# Delivering durable change by breaking lock-in

CASE STUDIES OF ANTIMICROBIAL RESISTANCE AND LITHIUM-ION BATTERIES

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# Delivering durable change by breaking lock-in: case studies of Antimicrobial Resistance and Lithium-ion Batteries

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## Executive summary

Lock-in describes the interplay of economic, technological, institutional, political, and social dynamics that reinforce and perpetuate unsustainable practices, even when their negative consequences are known. For the Global Environment Facility (GEF), understanding lock-in is essential to delivering durable and transformational change because many environmental problems persist not simply because of insufficient awareness, but because they are embedded within systems that make the status quo difficult to change. **Applying a lock-in lens can help identify the structural drivers that sustain harmful pathways and reveal leverage points where GEF interventions can shift system dynamics**.

This Information Note applies a lock-in framework to two case studies at the intersection of chemicals and waste and other GEF focal areas. The cases show how lock-in can operate both in mature global challenges, where harmful dynamics are already deeply embedded, and in emerging risks, where there remains a window to intervene before lock-in becomes harder to reverse.

**The first case examines antimicrobial resistance (AMR), a long-standing and worsening threat to human and ecosystem health**. The AMR case study shows that antimicrobial dependence is sustained by interacting structural drivers, including poverty and inequality manifested by inadequate sanitation and hygiene; weak animal health services; limited waste treatment capacity; fragmented governance across health, agriculture, and environment sectors; intensive food production systems; global supply chains for inexpensive generic antimicrobials; and climate change. In many settings, antimicrobials are used to compensate for deeper weaknesses in health, food, and environmental systems, creating reinforcing feedback that sustains dependence while undermining the long-term effectiveness of antimicrobials.

Within its mandate, the GEF can help address AMR lock-in by focusing on the structural drivers with upstream and downstream interventions.

- **Upstream actions focus on reducing the conditions that sustain antimicrobial dependence**: supporting One Health and whole-of-government policy coherence; integrating environmental considerations into national AMR action plans; promoting sustainable livestock, aquaculture, and crop production systems that reduce disease pressure; supporting animal vaccination, improved husbandry, biosecurity, hygiene, manure management, and other preventive approaches; and exploring transitional finance to help producers shift away from unnecessary antimicrobial use.
- **Downstream actions focus on reducing AMR transmission**: strengthening wastewater and waste treatment from human, agricultural, healthcare, and pharmaceutical sources; promoting nature-based treatment systems; supporting monitoring of antimicrobial residues and resistant organisms in aquatic environments; and improving

responsibility for curbing AMR through governance of shared river basins and coastal systems where AMR can spread through water.

These measures can be advanced through the GEF Chemicals and Waste, International Waters, Land Degradation, Biodiversity, and Climate Change focal areas, aligned with the Global Action Plan on AMR and its forthcoming guidelines, as well as through relevant Integrated Programs such as Food Systems, Clean and Healthy Ocean, and Blue and Green Islands, while working with partners to address broader health and socio-economic drivers.

**The second case examines the emerging issue of per- and polyfluoroalkyl substances (PFASs or "forever chemicals") in lithium-ion batteries** (LIBs) at end-of-life, where early action could help avoid long-term environmental and economic costs that are growing globally. LIBs are central to decarbonization, energy storage, electric mobility, and progress toward SDG 7 (affordable and clean energy). However, they also contain PFASs, creating risks across the life cycle. PFAS use in LIBs is becoming locked in through technological dependence on high-performing fluorinated materials, growing capital investment in battery production, entrenched supply chains, innovation pathways focused on optimizing existing materials, fragmented regulatory frameworks, and the externalization of PFAS-related health and environmental costs. This lock-in is reinforced by rapid growth in battery demand, driven by electric mobility, energy storage, consumer electronics, and broader patterns of energy consumption.

The GEF can help break PFAS lock-in in LIBs through both upstream and downstream interventions.

- **Upstream actions to shape battery innovation, markets, policies, and end-of-life systems before PFAS-dependent pathways become more deeply entrenched**: supporting demonstration and early deployment of PFAS-free batteries; integrating safer-material screening into e-mobility and energy storage projects; tracking flows and inventories of LIBs, and additional monitoring for life-cycle assessment; promoting policy coherence across climate, chemicals, circular economy, and waste agendas; and supporting regulatory controls and standards. Other actions include supporting market incentives that internalize environmental and health costs, and private-sector engagement to shift incentives toward safer materials and improved end-of-life management.
- **Downstream action to support environmentally sound management and circularity of LIBs:** investing in collection, reuse, safe dismantling, recycling, and second-life applications for batteries, particularly in lower- and middle-income countries (LMICs) that may receive growing flows of used electric vehicles and end-of-life batteries. This can also help prevent burden shifting by strengthening traceability, regional cooperation, and controls on transboundary movements of used batteries and battery waste.

GEF support for risk-management approaches can be pursued through the Chemicals and Waste focal area, aligned with the Stockholm Convention and the Global Framework on Chemicals. Downstream actions can be pursued under relevant Integrated Programs, including Eliminating Hazardous Chemicals from Supply Chains and Sustainable Cities. These provide platforms to embed battery sustainability criteria, safer procurement, circular economy strategies, and end-of-life safeguards into GEF programming.

As both cases illustrate, by applying a lock-in lens, the GEF can better identify where catalytic investments, policy support, finance, innovation, and partnerships can unlock system change and deliver more durable global environmental benefits.

## 1. Introduction: Lock-in

Why do societies and individuals continue with harmful practices despite awareness of their negative impacts? Many examples abound in the environmental sphere, including the reliance on fossil fuels that cause climate change and the continuing use of toxic lead that is estimated to incur costs of US$1.4 trillion to the global economy.[1] This phenomenon has been explained as the concept of "lock-in."[2] Understanding the drivers leading to lock-in can help design interventions to reverse or halt harmful practices.

**"Lock-in" refers to the interplay of economic, social, technological, and political dynamics that maintain and reinforce a particular socio-technological path.** Lock-in can explain why and how certain technologies and practices can dominate markets, even when they may be inefficient and/or harmful.[3] It can also help explain the systemic barriers that constrain transitions to more sustainable pathways, for example, in the energy sector, where existing infrastructures, regulatory frameworks, market incentives, and vested interests can create conditions that reinforce carbon-intensive systems. Thus, understanding lock-in is necessary to guide transformative pathways toward positive change and sustainability.

**The Global Environmental Facility (GEF)'s goals of delivering durable, scalable, and transformative change can be constrained by systemic lock-in** that undermines the effectiveness of potential solutions. Using a lock-in framework can help identify effective solutions by revealing structural drivers and reinforcing mechanisms that maintain unsustainable practices. Once structural drivers are identified, efforts can target effective leverage point(s) in the system.[4]

This STAP Information Note seeks to improve the effectiveness of GEF interventions, focusing on chemicals and waste, and their intersections with other focal areas, by applying a lock-in framework. Two case studies are used to illustrate the application of this approach. The first addresses antimicrobial resistance (AMR), a rising threat to human and ecosystem health, with complex structural drivers resulting in lock-in. The second is the emerging risks to human and ecosystem health from the use of per- and polyfluorinated alkyl substances (PFASs) in lithium-ion batteries (LIBs). These two case studies were chosen to contrast the use of a lock-in framework. The threat of AMR is long-standing and continues to grow, despite both local to global efforts to address the issue. In contrast, PFASs use in LIBs is an emerging issue for which data on scope are not yet available, and therefore early interventions could minimize harm. Although these two issues primarily concern chemicals and waste, they intersect with other GEF focal areas and Integrated Programs (IPs).

