between pilot demonstration and large-scale deployment, therefore, requires access to appropriate and sustained financing that can absorb risk and support scaling. Hence, the importance of financing instruments and private sector engagement in supporting technology diffusion and scaling has been recognized in the GEF-9 programming and policy directions, as well as the LDCF/SCCF strategy.⁵⁸

⁵¹ GEF IEO, 2025b; UNCTAD, 2025.

⁵² Wang et al., 2025; Pham et al., 2025; World Bank Group, 2021

⁵³ IEG, 2011; World Bank Group, 2016; World Bank Group, 2021; GEF IEO, 2025b; STAP 2025a

⁵⁴ GEF IEO, 2025b; OECD, 2019

⁵⁵ Stafford Smith et al., 2022a; Donaldson & Ratner, 2023

⁵⁶ IFC, 2025; Sheikh et al., 2025; UNEP, 2021

⁵⁷ GEF IEO, 2025a and 2025b

⁵⁸ GEF, 2025a, 2025b

Policy, regulatory, governance, and safeguards constraints. Technologies such as digital MRV systems, blockchain-based traceability, and AI applications depend on clear regulatory frameworks, institutional mandates, data governance arrangements, standards, and safeguards. The GEF-9 policy directions recognize the need to update safeguards and confidentiality frameworks to support blended finance and digital systems, while ensuring accountability and risk management.⁵⁹ At the same time, emerging digital technologies introduce new governance challenges, including data privacy, cybersecurity, algorithmic bias, environmental footprints, equity, and accountability, which are not yet consistently addressed in project design.⁶⁰ Technologies are more likely to deliver sustained environmental outcomes when supported by clear policy signals, regulatory frameworks, environmental regulations, data governance frameworks, and sectoral policies that create incentives for adoption and discourage unsustainable practices.⁶¹ Robust governance frameworks are also essential to ensure transparency, manage risks, and build trust among users and stakeholders, including by embedding ethical principles, safeguards, and accountability mechanisms from the outset.⁶²

Technical and institutional capacity constraints. Shortages of skilled personnel, limited digital literacy, and weak institutional resourcing constrain countries' abilities to adopt, govern, and sustain emerging technologies.⁶³ Wider inequalities in access to infrastructure, skills, and opportunity often compound these challenges, deepening existing disparities and undermining the legitimacy of technology-enabled interventions.⁶⁴ Effective deployment, therefore, requires local capacity development, clearly assigned responsibilities, trained personnel, and institutional arrangements that support long-term system ownership.⁶⁵ It also requires attention to inclusion and legitimacy so that technologies do not reinforce existing disparities or exclude those with weaker access to infrastructure, skills, or opportunity.

Project cycle, procurement, and adaptive management constraints. IEO evidence highlights misalignment between GEF project development timelines and the pace of technological change, as well as rigid procurement processes that can delay implementation and reduce adaptability.⁶⁶ Similar findings from OECD work on procurement for innovation underscore the need for more flexible and risk-tolerant approaches when engaging with emerging technologies.⁶⁷ Because many emerging technologies evolve rapidly and carry uncertainty, effective deployment requires adaptive design, learning, and feedback systems. This includes real-time monitoring, evaluation and learning systems, feedback loops, and adaptive management. STAP guidance emphasizes that

⁵⁹ GEF, 2025a

⁶⁰ Bressane et al., 2026; STAP, 2025a; OECD, 2019

⁶¹ OECD, 2023b

⁶² UNESCO, 2021; OECD, 2019

⁶³ UNCTAD, 2025

⁶⁴ UNCTAD, 2025

⁶⁵ GEF IEO, 2025b

⁶⁶ GEF IEO, 2025b

⁶⁷ OECD, 2017

designing for learning is essential to ensure technologies remain effective under changing environmental and institutional conditions.⁶⁸

The GEF-9 policy directions and the LDCF/SCCF programming strategy acknowledge many of these barriers and incorporate support to corresponding enabling elements. These include accelerated project modalities, strengthened results management and learning systems, expanded use of digital tools, targeted capacity-building and innovation windows, and greater emphasis on blended finance and private sector engagement. However, there is still need for an explicit focus on ensuring technologies fulfil their potential by embedding enabling conditions into project and programme design, implementation, monitoring and learning.

4.2 Limitations, trade-offs, and risks

While emerging technologies can enable significant environmental gains, the evidence is clear that their deployment also entails **limitations, trade-offs, and risks** that should be explicitly considered in GEF programming. Various potential limitations, trade-offs and risks can be identified:

Lock-ins and rebounds. Emerging technologies can reinforce existing production and consumption patterns, create new dependencies or generate rebound effects that offset environmental gains. For example, efficiency improvements enabled by digital optimization or advanced materials may lower costs but have an unintended consequence of increased overall consumption, thereby eroding net environmental benefits.⁶⁹ Similarly, rapid technological diffusion can lock systems into suboptimal pathways, particularly where early standards, infrastructure, or business models become difficult to reverse.⁷⁰

Environmental risks and unintended consequences. These can be significant, even for technologies explicitly designed for environmental purposes. For instance, nanomaterials used in remediation may pose long-term ecological risks if released into natural systems, including toxicity, bioaccumulation, and interactions with biological processes, because knowledge gaps remain regarding their environmental fate and impacts.⁷¹ Synthetic biology and gene-editing applications, although promising for conservation and agriculture, may produce unintended ecosystem-level effects, including horizontal gene transfer to non-target species and disruption of ecological interactions.⁷² These risks are often difficult to predict and may become visible only after deployment.