[1] Luby et al. (2024).
[2] Unruh (2000); Blumenthal et al. (2022); UNEP (2024).
[3] Cecere et al. (2014).
[4] Meadows (1999).

## 2. Case study 1: Addressing antimicrobial resistance (AMR)

### 2.1 Antimicrobial resistance

The development of antimicrobial resistance (AMR) is one of the most pressing issues facing human societies.[5] Deaths attributable to AMR were estimated at close to 5 million in 2021, and the rate is increasing rapidly, particularly among children, the elderly, and in low-income countries (LICs).[6] The death rate could exceed 8 million by 2050, especially in the "super-regions" of South Asia and Latin America and the Caribbean.[7] During low streamflow conditions, an estimated 6 million kilometers of global rivers experience antibiotic concentrations that exceed levels designated to protect ecosystems and limit the promotion of AMR.[8] AMR has been characterized as an "easy to get and hard to lose" pollutant because the evolutionary processes driving resistance enable resistant genes and organisms to persist and spread once established.[9]

AMR refers to the development of resistance to antibiotics caused by genetic mutation or gene transfer of viruses, bacteria, fungi, and parasites induced by exposure to antibiotics. AMR is a difficult problem[10] because it has multiple causes, involves complex and deep structural drivers that must be unlocked to achieve meaningful change, sits astride multiple government agencies' responsibilities, and involves multiple stakeholders with differing priorities. AMR has received considerable and sustained attention through United Nations agencies and other global actors because of its global scope (see Box 1), yet the risks it poses continue to mount.

**Applying a 'lock-in' perspective can help reveal the structural and behavioral patterns that entrench antimicrobial use and highlight opportunities for more effective, systemic interventions**. Such understanding is essential for designing programs that are durable and avoid reinforcing dependence on antimicrobials or displacing risk across sectors. AMR persists and intensifies not simply because antimicrobials are misused, but because they are embedded in reinforcing economic, institutional, and technological arrangements that make antimicrobials the default response to infection risk for humans, as well as for extensive use agricultural and aquacultural production.

[5] WHO (2021); Jabbour et al. (2026); World Bank Group (2017); Keenum et al. (2026).
[6] Naghavi et al. (2024).
[7] "Super-regions" refer to geographic locations where rates of AMR mortality are higher than the global average.
[8] Macedo et al. (2025).
[9] Marti et al. (2014).
[10] Rittel & Webber (1973).

**Box 1. International responses to AMR**

Many international activities are focused on AMR. At the World Health Assembly in 2015, United Nations member states adopted a Global Action Plan on AMR with the support of Food and Agriculture Organization (FAO), the World Organisation for Animal Health (WOAH) and the United Nations Environment Programme (UNEP).[11] The Global Action Plan stressed the need to take a One Health approach and involve multiple sectors and actors across human and veterinary health, agriculture, finance, and the environment. Also at the 2015 World Health Assembly, member states committed to develop National Action Plans to address AMR. Today, many National Action Plans contain gaps and differ widely in operationalization.[12] In 2022, a United Nations General Assembly (UNGA) resolution was adopted to significantly reduce global antibiotic use in the agrifood system by 2030 and to "strengthen and accelerate multisectoral progress" to tackle AMR.[13] In advance of the 2022 UNGA meeting, the World Health Organization (WHO) emphasized the importance of addressing AMR challenges through a One Health framework that includes environmental pathways, such as rivers.[14] In 2025, the United Nations Environment Assembly (UNEA) adopted a resolution on the environmental dimension of AMR.[15] Most recently, WHO updated its draft Global Action Plan on AMR which lists six interconnected strategic objectives including strengthening awareness and surveillance systems; intensifying infection prevention including human and animal health according to a One Health approach; ensuring equitable access and appropriate use; accelerating research and innovation; and strengthening multisectoral governance and sustainable financing.[16]

In response to the complexity of AMR, the Quadripartite Joint Secretariat on AMR (QJS) was established in October 2023 to convene FAO, WHO, UNEP and WOAH. The Multi-Partner Trust Fund (AMR MPTF) was set up under the United Nations in conjunction with the QJS agencies to provide financial resources to low- and middle-income countries (LMICs) to strengthen their responses to AMR, including completion of National Action Plans.[17] To support this, the Quadripartite is developing a global integrated surveillance architecture, collating FAO's Global AMR Monitoring system (InFARM), WHO's Global AMR Surveillance System (GLASS), and WOAH's Animal AMR Use Global Database (ANIMUSE) into a single comprehensive repository to facilitate the collection, analysis, and sharing of AMR and antimicrobial use data across all sectors.[18]

The FAO also has efforts directed towards stemming the misuse of antibiotics in the livestock sector, aquaculture, and crop production.[19] FAO has developed its Action Plan on Antimicrobial Resistance and advances One Health principles through its Animal Production and Health Division, which addresses "zoonotic diseases, and antimicrobial resistance in agrifood systems."[20] Additionally, UNEP is addressing

[11] WHO (2015).
[12] Charani et al. (2023).
[13] UNGA (2024).
[14] WHO (2022).
[15] UNEP (2025).
[16] WHO (2026).
[17] See https://www.qjsamr.org/multi-partner-trust-fund/about.
[18] WHO, FAO, UNEP & WOAH (2025).
[19] See https://www.fao.org/antimicrobial-resistance/en/.
[20] FAO (2021).

AMR by emphasizing the environmental dimensions.[21] Its *Superbugs* report[22] provides scientific evidence that the environment is a key driver in AMR spread, driven by pollution from wastewater containing pharmaceuticals used in human health care and veterinary applications. It advocates for a One Health approach and supported the 2025 UNEA draft resolution to strengthen environmental surveillance.[23] The United Nations Development Programme (UNDP) has also recognized AMR as an important global issue that requires multi-stakeholder strategies to achieve progress.[24] International Financial Institutions, such as the World Bank, Asian Development Bank, African Development Bank, Inter-American Development Bank, and the European Bank for Reconstruction and Development, and the International Fund for Agricultural Development, intersect with AMR through their lending, grants, and programs on healthcare, agriculture and livestock production—with opportunities to integrate antimicrobial stewardship into safeguards and veterinary access programs.

### 2.2 Drivers of AMR lock-in

The introduction of antibiotics was one of the greatest medical advances of the 20th century.[25] However, their use extends far beyond treating human disease. Antibiotics are widely used in veterinary practice, including animal husbandry and aquaculture, to prevent disease and, in some countries, to promote animal growth. They are also used in agriculture and personal care products.[26] A major paradox of antibiotic use is that some populations have insufficient access, while others overuse them.[27] Meanwhile, many countries are grappling with the rise of AMR, which threatens the many benefits antibiotics provide, although the main drivers vary by country.[28] Addressing AMR is urgent, as the development of new antibiotics is not keeping pace with the growth of resistance, and systemic lock-in is slowing the pace of new discoveries.[29]

At a system level, **lock-in reinforces dynamics in which antimicrobials are used to compensate for structural weaknesses in health, food, and environmental systems, while undermining their long-term effectiveness**.