Equity, distribution, and inclusion. Emerging technologies frequently concentrate benefits among actors with access to capital, infrastructure, data and skills, while excluding or

⁶⁸ STAP, 2025c; Bierbaum et al., 2024; Donaldson & Ratner, 2023

⁶⁹ OECD, 2023a; WEF, 2025

⁷⁰ OECD, 2024a

⁷¹ Keller & Slaveykova, 2025; Alizadeh et al., 2025; dos Santos et al., 2022; Florin, 2022; Barra & Leonard, 2018

⁷² Macfarlane et al., 2022; Aminian-Dehkordi et al., 2023; Florin, 2022; Barra & Leonard, 2018

disadvantaging others.⁷³ This is particularly evident in digital technologies such as AI and advanced analytics, where access to computing power, data and technical expertise is highly uneven.⁷⁴ As a result, technological deployment can exacerbate existing inequalities, including between countries, within societies, and across gender and social groups.⁷⁵ These dynamics can affect the legitimacy, uptake, and durability of GEF-supported interventions.

Data and knowledge asymmetries. Many emerging technologies rely on data sets that under-represent low-income regions, Indigenous territories, and ecologically complex systems. This can distort and/or bias model outputs, for example, by prioritizing donor or corporate interests over local environmental needs, thus eroding trust in technology-enabled governance systems.⁷⁶ In contexts where environmental outcomes depend on local knowledge and stewardship, such distortions can undermine effectiveness and social legitimacy.

Governance, ethical and accountability risks. These include: data privacy and cybersecurity risks; algorithmic bias and lack of transparency; vendor lock-in and loss of sovereignty over data and systems; and surveillance and misuse of monitoring technologies (case study 10). IEO findings indicate that such risks are not consistently addressed in project design, particularly for advanced technologies such as AI and blockchain. STAP's work on AI highlights governance challenges related to accountability and human oversight.⁷⁷

System-level and geopolitical risks. Emerging technologies may alter global value chains, create dependencies on specific suppliers or platforms, and restrict knowledge flows due to geopolitical tensions.⁷⁸ These dynamics can affect access to technology, affordability and long-term sustainability, particularly in developing countries.

⁷³ Bressane et al., 2026

⁷⁴ STAP, 2025a; UNCTAD, 2025

⁷⁵ Amnesty International, 2023

⁷⁶ STAP, 2025a

⁷⁷ Bierbaum et al., 2024,

⁷⁸ OECD, 2023a

Case study 10: Conservation monitoring technologies – the unintended risk of social surveillance⁷⁹

In India's tiger reserves, conservation monitoring increasingly relies on a suite of digital tools, including camera traps, drones and thermal surveillance. For example, the GPS-enabled [M-STRIPES](#) system was designed to support patrol management and ecological monitoring, as well as reducing human–wildlife conflict by integrating GPS, remote sensing, geographic information systems and mobile data collection into a single management platform.

These technologies aim to enhance environmental visibility, improve patrolling and anti-poaching activities, and provide more timely information for wildlife management. They support a clear conservation approach that relies on better data, quicker threat detection and more responsive decision-making.

However, these same tools can also cause social harm when deployed without adequate safeguards. Evidence from the Corbett Tiger Reserve shows that camera traps and drones also altered how local people used forest spaces. Women were particularly affected as they reported lowering their voices, stopping songs that normally helped warn off dangerous wildlife, and avoiding ordinary conversations because they did not know who might be watching or listening. In some instances, drones reportedly frightened women out of areas where they had legal rights to collect forest produce. Rangers also reported negative feelings towards the use of technology to monitor their activities, as they felt under constant surveillance. This example illustrates how certain technologies and applications can undermine trust-based human relationships and behaviours by reshaping relationships among communities, authorities, and front-line staff.

The context-specific lesson to emerge from this is that conservation monitoring technologies can deliver real gains when they are governed responsibly. Their use requires early community engagement, clarity over data ownership and use, safeguards against intimidation or secondary misuse, and governance frameworks that are sensitive to local social realities. Emerging technologies can improve the delivery of GEBs; but without adequate safeguards, they can also create exclusion, mistrust, and new forms of harm.

⁷⁹ Sources: Millner et al., 2024; National Tiger Conservation Authority, n.d.; Sandbrook et al., 2018; Sharma et al., 2020; Simlai, 2021; Simlai & Sandbrook, 2025

Evidence suggests that mitigation options are typically more effective and less costly at early stages of development but become more constrained as technologies scale and become embedded in socio-technical systems, while potential impacts increase. This dynamic can shift decision-making from proactive governance towards more costly and less-effective reactive responses if risks are not addressed early.⁸⁰ The absence of evidence of harm should not be interpreted as evidence of safety, particularly for technologies whose impacts may materialize over time or at different scales.⁸¹

For the GEF, this has several implications. First, risk assessment needs to consider not only project-level considerations but also incorporate systemic and long-term risks, including feedback effects and cross-sector interactions. Second, anticipatory and adaptive governance approaches, including early-stage assessment, iterative learning and monitoring, are essential for managing uncertainty and avoiding lock-in to unsustainable pathways.⁸² Third, equity and inclusion considerations must be embedded from the outset, rather than treated as secondary concerns, given their direct relevance to adoption, legitimacy and durability of outcomes.

5. Strategic engagement with emerging technologies

The preceding discussion underscores the need for a structured approach that clarifies when technologies can best be used, how they can be deployed, and under what conditions they can contribute to durable and transformational outcomes. This section outlines a possible framework.

5.1 Decision criteria for engaging

Strategic engagement of technologies requires selectivity. Not all emerging technologies are relevant to the GEF, and those that are may not be appropriate in all contexts. Three criteria are particularly important; these are discussed below and illustrated in Annex 2.

First, **strategic relevance to the GEF objectives** requires that selected technologies demonstrate a plausible contribution to GEBs and alignment with GEF-9 priorities, including integration across focal areas, systems transformation, and resilience. Technologies that deliver narrowly localized or commercially confined benefits, with limited scope for replication or policy influence, may not justify engagement, whereas those addressing systemic constraints across multiple contexts may be more aligned with the GEF's comparative advantage. *In practice*, strategic relevance can be assessed by judging alignment with project objectives and the theory of change, including whether the technology directly addresses key drivers of environmental degradation and contributes to the intended GEB outcomes.