*Poverty and inequality* are among the most important systemic drivers of AMR. In many LMICs, high burdens of infectious disease persist due to inadequate water, sanitation, and hygiene (WASH), overcrowded housing, limited access to preventive healthcare, weak or constrained

[21] See https://www.unep.org/topics/chemicals-and-pollution-action/chemicals-management/pollution-and-health/antimicrobial-3.
[22] UNEP (2023).
[23] See https://docs.un.org/en/UNEP/EA.7/L.16.
[24] UNDP (2018).
[25] Hutchings et al. (2019).
[26] Fuoco et al. (2026).
[27] Klein et al. (2024).
[28] AMR lock-in configurations vary across countries and sectors. In many low-income countries (LIC)s, high infectious disease burdens, limited WASH and diagnostic capacity, and weak regulatory enforcement sustain reliance on antimicrobials as coping mechanisms. In middle-income countries (MIC)s, lock-in dynamics may be more strongly driven by agricultural intensification, pharmaceutical manufacturing externalities, and high-volume generic markets. However, it is important to note that not all LICs share the same structural conditions, nor do all MICs exhibit similar dynamics. AMR drivers arise through configurations or reinforcing factors which may cut across income categories. As a result, countries or regions with similar structural configurations may face comparable AMR dynamics even if their gross domestic product (GDP) levels differ. Even within countries, smallholder systems, informal settlements, and industrial production sectors may exhibit different reinforcing feedback loops.
[29] Brussow (2024); Shalin et al. (2026).

animal health services, and limited water treatment. These conditions, and their link to AMR, are fundamentally rooted in poverty, rather than incidental factors i.e., they did not arise randomly or from isolated mistakes but are produced by deeper structural problems related to poverty. In such contexts, antimicrobials often become an accessible and immediate coping mechanism for managing infection risks.[30] Poverty, therefore, operates not as a microbiological mechanism, but as a structural condition that shapes infection risk, patterns of antimicrobial use and demand, and the feasibility of effective mitigation. In doing so, it reinforces system dynamics that sustain high antimicrobial dependence by creating forms of lock-in that make it difficult to change the economic, social, and institutional conditions that make antimicrobials the most accessible response to infection risk.[31]

Poverty and inequality can create a paradox in which *overuse of antimicrobials coexists with limited access to them*. In many LMICs, uncontrolled informal markets, empiric treatment,[32] and over-the-counter sales flourish because they provide rapid—and in many cases affordable—responses where diagnostics and preventive infrastructure are weak.[33] At the same time, shortages of quality-assured first- and second-line antibiotics[34] remain common, particularly in rural and underserved populations.[35] This coexistence of excess and scarcity in some countries reflects structural constraints rather than individual behavior and reinforces reliance on antimicrobials as a substitute for prevention, rather than investing in improved hygiene and stronger health care systems.[36] As such, poverty can lock systems into antimicrobial dependence by raising baseline infection risk while constraining access to non-pharmaceutical prevention options.

*Global antimicrobial supply chains* reinforce lock-in through high-volume production, procurement, and distribution models that make antimicrobials widely available at relatively low cost. First, these dynamics sustain the widespread availability of inexpensive generics, lowering the threshold for routine antimicrobial use in human medicine, livestock production, and aquaculture.[37] Second, thin profit margins during production discourage investment in environmentally sound manufacturing practices, including effective treatment of pharmaceutical effluent, contributing to the environmental release of antimicrobial residues and the evolution of resistant genes.[38] Third, the same market structures that enable overuse can also undermine

[30] WHO (2023).
[31] Anderson et al. (2024); Otaigbe and Elikwu (2023); Planta (2007)
[32] Empiric treatment refers to an initial treatment regime of antibiotics without a definitive identification of a microbiological pathogen or susceptibility testing to ensure that the course of action with antibiotics is warranted. See Strich et al. (2020).
[33] Gautham et al. (2021).
[34] First-line antibiotics are given first for treatment and if ineffective, the second-line antibiotics are prescribed or taken. WHO has provided guidance on which antibiotics should serve as first, second, etc. line for treatment. See Moja L et al. (2024).
[35] Murray et al. (2022).
[36] O'Neill (2016).
[37] Boeckel et al., 2015; Van der Velden et al. (in preparation).
[38] Panwar (2025).

innovation in drug design, quality assurance, and supply diversification and stability, contributing to periodic shortages and instability of generics.[39]

*Weak or fragmented governance and institutional capacity* is a central driver of AMR lock-in. Within countries, responsibilities for antimicrobial governance are typically spread across health, agriculture, environment, and industry ministries, often with limited coordination. This fragmentation hampers the development and implementation of coherent regulatory responses to address the underlying driving factors and to coordinate responses because, for example, there is leakage between health and veterinary uses of antibiotics. Furthermore, regulatory frameworks such as prescription-only policies and veterinary controls[40] are often introduced without adequate provision for professional disease diagnosis, access to human and animal health services, and enforcement capacity needed to make them effective. Moreover, where regulations exist but compliance is weak, antimicrobial use often shifts to informal, less visible markets that continue to provide access but are difficult to control. Likewise, standards for wastewater treatment, where they exist, are often insufficiently implemented, monitored, and enforced.[41] This creates gaps between formal environmental standards and effective implementation, allowing resistant organisms and residues to circulate beyond clinical settings.[42] While country-by-country strategies to address AMR are essential, they alone are insufficient because the *transboundary* spread of AMR occurs through (not exclusively) trade, migration, shared water bodies, and globalized food systems, while governance remains largely national. This mismatch between the scale of AMR drivers and the scale of governance reinforces lock-in through regulatory leakage and uneven implementation.

In *agriculture and aquaculture*, antimicrobial lock-in is driven by production models that prioritize high output but generate elevated disease pressure. The intensification of livestock and aquaculture systems, combined with fluctuating feed and energy prices, creates incentives for preventive antimicrobial use and, where permitted, the use of antimicrobials for growth promotion.[43] Inexpensive generics sustain this dependence by acting as an affordable risk-management tool that substitutes for investments in, for example, hygiene, reducing animal stocking density, animal vaccination, and husbandry improvements. Similarly, in highly intensive animal production systems, inexpensive antibiotics operate as a cost-effective risk-management tool that substitutes for longer-term investments in biosecurity, vaccinations, and reduced stocking density. Restricting agricultural antimicrobial use without addressing these structural

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[39] Shalin et al. (2026); Global Leaders Group on Antimicrobial Resistance (2024).
[40] Limiting access by requiring a prescription from a medical professional to obtain an antibiotic as done in most high-income countries (HICs), as is limiting access to antibiotics for veterinary use. See: Morgan et al. (2011).
[41] Iskandar et al. (2020); Panwar et al. (2025).
[42] Sambaza and Naicker (2023); Van der Velden et al. (in preparation).
[43]Iskandar et al. (2020); Panwar et al. (2025).

pressures risks jeopardizing farmers' incomes by reducing short-term productivity or shifting production geographically, rather than lowering overall antimicrobial reliance.

*Climate change can* act as a cross-cutting amplifier of AMR lock-in. Rising temperatures, extreme weather events, and flooding increase the incidence and spread of infectious diseases while disrupting water and sanitation systems[44] and straining health and veterinary services. These pressures raise demand for antimicrobials where preventive and adaptive capacity is weakest. At the same time, climate-related impacts, such as flooding, can disrupt wastewater treatment, manure management, and pollution control systems, increasing the environmental distribution of resistant organisms. Conversely, drought-induced low river flows can elevate antibiotic concentrations in surface waters, creating conditions that may facilitate AMR amplification by intensifying selection for resistant microorganisms, and promoting gene transfer.[45]

Taken together, these dynamics illustrate how antimicrobial resistance becomes locked into existing socio-technical systems, as represented in Figure 1. **AMR is not sustained by a single factor, but by the interaction of economic conditions and incentives, institutional arrangements, technological practices, and social conditions that collectively reinforce reliance on antimicrobials**. Poverty and inequality increase infection risks and limit preventive options; supply chains and market structures shape the availability and affordability of antimicrobials; fragmented governance weakens regulation and oversight; intensive food production systems create persistent disease pressures; and climate change further amplifies these vulnerabilities. These interconnected drivers can reinforce feedback that maintains antimicrobial dependence even while undermining long-term health, environmental, and economic outcomes. Understanding AMR through a lock-in lens can identify leverage points within these systems that help shift system dynamics and reduce the conditions that sustain antimicrobial dependence.