⁸⁰ Florin, 2023a; IRGC, 2015; Sach, 2022; OECD, 2024b

⁸¹ Florin, 2022, 2023a, 2023b; OECD, 2023b, 2024; WEF, 2025

⁸² OECD, 2024b

Second, **transformational potential** distinguishes between incremental improvements and system-level change. Evidence shows that transformative impact depends on whether interventions influence underlying drivers such as incentives, governance structures, and behavioural patterns, rather than simply improving efficiency within existing systems.⁸³ Technologies are most relevant when they enable broader transition pathways, such as decarbonization, ecosystem recovery, and circular economy systems, by supporting systemic shifts, improving resource efficiency, and facilitating the scaling of sustainable practices and policies.⁸⁴ **In practice**, the ability to deliver systemic impact in a specific context can be assessed by analysing the technology’s scalability, replication potential, and ability to affect incentives, coordination, or governance across actors and sectors.

Third, **appropriateness and readiness for GEF engagement** must be assessed relative to country and institutional contexts. Readiness includes not only technical maturity but also the presence of enabling conditions such as infrastructure, data systems, governance frameworks, and human capacity. Unmet assumptions regarding operation and maintenance, data governance, and institutional capacity are among the most common causes of underperformance in technology-focused interventions.⁸⁵ Appropriateness also depends on whether the associated risks are broadly manageable within the GEF institutional context. This includes alignment with the GEF risk appetite framework, which specifies a high appetite for innovation risk, provided that the risks are justifiable within a sound theory of change that targets transformational outcomes.⁸⁶ **In practice**, this can be assessed through feasibility analysis of local conditions, including institutional capacity, infrastructure, market readiness, affordability, and compatibility with existing systems and practices.

5.2 Considerations for responsible deployment

Even when technologies meet these criteria, their effectiveness depends on how they are deployed. This section outlines four guiding considerations for selecting and deploying technologies (see also Annex 2 and 3).

A central issue is **governance, equity, and accountability**. Emerging technologies can reshape access to information, control over resources, and decision-making authority, often in ways that are not immediately visible. Without appropriate safeguards, benefits may accrue disproportionately to actors with greater technical or financial capacity, while risks could be shifted to less powerful groups.⁸⁷ Unequal access to digital infrastructure and data capabilities can reinforce existing asymmetries in environmental governance.⁸⁸ Equity is particularly

⁸³ Geels, 2019; Andersson et al., 2023

⁸⁴ OECD, 2022; Donaldson & Ratner, 2023; UNEP, 2025b

⁸⁵ GEF IEO, 2025b

⁸⁶ GEF, 2024b; Stafford Smith & Ratner, 2024

⁸⁷ Florin, 2023a; UNCTAD, 2025

⁸⁸ STAP, 2025a

important because many environmental outcomes depend on the participation, trust, and long-term stewardship of local actors, including Indigenous Peoples and local communities.⁸⁹ *In practice*, governance, equity and accountability can be assessed by evaluating existing or planned governance frameworks, including safeguards, regulatory oversight, and the capacity to manage risks and ensure transparency.

Equally important is **context alignment and participation**. Technologies that are not adapted to local institutional, cultural and knowledge systems may fail to deliver expected outcomes or undermine local ownership.⁹⁰ Research shows that context-specific adaptation and stakeholder participation are critical determinants of long-term success.⁹¹ *In practice*, context alignment and participation can be assessed by reviewing whether technologies are adapted to local conditions, whether relevant stakeholders have been meaningfully involved in design and implementation, and whether the intervention is likely to build trust, ownership and long-term uptake.

A further consideration is **environmental safeguards and risk–benefit trade-offs**. Emerging technologies may generate unintended consequences, including rebound effects, ecological pressures and systemic risks. For example, lithium-ion batteries are central to energy decarbonization but also introduce new environmental pressures, including mining impacts, chemical pollution (e.g. per- and polyfluoroalkyl substances or PFAS), and waste management challenges.⁹² Similarly, gene-editing technologies, such as Clustered Regularly Interspaced Short Palindromic Repeats (CRISPR), proposed for pest control or conservation, may pose ecological risks, including unintended gene flow and ecosystem disruption.⁹³ Also, AI can pose systemic risks when embedded in interconnected infrastructure and decision-making systems, where failures, biases, or cyber vulnerabilities can cascade across sectors and scales.⁹⁴ Environmental gains must be assessed relative to potential risks and alternative interventions, and that monitoring and adaptive management are essential as emerging technologies are deployed.⁹⁵ *In practice*, environmental safeguards and risk–benefit trade-offs can be assessed through life-cycle analysis,⁹⁶ environmental and social risk assessments, comparison with alternative interventions, and the inclusion of monitoring and adaptive management systems in project design.

The issue of **economic sustainability and life-cycle viability** is also critical. It is essential that projects embed durability, affordability, and institutional fit in their design, through life-cycle costing, local capacity development, reduced dependence on proprietary and imported systems, and clear post-project financing pathways. Technologies should be selected based on their ability

⁸⁹ STAP 2025a, 2025d

⁹⁰ Kuhlmann et al., 2019; OECD, 2024b

⁹¹ Brondízio et al., 2021; Stilgoe et al., 2013

⁹² UNEP, 2024c

⁹³ National Academies of Sciences, Engineering, and Medicine, 2016

⁹⁴ OECD, 2023b; Galaz et al., 2021

⁹⁵ Florin, 2023a; OECD, 2024b; UNEP, 2025a; 2025b

⁹⁶ ISO 2006

to function within local market and governance conditions, with defined ownership, maintenance arrangements, and adaptive management mechanisms to ensure sustained use beyond GEF support. ***In practice***, economic sustainability and life-cycle viability can be assessed through life-cycle costing,⁹⁷ analysis of operation and maintenance requirements, evaluation of local market and institutional capacity, and identification of clear financing and ownership pathways beyond the project life cycle.

6. Conclusions and strategic implications for the GEF

Emerging technologies are increasingly relevant to the GEF because of their potential to shape how environmental interventions are designed, implemented and sustained — and because of the systemic impacts they bring to the sectors the GEF aims to influence. Recent developments make GEF’s strategic engagement increasingly important, including: the rapid convergence of digital, data, and environmental monitoring systems; the falling costs of distributed and modular technologies; the growing demand for traceability, transparency, and environmental compliance; and the increasing global emphasis on climate information, early warning, and resilient infrastructure.

The analysis in this paper has considered a broad set of technology categories and applications, including environmental sensing and intelligence systems, traceability and governance infrastructure, clean energy and industrial transition technologies, circular materials and pollution management technologies, biotechnologies, and frontier innovations. The objective is not to help the GEF pick “winners” among these technologies, but to support more systematic attention to how technologies are selected, embedded, governed, deployed, and sustained within project and programme contexts for durable GEBs and transformational change.

The following are overarching conclusions of this paper:

- **Emerging technologies are not neutral tools.** Their contribution to GEBs depends on how they are embedded in institutions, governance arrangements, infrastructure, markets and social contexts. They are best understood as socio-technical systems rather than isolated technical solutions. Context is also critical: technologies that are mature in one setting may be emerging in another because of differences in institutional capacity, governance, infrastructure and market conditions. For the GEF, this means that technological promise alone is never sufficient; what matters is whether the broader system in which technology is introduced can support and sustain environmental gains over time.
- **The function of emerging technologies is more important than their novelty.** Their value lies in the pathways through which they influence environmental outcomes,

⁹⁷ https://green-forum.ec.europa.eu/green-business/green-public-procurement/life-cycle-costing_en

including by improving decision-making, coordination, incentives and overall system performance. Emerging technologies can strengthen environmental monitoring and early warning, improve transparency and accountability, enable optimization and efficiency gains, support adaptation and resilience, and accelerate transitions in production and consumption systems. In many cases, their most important contribution lies less in direct biophysical effects than in reshaping information flows, governance systems, and implementation dynamics.

- **Context determines success or failure.** Without adequate policy alignment, institutional capacity, financing, infrastructure, and governance, emerging technologies are less likely to scale or deliver durable GEBs. Evidence from the literature, evaluations, expert consultations and case studies consistently shows that successful deployment depends on enabling conditions such as institutional readiness, sustainable financing, technical capacity, safeguards and trust. For the GEF, this underscores the importance of assessing contextual fit and long-term viability, not just technical potential.
- **Risks and trade-offs must be addressed early.** Poorly governed or prematurely deployed technologies can create lock-ins, rebound effects, exclusion, unequal distribution of benefits and unintended environmental harm, including new ecological pressures. These risks are often greater in lower-capacity settings and in contexts where governance systems lag behind innovation. Effective engagement therefore requires early assessment of risk–benefit trade-offs, safeguards and long-term implications, supported by monitoring and adaptive management.
- **The GEF’s comparative advantage lies in enabling strategic, responsible deployment and scaling.** The GEF can add the greatest value by creating enabling conditions, supporting piloting and learning, and helping scale technologies that contribute to transformation, adaptation, and resilience. Given the rapid pace and uncertainty of technological change, this requires anticipatory, evidence-based, and adaptive engagement, including informed selection, phased deployment, continual monitoring, and iterative course correction. It also requires risk assessment that goes beyond project-level risks to consider systemic and long-term effects, including feedback, cross-sector interactions, and potential lock-in, while embedding equity and inclusion from the outset as essential conditions for adoption, legitimacy, and durability.

Strategic engagement with emerging technologies requires coordinated action across the GEF partnership. The roles of different actors within the GEF partnership are complementary but distinct:

The **GEF Secretariat** could play a strategic role by helping to shape how the partnership engages with emerging technologies in ways aligned with GEF programming directions and policy

frameworks. This includes strengthening portfolio-level learning and knowledge exchange,⁹⁸ and ensuring technology-related interventions align with the GEF's safeguards, risk appetite and operational policies. Through programming guidance, incentives and knowledge management systems, the Secretariat can help promote technology applications that support systems transformation, while facilitating more consistent and informed decision-making across countries, agencies and focal areas.

GEF agencies could translate strategic direction into operational practice by integrating emerging technologies into project and programme design and implementation across focal areas and integrated programmes. They can bridge internal silos, particularly between innovation, research and technical units and GEF-facing teams within their organizations, to ensure emerging opportunities are reflected in GEF programming. Agencies can also build partnerships with the private sector, research institutions and technology providers to access expertise, innovation pathways and co-financing. Through their leadership of integrated programmes and associated global platforms, agencies also play an important role in facilitating knowledge exchange, learning, replication and scaling across countries and regions.

Countries are central to ensuring engagement with emerging technologies is grounded in national priorities, institutional realities and long-term development trajectories. They can play a defining role in identifying context-specific needs and ensuring policy coherence across sectors so that technology deployment aligns with broader environmental, economic and social objectives. Countries are also critical to strengthening governance and institutional frameworks, including those related to data management, safeguards and equity, and to establishing enabling conditions for implementation, such as regulatory frameworks, infrastructure and human capacity. Long-term ownership and oversight by countries will be essential to ensure technologies remain functional, adaptable and impactful beyond the life of GEF-supported interventions.

⁹⁸ These functions are explicitly emphasized in the GEF's *Strategy for knowledge management and learning* (GEF, 2024b).

Annex 1: Illustrative examples of emerging technologies in GEF-supported projects

The examples presented below illustrate some of the technology-enabled approaches already present in the GEF portfolio. These are illustrative rather than exhaustive; they span multiple focal areas and operational contexts and include earlier projects that helped introduce then-novel technologies into GEF programming and later ones that are using advanced digital, monitoring, finance and industrial transition tools.