[44] Mora et al. (2022).
[45] Shan et al. (2026); Ghaly (2026); Sasi et al. (2025).

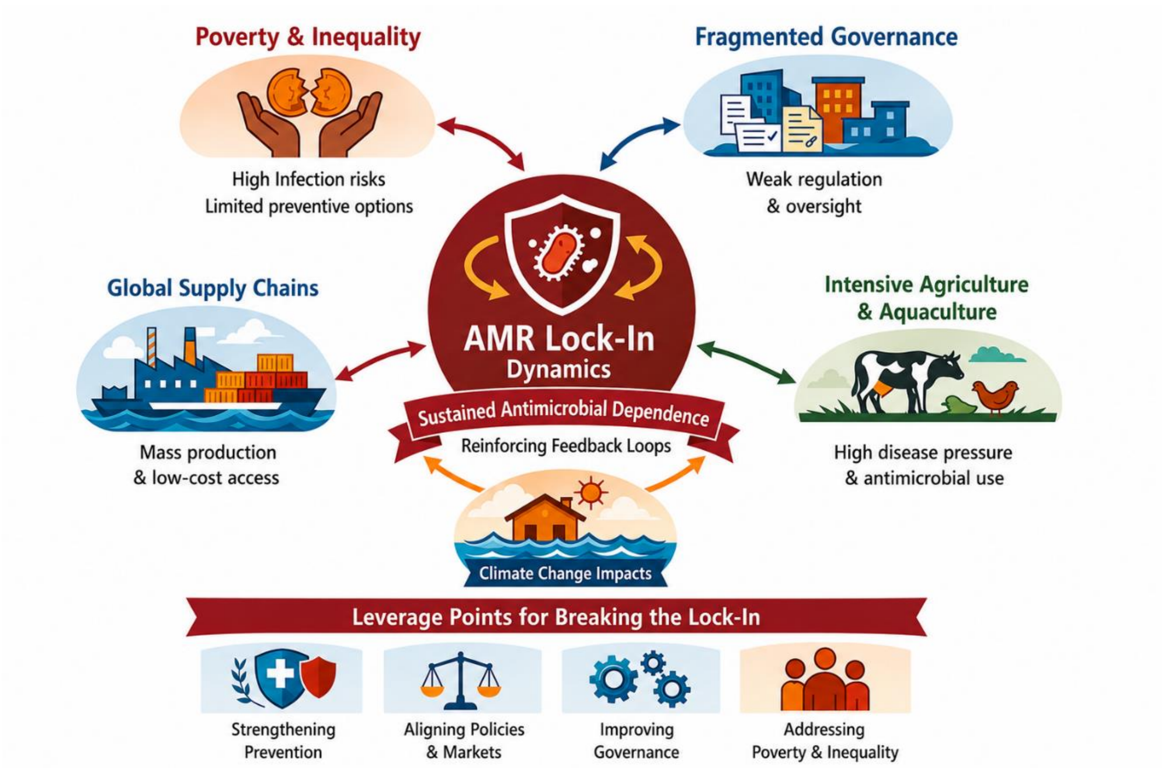


Figure 1: How interactions can reinforce AMR lock-in and potential leverage points for intervention. Interconnected drivers, including poverty and inequality, fragmented governance, intensive agriculture, global supply chains, and climate change, create reinforcing feedback loops that sustain antimicrobial dependence. Key leverage points for breaking this lock-in include prevention, policy alignment, improved governance, and addressing socio-economic vulnerabilities.

### 2.3 Why and how the GEF can contribute to curbing AMR

AMR is a socioeconomic and environmental challenge with direct implications for the GEF's mandate to generate durable global environmental benefits. Environmental pathways, including water systems, agricultural runoff, and waste from human and animal use of antimicrobials, play a critical role in the emergence, amplification, and spread of resistance. These dynamics intersect with multiple GEF focal areas, including Chemicals and Waste, International Waters, Land Degradation, Biodiversity and Climate Change.

**The GEF is uniquely positioned to support programming to tackle structural drivers that lock in AMR** because of its ability to work across multiple focal areas in LMICs where threats from AMR are most pressing. The GEF focal areas provide the "entry points" to act:

- Chemicals and Waste: The GEF supports certain strategic objectives under the Global Framework for Chemicals (GFC) and its predecessor the Strategic Approach to International Chemicals Management (SAICM). One key issue in these frameworks is "environmentally persistent pharmaceutical pollutants" (EPPPs) that include antibacterial agents used in human and veterinary treatments.[46]

- International Waters: Rivers, lakes, and groundwater are the arteries of AMR transport[47] and thus present a source-to-sea problem. At the same time, some countries and basins (national and cross-border) have basic legal and institutional mechanisms in place, some of which explicitly address water quality, to which AMR monitoring and consideration could be added.
- Land Degradation and Biodiversity Loss: Antimicrobials and resistant organisms threaten soil health by altering soil and water microbiomes, disrupting native microbial and lower trophic level communities in waters and soils.[48]

GEF-8 laid preliminary groundwork for addressing AMR, both directly and indirectly, through GEF focal areas and IPs.[49] The Climate Change focal area promotes improved livestock, nutrient, and manure management in line with the Koronivia Joint Work on Agriculture.[50] These measures, although not AMR-specific, help reduce AMR risks. The International Waters focal area has supported several basins in improving water quality, whether through establishing or strengthening legal and institutional frameworks or improving water quality monitoring (that may or may not include AMR surveillance) and developing specific measures to limit pollution. Similarly, the Wildlife Conservation for Development IP applied a 'Healthy Planet, Healthy People' framework that supports reduced zoonotic spillover, offering an initial entry point for AMR-related action; and the Food Systems IP addresses the underlying drivers of unsustainable food systems, including interventions to strengthen disease prevention and control in animal production systems.

The GEF-9 Programming Directions[51] acknowledge AMR as a rapidly evolving global environmental and health priority. GEF-9 identifies AMR alongside *environmentally persistent pharmaceuticals* as priorities under the GFC. The programming further recognizes the risks posed by intensive livestock systems, including antibiotic overuse and waste management challenges. A *One Health* approach is incorporated into the Biodiversity focal area through the Global Action Plan on Biodiversity and Health (CBD COP 16). The GEF-9 Results Management Framework[52] also introduces a dedicated indicator, EP-CW-08, for pharmaceuticals and AMR agents released into the environment. This requires antimicrobial substances to be identified and reported separately from broader chemical categories. The framework also captures AMR-relevant actions through

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[46] See: https://saicmknowledge.org/epi/pharmaceutical-pollutants.
[47] Macedo et al. (2025); Jampani et al. (2024).
[48] Wang et al. (2023).
[49] GEF (2022).
[50] The Koronivia Joint Work on Agriculture was the response to decision 4/CP.23 of the United Nations Framework Convention on Climate Change (UNFCC) Conference of the Parties (COP) held in 2017. It accounts for the vulnerability of agriculture to climate change while addressing food security. See: https://unfccc.int/topics/land-use/workstreams/agriculture/KJWA#SBSTA-SBI-56-June-2022.
[51] GEF (2026a).
[52] GEF (2026b).