UAVs/drones for Equitable Climate Change Adaptation: Participatory Risk Management through Landslide and Debris Flow Monitoring in Mocoa, Colombia (GEF ID 10438; GEF-7; Development Bank of Latin America - CAF)

This project applies a package of emerging technologies to strengthen climate risk management in Mocoa, Colombia, which is a city highly exposed to landslides and debris flows. At its core, the project combines **UAVs/drones, LiDAR sensing, GNSS stations, geospatial data-processing software and machine learning models** to generate detailed terrain and risk information for landslide monitoring and risk projection. The project was explicitly designed to reduce vulnerability and increase resilience by creating a community-based monitoring system capable of improving understanding of current risks and supporting the prediction of future landslides.

One of the most innovative features of this project is the way in which multiple technologies are combined into a broader environmental intelligence system. The project transferred a suite of technologies to [CORPOAMAZONIA](#), including a Matrice 350 drone, a ROCK R2A LiDAR sensor, two Emlid Reach R2S+ stations and processing software, while also developing flight protocols, data management procedures, and susceptibility modelling methods adapted to the challenging highland and forested conditions of Mocoa. By mid-2025, all data-collection activities had been finalized, including LiDAR data sets covering 16 polygons and 408.5 hectares, and the project had developed and refined machine learning models for landslide detection and susceptibility analysis. These technologies help generate more precise and timely information on terrain instability, thereby improving the basis for local adaptation planning, risk reduction and early action.

The project's experience so far illustrates how emerging technologies can contribute to environmental and adaptation outcomes by strengthening the institutions and knowledge systems needed to use risk information effectively. A major part of the initiative has focused on building local capacity through training, technical assistance and participatory governance. This included the establishment of a **Community Researchers Network**, an **Advisory Committee**, repeated public meetings and workshops, and training for local pilots, students and technical staff. The result was not simply the production of new data, but the creation of a more participatory and locally grounded risk-management process, supported by a prototype decision-support platform designed to make results more accessible and usable to communities, public authorities and other actors.

At the same time, the project implementation review (PIR) highlights several enabling conditions for effective deployment. The project's success depends on strong technical support, iterative troubleshooting, adaptive management and sustained engagement with local stakeholders. The PIR has also identified practical barriers, including export-control issues, drone malfunction, gaps in data set generation, and the need to recollect and reprocess part of the LiDAR data. These challenges underscore that the value of such technologies lies not in the hardware alone, but in the surrounding system of local capacity, maintenance arrangements, quality control, participatory governance and long-term institutional ownership.

Restoration Challenge Grant Platform for Smallholders and Communities, with Blockchain-Enabled Crowdfunding (GEF ID 10637; GEF-7; International Union for Conservation of Nature - IUCN).

This project combines digital applications, **blockchain-enabled traceability** and crowdfunding features to support smallholder and community-led forest landscape restoration in Cameroon and Kenya. From the outset, the project was designed to use mobile technology and payment-transfer services to provide small grants or payments for restoration work, while using **blockchain** as the central pillar to strengthen transparency, trust, monitoring and mobilization of future investment. In this model, restoration is not treated simply as a planting exercise but as a digitally enabled system that links seed sourcing, tree nursery production and planting, verification of restoration work and finance.

This example is especially relevant in the way in which blockchain is positioned within a broader digital platform for verifiable restoration. The project documents describe blockchain as a means to ensure transactions along the restoration chain are unique, traceable, unchangeable and verifiable, thereby increasing transparency and confidence for implementers and prospective investors. In practice, the platform has already developed and deployed user-friendly mobile applications that support field verification, monitoring and direct payments to beneficiaries, while also advancing a **Hyperledger blockchain** in a test environment and introducing blockchain verification and crowdfunding features. This architecture is intended to reduce transaction costs, improve accountability and help crowd in additional finance for restoration by making environmental action more transparent and investable.

The project shows how digital and blockchain-enabled systems can contribute to GEBs by strengthening the implementation and financing of restoration at the landscape level. According to the latest progress report, the platform has supported the planting of more than **355,000 trees** across Cameroon and Kenya, restoring or improving management on over **2,200 hectares** and reaching more than **4,000 direct beneficiaries**. It has also helped organize restoration supply chains by: registering farmers, seed collectors and nurseries; supporting the production and distribution of diverse, native and site-adapted seedlings; and linking verification to payment authorization. This provides a strong example of how blockchain-related infrastructure can support GEBs not directly through the technology itself, but by making environmental interventions such as restoration more verifiable, coordinated and therefore financeable, while helping to channel incentives to local actors carrying out the work on the ground.

At the same time, the experience highlights important enabling conditions and limitations. The progress reports make clear that deploying blockchain-enabled restoration finance in rural settings depends on much more than software alone. It also requires reliable digital and physical infrastructure (e.g. mobile applications, offline functionality and functioning payment interfaces), as well as capacity-building (e.g. digital literacy), access to technology (e.g. smartphones) and community support.

Global Clean Hydrogen Programme (GEF ID 11437; GEF-8; United Nations Industrial Development Organization - UNIDO)

Approved in GEF-8, this programme proposes to support the uptake of clean/green hydrogen technologies in developing countries as a means of decarbonizing hard-to-abate industrial sectors and selected transport applications. It is designed to strengthen the enabling conditions required for hydrogen deployment rather than simply fund stand-alone technology installation. It combines support for policy and regulatory development, technical readiness assessments, pilot project preparation and financing mechanisms, with the stated objective of enhancing institutional capacity and supporting net-zero development with social considerations and benefits.

The IEO identifies green hydrogen as a still-nascent but growing area in the GEF portfolio, particularly relevant to hard-to-abate sectors.⁹⁹

This programme provides a good example of an emerging technology (i.e. green hydrogen) being integrated from the start and supported by a broader socio-technical system of standards, infrastructure planning, industrial clustering and investment design. The proposal identified several key barriers that constrain uptake in developing countries, including weak policy frameworks, limited technical readiness, insufficient bankable projects and underdeveloped financial mechanisms. It proposed to overcome these by helping to set up the wider institutional and market architecture required for its adoption.