SC-FL-01, an indicator which measures the adoption of agroecological and regenerative practices in the food sector, including improved animal health practices that reduce antimicrobial use. In addition, the indicator SC-FL-02 tracks the adoption and implementation of policy and regulatory frameworks, including One Health approaches that integrate livestock, human health, and environmental governance to reduce AMR and zoonotic disease risks. These developments indicate that GEF-9 provides an important foundation for integrating AMR more coherently across relevant focal areas and programming.

Existing GEF programming also offers examples of how an integrated approach can be applied to address some of the structural drivers of AMR (and thus help unlock the system) while realizing additional benefits. Furthermore, several GEF agencies have active programs to tackle AMR that the GEF can build upon. These are elaborated in Box 2.

**Box 2. Examples of GEF's AMR-related investments and activities of Agencies**

GEF-8[53] and GEF-9[54] Programming Directions explicitly recognize antimicrobial resistance as linked to pollution and ecosystem degradation, providing opportunities to act. Examples from the GEF portfolio include the "Mexico's first national policy for deforestation-free and low-emission livestock" (GEF ID 12063; GEF-8) project, which targets livestock-sector transformation and policy coherence and addresses upstream leverage points for reducing disease pressure and antimicrobial dependence in production systems. The UNEP-led project "Global best practices on emerging chemical policy issues of concern" (GEF ID 10119; GEF-7) has worked with WHO to develop a global guidance on reducing wastewater and solid waste pollution from the manufacturing of antibiotics.[55]

GEF agencies are already acting on complementary leverage points, often outside GEF financing but aligned with their mandates. For example, FAO leads global efforts on AMR in agrifood systems, including its Action Plan (2021–2025) and the InFARM surveillance system, addressing upstream drivers such as livestock practices and antimicrobial use.[56] UNEP has established a strong role on environmental dimensions of AMR, highlighting wastewater, pollution, and ecosystem pathways as critical to the emergence and spread of resistance.[57] UNDP supports governance and coordination through mechanisms such as the AMR Multi-Partner Trust Fund, thereby strengthening multisector policy and institutional responses.[58] The World Bank also provides financing and analytical support for AMR through its operational framework, including investments in water, sanitation, and health systems that influence AMR dynamics, and it is currently financing 47 projects across 40 countries.[59] Agencies, such as the International Fund for Agricultural Development (IFAD) and Asian Development Bank (ADB), are

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[53] GEF (2022).
[54] GEF (2026a).
[55] See: https://iris.who.int/server/api/core/bitstreams/0786ae95-e9ba-4fb4-b6ac-94cf2cea9423/content and https://publicpartnershipdata.azureedge.net/gef/GEFProjectVersions/8b105a54-e2c6-e811-813e-3863bb2e1360_2nd%20PIR.pdf.
[56] See: https://www.fao.org/one-health/areas-of-work/antimicrobial-resistance/en.
[57] See: https://www.unep.org/topics/chemicals-and-pollution-action/chemicals-management/pollution-and-health/antimicrobial.
[58] See: https://mptf.undp.org/fund/amr00.
[59] World Bank Group (2024).

contributing through One Health approaches in agriculture and livestock systems, particularly in strengthening animal health and reducing misuse of antimicrobials.[60]

These examples suggest that while the GEF cannot completely address core drivers, such as poverty, inequality, and health system capacity, it can work with other organizations to complement broader efforts by shifting environmental conditions that sustain antimicrobial dependence—consistent with its mandate to deliver global environmental benefits.

### 2.4 How GEF can promote breaking the lock-in of AMR

While drivers of AMR lock-in, such as poverty, inequality, and structural weaknesses in health systems, lie largely outside the GEF's direct mandate, understanding the drivers can nonetheless play an important role in addressing leverage points within food, water, and environmental systems that influence AMR dynamics.

T**he GEF can support interventions that reduce sources of AMR, which is the most effective management intervention, as well as interventions that reduce AMR distribution and growth within environmental reservoirs, such as water bodies**. The GEF can also support efforts to alleviate conditions that reinforce antimicrobial dependence. Examples include improving environmental governance of chemicals and waste, promoting sustainable food production systems, strengthening pollution control and wastewater management, supporting integrated approaches to land, water, and ecosystem management, and raising community awareness.

It is important to acknowledge that environmental interventions alone will not be sufficient to fully break AMR lock-in, as drivers such as poverty, inequality, and structural weaknesses in health systems lie in social, economic, and health system domains that are beyond the GEF's mandate. Progress toward achieving lasting reductions in antimicrobial dependence and the rise of resistance necessitate addressing these underlying drivers. This could be achieved by GEF partnering with other organizations with broader mandates to embed the environmental dimension in their activities and ensure the effectiveness of GEF investments. Such partnerships could include GEF agencies such as FAO, IFAD, the multilateral development banks (MDBs): World Bank Group, African Development Bank (AfDB), ADB, Inter-American Development Bank (IADB), and European Bank for Reconstruction and Development (EBRD); non-GEF organizations, including WHO, WOAH; or specialized public-private partnerships, like the Combating Antibiotic-Resistant Bacteria Biopharmaceutical Accelerator (CARB-X), the Global Antibiotic Research & Development Partnership (GARDP), and the AMR Industry Alliance.

The GEF could address some of the structural drivers of AMR through the following:

- The **Food Systems IP (FSIP)**[61] could address structural drivers of AMR by targeting source reduction in food systems. FSIP interventions can address structural drivers of

[60] Asian Development Bank (2022); IFAD (2021); IFAD (2024).
[61] See: https://www.fao.org/gef/Portfolio/FSIP/en.

disease pressure in food systems by, for example, promoting sustainable agricultural practices;[62] improving animal husbandry and welfare;[63] implementing integrated landscape management, and supporting stronger governance of food production systems. These efforts can reduce reliance on routine antimicrobial use by strengthening preventive approaches in food production systems and improving environmental management, while reducing land degradation and improving food security and water quality.

- The **Clean and Healthy Ocean IP[64]** can help address environmental pathways in aquatic systems by targeting land-based sources of marine pollution across the "source-to-sea" continuum, including wastewater, agricultural runoff, and industrial discharges. While the program's primary focus is on nutrients and broader pollution management, efforts to improve wastewater treatment and reduce land-based pollution offer leverage points for addressing the environmental dimensions of AMR.
- The **Blue and Green Islands IP,[65]** which emphasizes ecosystem restoration, sustainable food and fisheries systems, and improved waste and pollution management in Small Island Developing States (SIDS), can help address sources of AMR and "downstream" environmental conditions that facilitate the spread of contaminants, including pharmaceutical residues, in fragile island ecosystems. Strengthening ecosystem resilience and improving waste and wastewater management can contribute indirectly to addressing environmental pathways relevant to AMR dynamics.
- **The GEF chemicals and waste focal area**, through its support for the GFC, can support investments in upstream preventative measures by, for example, promoting technologies that reduce antibiotic use (e.g., vaccination, genetics, biosecurity measures, use of biological agents, and digital technologies[66]). The GFC can also promote practices that help reduce the pressures that promote the evolution and spread of resistant organisms in ecosystems, such as reducing antimicrobial releases from manufacturing, healthcare, livestock production, and aquaculture. Examples of measures to achieve this include supporting improved wastewater treatment, pharmaceutical effluent management, and pollution control systems in both urban and agricultural settings. Additional measures could include strengthening monitoring systems for antimicrobial residues in aquatic environments.
- Through its **International Waters** programming, the GEF can support interventions that reduce the spread of antimicrobial residues and resistant organisms in shared water bodies and aquatic ecosystems. This may include strengthening watershed

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[62] For example, agroforestry, crop rotation, manure treatment and composting, and runoff control.
[63] For example, reduced overcrowding, vaccination programs, better hygiene and sanitation, and improved nutrition.
[64] See: https://www.fao.org/gef/Portfolio/choip/en.
[65] https://www.undp.org/nature/our-flagship-initiatives/bgi-ip.
[66] HealthforAnimals (2024); Lucero-Prisno et al. (2025).

management and supporting nature-based solutions[67] that enhance water quality and ecosystem resilience. The GEF International Waters investments can also address the transboundary dimensions of AMR, particularly where resistant organisms and antimicrobial residues spread across borders through shared water systems, trade, and interconnected ecosystems. Through regional cooperation, the GEF can facilitate collaborative approaches to monitoring, pollution control, and ecosystem management across shared basins and marine environments. Such transboundary cooperation can help reduce regulatory leakage and uneven implementation, which are key features of AMR lock-in in a globalized system.