In this context, the application of clean hydrogen is expected to generate GEBs by supporting participating countries in reducing emissions from industrial production and transport while contributing to national net-zero and Nationally Determined Contributions pathways. The programme proposes to identify priority sectors, assess new hydrogen-based industrial opportunities, support pre-feasibility studies and pilot projects, and develop financial mechanisms that could help translate hydrogen ambition into implementable investment pathways.

The project proposal highlights important conditions that will determine whether such technologies deliver meaningful results, including the need for appropriate regulation and standards, technical and institutional capacity, investment readiness and safeguards related to water use, land use, energy access and local community inclusion. It also underlines the importance of coupling technology deployment with public-private coordination, skills development and knowledge-sharing across countries.

⁹⁹ GEF IEO, 2025b

Accelerating Electronic Monitoring (EM) in Tuna Fisheries for Strengthening Transparency and Addressing Illegal, Unreported, and Unregulated Fishing (GEF ID 11996; GEF-8; Conservation International)

This project aims to expand the use of EM systems in global tuna fisheries to strengthen transparency and reduce [IUU fishing](#). The technology package adopted centres on **on-board video cameras, gear sensors, GPS and digital data transmission systems** that can monitor, verify and transmit information on industrial fishing activity. In addition, the project proposes to trial **edge AI computing**¹⁰⁰ in at least one national EM programme, to process footage more efficiently and enable faster identification of potentially risky activity. Rather than treating EM simply as a compliance tool, the project proposes to use it as a broader digital transparency system linking fisheries governance, supply chain assurance and market access.

The project aims to support regional fishery management organizations in strengthening monitoring policies, assist at least six coastal states in building national EM programmes, and work with private and public actors to integrate EM into sourcing policies, fishery improvement projects, and import control and enforcement systems. It also proposes to create the enabling architecture for wider uptake, including programme standards, financing strategies, legal reforms, implementation plans and knowledge-sharing resources. This makes it a prime example of how an emerging digital monitoring technology may contribute to environmental outcomes when effectively embedded within wider institutional, regulatory and market systems.

The use of technology is expected to generate GEBs by increasing independent monitoring coverage in industrial tuna fisheries, improving the accuracy and credibility of fisheries data, deterring IUU fishing, strengthening compliance with conservation and management measures, and supporting more sustainable tuna fisheries. The project links intervention to expected environmental benefits for at least **three large marine ecosystems**, and **443,712 metric tonnes of fish within globally over-exploited fisheries**. It also argues that improved data and transparency can support climate-ready fisheries management by strengthening long-term decisions on stock health, by-catch, and ecosystem resilience in the face of climate-driven changes in tuna distribution and biomass.

In terms of potential challenges and limitations, the project proposal recognizes that successful uptake depends on several enabling conditions, including stronger regional and national monitoring regulations, technical capacity to design and administer EM programmes, sustainable financing arrangements, private sector cost-sharing, and broader acceptance among fishers and vessel operators. It also identifies governance and social issues that will need careful handling, including

¹⁰⁰ “Edge AI” consists of using AI in combination with edge computing to allow data to be collected at or near a physical location. For example, an image recognition algorithm will perform better if it is closer to the data source. Edge AI allows responses to be delivered almost instantly. With edge AI, data is processed within milliseconds, providing real-time feedback with or without an internet connection because AI algorithms can process data closer to the device. This process can be more secure when dealing with sensitive data because it never leaves the “network edge”. Edge AI differs from traditional AI because instead of running AI models at the backend of a cloud system, they run on connected devices operating at the network edge. This adds a layer of intelligence where the edge device not only collects metrics and analytics but is also able to act upon them via an integrated machine learning model within the edge device.

legal frameworks, worker safety, gender dimensions and the potential distributional effects of reducing IUU-linked catch flows.

Wildlife Conservation for Development Integrated Program (GEF ID 11148; GEF-8; The World Bank; United Nations Development Programme- UNEP; United Nations Environment Programme - UNDP; International Union for Conservation of Nature- IUCN; Asian Development Bank- ADB; World Wildlife Fund – WWF; Conservation International- CI)

The GEF-8 Wildlife Conservation for Development Integrated Program (WCDP), which builds on the earlier GEF-6–GEF-7 Global Wildlife Program (GWP), provides an important example of how emerging and digital technologies can support wildlife conservation as part of a broader system of interventions involving governance, enforcement and landscape management. The programme is explicitly designed to address the interconnected drivers of wildlife loss through national, regional and global interventions, with the objective of conserving wildlife and landscapes to maximize GEBs while ensuring countries and communities benefit from these natural assets. Its architecture combines connected landscape management, action against illegal and unsustainable wildlife trade, wildlife-based development pathways, and a global coordination and knowledge platform intended to support learning and scaling up.

Within this wider framework, the WCDP draws on a range of technology-enabled tools and systems to strengthen monitoring, enforcement and management. These include digital technologies for wildlife monitoring, anti-poaching, surveillance and data management such as [SMART](#), national wildlife databases and mobile applications for real-time reporting. The 2024 GEF IEO evaluation of the GWP¹⁰¹ similarly notes that GWP projects have used technologies such as [eCITES](#), SMART, drones, camera traps, AI-enabled tools and traceability systems to strengthen wildlife monitoring, anti-poaching surveillance, protected-area management, criminal investigations and evidence gathering for wildlife crime prosecution. According to the evaluation, these tools have improved the collection and analysis of field data, enabled more rapid and strategic responses to threats, helped trace the origin of seized wildlife products, and in some cases supported concrete enforcement outcomes, including the arrest and prosecution of poachers, as well as stronger management effectiveness in protected areas.

The specific added value of this approach lies in how technology is used to support broader conservation outcomes and efficiency, rather than narrow technical improvements. In this sense, the GWP illustrates how digital and emerging technologies can contribute to GEBs by improving the management of protected areas and wildlife landscapes, strengthening responses to poaching and trafficking, and supporting more coordinated conservation action across borders and institutions.