The GEF can support countries in strengthening governance systems that address source control and the post-release environmental dimensions of AMR through cross-sectoral planning and implementation. This may include supporting national action plans that integrate environmental considerations into AMR strategies, strengthening regulatory frameworks for source and pollution control, improving environmental monitoring and data systems, and fostering cooperation across ministries and institutions (promoting a Whole-of-Government approach and facilitating policy coherence), and ensuring all stakeholders are engaged (promoting a Whole-of-Society approach).

Table 1 summarizes an illustrative set of activities the GEF could support through its programming categorized into upstream and downstream actions. While downstream measures to limit the environmental dissemination of antimicrobial residues and resistance genes are important, greater impact is likely to come from upstream, preventative interventions that reduce the conditions driving antimicrobial reliance. Those upstream interventions include supporting efforts to improve access to high-quality antimicrobials where access remains limited, while also reducing the overuse and misuse of antimicrobials in human healthcare, livestock production, aquaculture, and crop production across countries.

Of course, technological solutions need to fit the circumstances: advanced treatment technologies are often capital-intensive, energy-dependent, and difficult to operate and maintain (e.g., the use of vaccinations in aquaculture). This creates dependence on centralized, high-tech solutions that may not be easily scalable or sustainable in resource-constrained settings—another type of lock-in. Without complementary upstream measures to reduce disease pressure, such technologies risk becoming compensatory rather than transformative, and put GEF investment at risk of being ineffective.

[67] Pastor-López et al. (2024).

## Table 1. Selected activities the GEF could support to address AMR lock-in

| | Governance & policy | Financial leverage | Innovation & learning | Multi-stakeholder dialogue |
|---|---|---|---|---|
| **Upstream or source reduction** *(remove or reduce the need for antimicrobials in farming, aquaculture, and crop production by lowering disease pressure and strengthening preventive systems)* | • Policy coherence across agriculture, environment, and health sectors (One Health / Whole-of-Government approaches)<br>• Antimicrobial-smart farming standards and sustainable food system policies<br>• Restrictions for antimicrobial growth promotion and routine preventive use in livestock where feasible<br>• Integration of environmental considerations and surveillance into national AMR action plans | • Transitional financial support for farmers adopting antimicrobial-free production systems<br>• Incentives linked to reduced antimicrobial intensity in food production systems<br>• Risk-sharing finance for sustainable livestock and aquaculture systems | • Innovations such as integrated multi-trophic aquaculture, precision livestock systems, and circular manure systems<br>• Demonstration of sustainable production systems, e.g., agroforestry, crop rotation, manure treatment, improved animal husbandry, vaccination, nutrition, and biosecurity<br>• Monitoring and surveillance with citizen involvement<br>• Farmer and smallholder training programs | • Engagement of veterinarians, healthcare providers, extension services, and value-chain actors<br>• Consumer and producer awareness initiatives on food safety and hygiene |
| **Downstream prevention** *(prevent antimicrobial residues and resistance genes from entering water, soil, and marine ecosystems)* | • Water-quality regulations and pollution control frameworks for antimicrobial residues and antimicrobial resistance genes<br>• Governance improvements for wastewater, coastal, and marine ecosystems<br>• Monitoring, enforcement, and environmental data systems strengthening | • Blended finance for wastewater treatment infrastructure and retrofits<br>• Financing new wastewater treatment plants and water reuse systems<br>• Financial incentives for pollution control in agriculture, aquaculture, and pharmaceutical manufacturing | • Demonstration of affordable wastewater treatment technologies, nature-based solutions systems, and integrated watershed management<br>• Monitoring of antimicrobial residues in aquatic environments<br>• Source-to-sea pollution reduction interventions<br>• Ecosystem restoration and waste management innovations | • Community water-watch groups and citizen monitoring initiatives<br>• Regional and national roundtables on pollution control<br>• Coordination through river basin organizations and transboundary platforms<br>• Cross-sector engagement among environmental authorities, utilities, agriculture, and industry |

## 3. Case study 2: Addressing PFAS use in lithium-ion batteries

### 3.1 Lithium-ion batteries

Lithium-ion batteries (LIBs) are a cornerstone of the global energy transition, enabling electricity storage and supporting decarbonized transportation systems, while also introducing new environmental challenges across their lifecycle.[68] The use of LIBs is expanding rapidly across key sectors. They underpin electric mobility, including electric vehicles (EVs), e-bikes, e-scooters, and two- and three-wheelers, as well as stationary energy storage systems, including uses for residential and industrial power. Demand is also rising with the growth of digital technologies, data centers (so far concentrated in wealthier countries) and miniaturized consumer electronics, such as mobile phones, laptops, e-cigarettes, hearing aids, and wireless earbuds. This rapid uptake of LIBs in many cases is contributing to progress toward Sustainable Development Goal (SDG) 7: ensuring access to affordable, reliable, sustainable, and modern energy, and SDG 11: sustainable cities and communities, by enabling cleaner energy systems and supporting low-emission transport.[69]

Global demand for LIBs surpassed 1 Terawatt-hour (TWh) in 2024 driven largely by uptake of EVs, and is projected to grow at approximately 30% annually.[70] Market value is expected to exceed US$400 billion by 2030.[71] In 2024, over 17 million new EVs equipped with LIBs were sold, an increase of 25% compared to 2022.[72] By 2030, the global EV fleet could exceed 300 million vehicles, with most batteries designed to last approximately eight years or 100,000 miles.[73]

Growth in LIB demand and use is uneven across regions. High income countries HIC) dominate LIBs' demand mainly for automotive applications.[74] By contrast, emerging markets and developing economies, excluding China, accounted for only about 5% of global demand in 2024, although their share has doubled since 2022, driven by growth in Southeast Asia, India, and Brazil.[75] In LMICs, LIBs are widely used in two- and three-wheelers for mobility, particularly among lower-income households.[76] In India, for example, around 2 million e-rickshaw drivers rely on low-cost batteries; historically dominated by lead-acid batteries, but rapidly shifting to LIBs.[77] Electric mobility is expected to scale to hundreds of millions of users in the country, particularly among low-income households relying on two- and three-wheelers, supported by affordable battery

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[68] Gutsch & Leker (2022); IEA (2025).
[69] See: https://sdgs.un.org/goals/goal7 and https://sdgresources.relx.com/sustainable-lithium-ion-batteries.
[70] The electrical energy storage capacity of batteries is most accurately expressed in watt-hours (or here terawatt-hours rather than the number of batteries because of progressive increases in the efficiency of batteries. Global energy demand in 2023 was 29,665 Terawatt-hour, https://www.globalelectricity.org/electricity-consumption-by-country/.
[71] Fleischmann et al. (2023); Marjolin (n.d.); IEA (2025a).
[72] IEA (2025a).
[73] Miao et al. (2022.
[74] IEA (2025b).
[75] IEA (2025b).
[76] IEA (2024a).
[77] Chauhan (2025).