The IEO evaluation concludes that, while progress has been made, important challenges remain in knowledge management, results monitoring, coordination, safeguards, and engagement with Indigenous Peoples, local communities and the private sector. It also notes that technology-related

¹⁰¹ GEF IEO, 2024b

gains have been uneven and that reporting, implementation quality and institutional alignment have, in some cases, constrained programme-level additionality and impact.¹⁰² This confirms that technology can strengthen environmental interventions in conservation, and that it does so most effectively when it is embedded within strong institutions, inclusive stakeholder engagement, cross-border cooperation, and adaptive systems for learning and implementation.

Sustainable Cities Integrated Program (GEF ID 11287; GEF8; The World Bank; Development Bank of Southern Africa - DBSA; International Union for Conservation of Nature – IUCN; United Nations Environment Programme- UNEP; Inter-American Development Bank – IADB; United Nations Development Programme – UNDP; Food and Agriculture Organization -FAO; United Nations Industrial Development Organization – UNIDO; West African Development Bank - BOAD).

The GEF Sustainable Cities Integrated Program provides an example of how emerging urban technologies can support broader environmental transformation when embedded in integrated planning and governance systems, rather than deployed as stand-alone technical fixes. In Melaka State, Malaysia, the programme supports the implementation of a **smart energy grid system** that integrates renewable energy, solar-powered electric vehicle charging, battery energy storage, smart meters and an energy monitoring dashboard.

This provides a good example of how different technologies are integrated into a system designed not simply to improve the performance of isolated infrastructure components, but to support a more coordinated approach to generating, distributing, monitoring and managing energy across the urban system. In this context, the technology package is linked to a broader urban transition strategy under Melaka’s “Green City State” vision, which integrates digitalized energy and monitoring technologies into wider planning, financing and governance processes.

The underlying integrated approach includes support for a Municipal Public–Private Partnerships Framework, which helps municipalities identify, prepare and manage public–private partnership projects, while also building practical know-how, technological capabilities and workable business models.

The environmental value of this approach lies in its potential to generate benefits beyond single technologies or individual assets. By integrating solar farms, rooftop solar, solar thermal systems, smart meters, electric vehicle charging stations, battery systems and energy monitoring into a single urban energy management platform, the intervention supports a systemic reorganization of low-carbon urban infrastructure. This can help reduce greenhouse gas emissions, improve energy efficiency and strengthen the capacity of cities to manage increasingly complex urban energy systems in a more coordinated and evidence-based manner. The example is therefore useful not because it showcases one discrete technological innovation, but because it demonstrates how integrated urban platforms can enable wider low-carbon urban transition.

¹⁰² GEF IEO, 2024b

At the same time, the Melaka experience highlights an important lesson central to this paper, which is that the contribution of emerging technologies depends heavily on the enabling system surrounding them. In this case, the value of the technologies is amplified by their being embedded in a broader framework of urban planning, governance, finance and public–private partnerships.

Annex 2: Selection criteria for GEF engagement with emerging technologies

Selection criterion	Key question	Main parameters to assess
1. Strategic relevance to the GEF mandate	Is this technology meaningfully relevant to the GEF's policy and programming objectives?	• Plausible contribution to GEBs; • Relevance across multiple focal areas or integrated programmes where system-level benefits are plausible; • Relevance across multiple countries, regions or ecosystems, or strong potential for scaling and replication; • Relevance to developing countries, especially least developed countries and small island developing States; • Alignment with priorities and objectives under GEF-9 strategy and programming directions.
2. Transformational potential	Does the technology have the potential to enable or drive transformational change rather than marginal improvement?	• Potential to extend the durability of GEF investments; • Potential to facilitate cross-focal area impacts and support integrated programming; • Potential to influence system dynamics, incentives or behaviours; • Potential to enable meaningful, positive and lasting social change; • Potential to accelerate positive environmental transitions, such as decarbonization, ecosystem recovery or circular economy; • Potential to support policy, institutional or financial system-wide reforms.
3. Appropriateness and readiness for GEF engagement	Is engagement with this technology appropriate for GEF support at this time, and under what conditions?	• Technology readiness relative to the GEF operational and country context, rather than technology readiness levels alone; • Whether implementing partners or countries have sufficient institutional and human capacity to deploy, govern and sustain the technology being considered; • Ability to meet data, infrastructure, and long-term operation and maintenance requirements; • Ability to manage associated environmental and social risks within the GEF risk appetite framework.

Annex 3: Guiding considerations for the deployment of emerging technologies

Guiding consideration	Why it matters	Main aspects to check/ensure
1. Governance, equity and accountability	Technologies can reshape power relations, access to information and control over resources. Without adequate governance, benefits may concentrate while risks and costs are shifted onto less powerful groups.	• Transparency and accountability arrangements; • Distribution of benefits and risks; • Potential exclusion, elite capture or dependency; • Data governance and oversight mechanisms; • Institutional capacity to govern use under uncertainty.
2. Context alignment and participation	Technologies are more likely to deliver durable outcomes when adapted to local contexts rather than deployed, transferred or applied as standardized solutions.	• Fit with local institutional and social norms; • Participation and local ownership; • Compatibility with Indigenous knowledge and cultural practices; • Alignment with local needs and governance priorities.
3. Environmental safeguards and risk–benefit trade-offs	Even environmentally oriented technologies may create hidden harms, rebound effects or new ecological pressures if deployed without adequate scrutiny.	• Likely environmental gains relative to risks; • Comparison with lower-risk or non-technological alternatives; • Potential rebound, displacement or lock-in effects; • Safeguards and ex ante risk assessment; • Capacity for adaptive monitoring and response.
4. Economic sustainability and life-cycle viability	Technologies that are technically promising may still fail if they are unaffordable, dependent on external support or difficult to maintain beyond the life cycle of the funding project under which they are deployed.	• Long-term affordability related to socioeconomic context; • Long-term operation and maintenance needs; • Dependence on imported spare parts, proprietary systems and/or software; • Dependence on specialized expertise not readily/widely available in country; • Realistic financing strategy/plan beyond GEF support.