technologies.[78] Beyond transport, LIBs are increasingly used in LMICs for decentralized energy solutions, including storage for solar-powered rural electrification and off-grid applications.[79]

LIBs contain a range of valuable critical minerals, including lithium, cobalt, copper, nickel, manganese, and aluminum, as well as trace amounts of lead, thallium and silver.[80] Some of these metals are toxic, and their extraction and processing are associated with significant environmental and social impacts, including habitat destruction, biodiversity loss, and pressure on water quantity and quality.[81] In addition, LIBs contain per- and polyfluoroalkyl substances (PFASs), often referred to as "forever chemicals," including fluoropolymers used as a binder to the electrode materials and fluorinated compounds used as electrolytes.[82] The production and processing of fluoropolymers can result in emissions of persistent pollutants,[83] and their presence in batteries can reduce the efficiency of metal recovery during recycling.[84]

Once released from LIBs, for example after landfilling,[85] PFASs are highly persistent and mobile, readily transported through the water cycle, leading to widespread contamination of surface and groundwater.[86] To compound the problem, their removal from the environment is technically challenging and costly: remediation costs in the European Union alone were estimated at approximately €3.8 billion in 2024, while associated health costs were estimated at around €39.5 billion.[87] Furthermore, end-of-life (EoL) LIBs are projected to reach 5–8 million tonnes by 2040,[88] potentially containing tens of thousands of tonnes of PFAS-related materials, including roughly 100,000 tonnes of electrolytes and 10,000 tonnes of fluoropolymers per 1 million tonnes of batteries,[89] highlighting a significant and growing environmental risk.

Recycling EoL LIBs is essential for recovering critical minerals and reducing greenhouse gas emissions from the extraction of primary materials.[90] However, only about 22% of global e-waste[91] is recycled in an environmentally sound manner, and reliable global estimates for LIBs recycling remain lacking—the often-quoted figure of ~5% [92] is not reliable.[93] Available data indicate that around 97,000 tonnes of LIBs were treated globally in 2018, with approximately 70%

78 Ali & Tongia (2018); Mukherjee (2022).
79 IEA (2024a).
80 Kang et al. (2013); Berthet et al. (2024).
81 Berthet et al. (2024).
82 PFAS used as binders are polyvinylidene fluoride (PVDF) or sometimes polytetrafluoroethylene (PTFE). The electrolytes can be a fluorinated lithium-phosphate, the lithium salt of bis(trifluoromethylsulfonyl)imide (bis-FMeSI), perfluoroalkyl carboxylates (PFCAs) or others. See: Rensmo et al. (2023), Guelfo et al. (2024), Shojaei et al. (2025).
83 Lohmann et al. (2020).
84 Wang et al. (2023).
85 Shojaei et al. (2025).
86 Ackerman Grunfeld et al. (2024).
87 WSP, Ricardo & Trinomics (2026).
88 Etude et al. (2024); IEA (2019).
89 Estimates based on the electrolyte at 10% (could be 10–15%) and binder at 1% (could be 1–4%) of weight of the battery. See Velazquez-Martinez, et al. (2019); Mossali et al. (2020); Ordonez et al. (2016).
90 Llams-Orozco et al. (2023).
91 Balde et al. (2024).
92 Etude et al. (2024); Jacoby (2019).
93 Melin (2019).

processed in China and 20% in South Korea, suggesting limited and geographically concentrated recycling capacity.[94] Box 3 highlights the progress and persistent gaps in LIB recycling where most information relates to EVs.

**Box 3: Recycling of lithium-ion batteries: progress and persistent gaps**

Recycling technologies for EoL LIBs are advancing, with hydrometallurgical and pyrometallurgical processes increasingly deployed to recover valuable metals.[95] However, these systems are not designed to safely manage PFASs. Mechanical pre-treatment steps (e.g., dismantling, shredding) can release PFASs, whereas hydrometallurgical processes (<600°C) are unlikely to destroy them, potentially leading to releases into wastewater.[96] Pyrometallurgical processes (>1,000–1,600°C) may achieve partial destruction, but outcomes remain uncertain and entail trade-offs, including high energy demand and lithium losses in the slag.[97] Moreover, PFAS-containing components can reduce metal recovery efficiency,[98] and economically viable recycling systems that simultaneously recover metals and safely manage PFAS have yet to be demonstrated at scale.

For EVs, recycling remains constrained by cost, technical complexity, and uneven global capacity. Global recycling capacity was estimated at around 1.6 million tonnes per year in 2024, heavily concentrated in China, with far more limited capacity elsewhere (around 200,000 tonnes/year in Europe and 144,000 in North America).[99] This recycling capacity would seem to match estimates of LIBs reaching EoL annually,[100] indicating the high uncertainties in these estimates. Yet, this assessment seems to contradict other commentaries suggesting that most LIBs are mostly landfilled or stockpiled.[101] Recycling systems are further challenged by high logistics and compliance costs—often exceeding 30% of total recycling costs.[102]

Recycling capacity remains limited in LMICs. At the same time, rapid LIB usage in LMICs and EV adoption in HICs may increase flows of used, shorter-lifespan vehicles and their associated batteries to LMICs that lack adequate end-of-life management systems, echoing the burden-shifting patterns seen in e-waste and other hazardous waste streams[103] and increasing the risk of dumping, informal processing, and open burning. These practices can release hazardous metals and PFASs into soil, water, and food systems,[104] with additional risks posed by battery fires that emit toxic gases.[105]

Extended Producer Responsibility (EPR) schemes can provide the incentive for battery recycling; however, their application to LIBs remains limited globally, and where they exist, such as in the European Union, they primarily focus on metal recovery and do not yet address PFAS risks.[106]

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[94] Melin (2019).
[95] Harper et al. (2019); IEA (2024).
[96] Rensmo et al. (2023); Huang et al. (2022).
[97] Tembo et al. (2024); Harper et al. (2019).
[98] Wang et al. (2023).
[99] Miao (2025); IEA (2024).
[100] Etude et al. (2024).
[101] Mrozik et al. (2021);Miao (2025); Schlott et al. (2025).
[102] Baum et al. (2022).
[103] Balde et al. (2024); World Economic Forum (2023); Tong et al. (2022).
[104] Hynynen et al. (2023); Wang et al. (2023.
[105] Mrozik et al. (2021); Jahl et al. (2025).
[106] See: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32023R1542.

Together, these technological, economic, and governance gaps present a major challenge to achieving circular economy objectives for LIBs, particularly as global battery demand and waste volumes continue to grow.

**LIBs are essential for achieving SDG 7 and reducing reliance on fossil fuels, yet the environmental risks associated with their EoL management are significant and growing**. Reliable global data on the volumes and fate of EoL LIBs remain limited, regulatory responsibilities are fragmented across institutions, and the costs of improper disposal are often externalized, with impacts, such as contamination of water and food systems, emerging over time. LIBs are now firmly locked into global energy and transport systems, and the risks posed by EoL mismanagement are an emerging concern warranting urgent attention, particularly in LMICs, where waste management infrastructure, capacity, and finance are constrained.

The presence of PFASs in EoL LIBs has received limited attention compared to the much-recognized need for metal recovery and the risks from unsound EoL LIBs management.[107] Yet, emerging evidence of PFAS contamination in waters and soils worldwide[108] highlights the importance of early action, when interventions can be more effective and less costly than remediation.