Annex 4: Analytical synthesis of expert consultations

STAP consulted 21 experts working across different dimensions of emerging technologies. These experts brought perspectives from multilateral institutions, evaluation and learning, conservation technology, digital governance and, to a lesser extent, energy and industrial innovation. Interviews were conducted on a non-attribution basis to encourage open and candid discussion.

Although the purpose of the consultations was not to conduct a simple classification or ranking exercise, several technology families were identified or mentioned consistently. By far the most frequently referenced category was **digital and data technologies**, which included: AI-enabled analytics, remote sensing, satellite and geospatial systems, sensor networks, IoT-based environmental monitoring, data platforms, digital MRV systems and traceability or registry tools. These were repeatedly identified as important and relevant for biodiversity, climate, land, chemicals, waste and international waters because they can significantly improve monitoring, verification and decision-making. Many respondents also effectively considered these tools as part of a broader ecosystem of emerging technologies and/or applications rather than as a narrow technology category.

A second recurring cluster comprised **environmental monitoring technologies**, especially as applied to conservation: acoustic sensors, camera traps, eDNA, drones, bioacoustics, wildlife monitoring platforms and related analytics. Here, the consultations suggested that the technological and applications frontier is shifting away from data generation alone and towards systems that connect data streams to decisions. Multiple respondents argued that the central problem is no longer the absence of tools, but fragmented data pipelines, weak stewardship and limited ability to move from observation to governance action.

A third group of responses highlighted **energy and industrial transitions**. These included distributed renewable energy, local and weak-grid systems, long-duration storage, industrial decarbonization in cement and steel, next-generation geothermal, and, in one particularly distinctive intervention, advanced transmission as a potentially underappreciated transformational technology. These perspectives broaden the paper beyond digital technologies and point towards a set of GEF-relevant applications where the challenge is more about finance, infrastructure, policy reform and regulatory readiness.

A smaller but still important set of consultations highlighted **biotechnology, genomics, nanotechnology, quantum computing, and advanced materials**. These were generally framed as horizon-scanning issues rather than near-term portfolio priorities. Evidence from the consultations did not support ignoring them, but it did suggest they should be considered by the GEF selectively if suitable opportunities arise.

An important set of insights from the consultations concerns the conditions under which emerging technologies become system-relevant and durable. Respondents emphasized that system change often requires both bottom-up experimentation and top-down institutional embedding. Pilot projects, sandboxes, and local demonstrations can build confidence and reveal practical use cases,

but they are unlikely to scale without supportive policy frameworks, standards, market creation, and cross-ministerial coordination.

Governance, safeguards, and social legitimacy were also recurring concerns. Experts stressed that the most important risks are not always narrowly environmental; they often relate to data governance, rights, accountability, surveillance, consent, and asymmetries in control over digital infrastructure. This was especially clear in discussions on conservation technologies, where tools such as camera traps, drones, and AI-enabled imagery can generate ecological benefits while also affecting community trust and behaviour if not governed appropriately.

The consultations also reinforced the need to move beyond narrow assessments of technical readiness. Readiness was described as systemic: weaknesses in connectivity, legal frameworks, institutional capacity, local technical support, procurement, maintenance, or financing can undermine the entire deployment chain. Similarly, respondents emphasized that hidden harms and life-cycle implications, such as energy and water use, e-waste, critical mineral demand, rebound effects, social disruption, and unequal burden-shifting, should be treated as central to technology assessment, not peripheral.

These themes point to broader questions about equity, sovereignty, sustained use, and the GEF's comparative advantage, summarized in Box A1.

Box A1. Cross-cutting insights from expert consultations: equity, sustained use, and GEF's comparative advantage

Expert consultations highlighted three cross-cutting issues that should inform how the GEF engages with emerging technologies.

First, they emphasized that technology diffusion is not only a technical issue, but also a question of equity, sovereignty, and political economy. Emerging technologies can concentrate capital, data, computational infrastructure, platform power, and standards-setting authority among a limited set of actors. This creates risks for developing countries, including exclusion from value creation, exposure to environmental burdens from extraction, hardware turnover and waste, and limited control over data and digital systems. Technology sovereignty, in this sense, is not simply about owning hardware or hosting data centers. It depends on whether countries and communities can adapt technologies to local needs, control data, negotiate platform terms, maintain systems over time, and participate in value capture.

Second, the consultations identified real opportunities for leapfrogging but stressed that these are conditional rather than automatic. Distributed energy systems in weak-grid contexts, lower-cost biodiversity monitoring tools, open-source or adaptable digital platforms, and South–South pathways for technology diffusion can help countries avoid older, less efficient systems. However, these opportunities depend on local innovation ecosystems, skills, interoperability, financing, governance arrangements, and reduced dependence on single vendors or external gatekeepers. Digital product passports, traceability rules, and environmental compliance systems may improve transparency and circularity, but may also become trade barriers where countries lack the capacity to comply.

Third, experts repeatedly pointed to a supporting infrastructure problem: pilots and proof-of-concept demonstrations attract attention, but scaling, maintenance, upgrades, data cleaning, interoperability, software upkeep, and institutional embedding are often underfunded. This can lead to abandoned systems or technologies that function only during a project's lifetime. The problem is not experimentation itself, but experimentation without an adoption architecture. For the GEF, this suggests that pilots are most valuable when explicitly linked to a scaling pathway, a readiness strategy, a financing model, and an ecosystem of support.

Taken together, these insights suggest that GEF's comparative advantage lies less in selecting specific technologies and more in shaping the conditions under which technologies are deployed. The GEF can act as a system enabler, neutral convener, knowledge broker, risk-sharing financier, and supporter of public-good infrastructure, governance, capacity, and safeguards. Its value lies in helping ensure that technology diffusion is adaptive, inclusive, durable, and aligned with the delivery of Global Environmental Benefits.

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