### 3.2 Drivers of lock-in of PFAS use in LIBs

**The continued reliance on PFASs in LIBs reflects a form of socio-technological lock-in.**[109] Several reinforcing drivers underpinning this are discussed below.

Central to PFAS lock-in in LIBs are *technological and performance dependencies*. PFAS-based polymers, such as polyvinylidene fluoride (PVDF), are widely used as cathode binders because their properties contribute to battery longevity and safety.[110] This has resulted in strong growth in demand. PVDF use in LIBs accounted for less than 10% of global production in 2018 but rose to approximately 40% by 2024,[111] thereby entrenching *technological dependence*. Incentives to seek alternatives to PFASs are limited as they perform well (with no evidence to the contrary), and the environmental and health costs of PFAS contamination are largely externalized. Furthermore, the design, manufacturing equipment, process optimization, and supply chains of LIBs have co-evolved with these materials and have been optimized for PFAS-based systems over the past decade, creating path dependencies that make substitution technically complex.[112]

The rapid expansion of battery manufacturing, driven by the electrification of transport and energy systems, has led to large-scale capital investments in LIB production facilities

[107] Etude et al. (2024); Ngoy et al. (2025); Miao et al. (2022).
[108] Ackerman Grunfeld et al. (2024); Wei et al. (2025).
[109] Arthur (1989); Seto et al. (2016)
[110] Lee et al. (2023).
[111] ChemSec (2024).
[112] Harper et al. (2019).

worldwide.[113] These *sunk investments* or *capital deployment* create investment lock-in and reduce motivation to invest in alternatives. Retrofitting production lines or requalifying alternative materials entails high cost and operational risk,[114] hence, firms tend to prioritize incremental improvements over disruptive changes,[115] thereby reinforcing continued reliance on established PFAS-based systems. It is, therefore, unsurprising that the industry has sought derogations from proposed PFAS restrictions in the European Union,[116] which would prolong their use and protect significant investments in PFAS manufacturing capacity. At the same time, *supply chains are becoming increasingly entrenched* in the absence of clear regulatory or market incentives. This is, however, evolving, particularly as the costs associated with legal settlements in some HICs rise.[117]

Research and development pathways further reinforce PFAS lock-in by focusing on optimizing existing systems rather than replacing them. Historically, research and development (R&D) investments have prioritized performance metrics, such as energy density, cycle life, and cost, over chemical safety or environmental persistence.[118] Although substitutes for PFASs in LIBs (and other applications) are being developed, they have yet to achieve commercial deployment.[119] Looking ahead, the rechargeable battery market is likely to evolve toward solid-state batteries, driven by their higher energy density and improved safety. However, this too may also rely on PFASs, potentially perpetuating existing dependencies.[120]

Another driver of lock-in lies in *uneven policy and regulatory frameworks* governing PFASs and battery technologies. Climate and industrial policies strongly promote rapid scaling of battery production to support decarbonization, as noted earlier; yet, policies and regulations for the design, manufacturing, and EoL management of LIBs lag behind. For example, there are no unified standards for waste disposal of LIBs.[121] This creates a policy misalignment: environmental regulations seek to limit PFAS risks but lack an effective, standardized framework for LIBs, while climate policies incentivize the rapid deployment of existing battery technologies. Without integrated and coherent policy approaches, clean energy transition objectives will continue to inadvertently reinforce PFAS use.

Lock-in is further reinforced by *gaps in data and knowledge* regarding the full environmental and health impacts of PFAS use in batteries across their life cycle. Information and data on PFAS

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[113] IEA (2024).
[114] Harper et al. (2019).
[115] IEA (2023).
[116] European Chemicals Agency (2025).
[117] Swiss Re (2021)
[118] IEA (2023).
[119] Savvidou et al. (2024)
[120] Tawalbeh et al. (2025)
[121] See: Mrozik W et al. (2021). In the EU, EoL batteries are regulated by the End-of-Life and Waste Battery Directives, but their implementation is unclear (Directive 2006/66/EC of the European Parliament and of the Council; Directive 2000/53/EC of the European Parliament and of the Council). The Basel Convention has draft guidance for the environmentally sound management of EoL batteries that include LIBs, but this has yet to be finalized (Basel Convention, 2023).

emissions during manufacturing, release during recycling or disposal, and long-term environmental fate remain limited.[122] These uncertainties can delay regulatory action and reduce incentives for industry to invest in alternatives. Similarly, although research into battery performance is ongoing, the comparative environmental performance of alternative materials has not yet been investigated, with significant uncertainties regarding trade-offs between performance, environmental impacts, and economic feasibility.[123]

The rising demand for LIBs is shaped not only by technology and policy, but also by *structural patterns of energy consumption: energy overconsumption in HICs* and *insufficient provision of energy needs in LMICs*. Rising energy demand is occurring largely without commensurate policies and incentives to reduce overall demand.[124] Growth in battery deployment indirectly amplifies and locks in the demand for PFASs. At the same time, given that EVs require significantly more minerals than conventional vehicles, the material intensity of battery-based technologies links rising energy consumption in high-income contexts to expanded extraction and manufacturing impacts elsewhere, especially in LMICs, such as Argentina, Bolivia, Chile (the Lithium Triangle), and the Democratic Republic of Congo, that supply the raw materials.[125] In this way, *patterns of energy overconsumption* in HICs act as a structural driver that reinforces both LIB demand and the associated use of PFASs not balanced by attention to environmental and social costs, especially in LMICs.

At a more fundamental level, the continued use of PFASs in LIBs is underpinned by the *externalization of their costs to human health and the environment*. These costs are substantial: recent estimates suggest that PFAS-related health impacts in Europe alone amount to up to €84 million, with additional billions required for environmental remediation.[126] Yet these costs are not reflected in market prices for battery materials or products and are largely borne by society. Data on the extent of PFAS contamination in LMICs remain limited,[127] constraining understanding of its scale and contributing to *regulatory gaps and policy asymmetries.* This also contributes to *burden shifting* by obscuring where and how environmental and health impacts occur, thereby weakening accountability across global supply chains, as regulators and markets cannot fully assess risks or assign responsibility to producers and users. Addressing this underlying driver will require policy approaches that internalize lifecycle costs[128] through regulation, standards, and economic instruments, thereby aligning market incentives with the development and uptake of safer, PFAS-free battery technologies.

[122] Guelfo et al. (2024); Rensmo et al. (2023); Xi et al. (2026).
[123] Savvidou et al. (2024); Xi et al. (2026); Li et al. (2025).
[124] Climate Change Performance Index (2024); World Bank Group (2025).
[125] Li & Wang (2025); IEA (2021); Miao (2025); Flexer et al. (2018); Calvao et al. (2021).
[126] WSP & Trinomics (2026); Nordic Council of Ministers (2019); European Environment Agency (2019).
[127] Ackerman Grunfeld et al. (2024); Wei et al. (2025).
[128] WSP & Trinomics (2026).

Taken together, these dynamics illustrate how PFAS use in LIBs has become "locked-in" through the interaction of *reinforcing technological dependencies, capital investments, supply chain structures, innovation pathways, policy misalignments, and externalized environmental and health costs*. No single factor sustains the status quo; rather, it is the cumulative effect of mutually reinforcing feedback that stabilizes and perpetuates PFAS-based systems, even in the presence of important concerns and emerging alternatives. **Breaking this lock-in, therefore, requires identifying and acting on strategic leverage points within the system**, particularly those that influence upstream drivers such as innovation trajectories, market incentives, regulatory coherence, and information transparency. Interventions that internalize external costs, reduce uncertainty, and create incentives for safer substitutes can help shift the system toward alternative pathways, demonstrating that effective responses must be systemic rather than incremental.

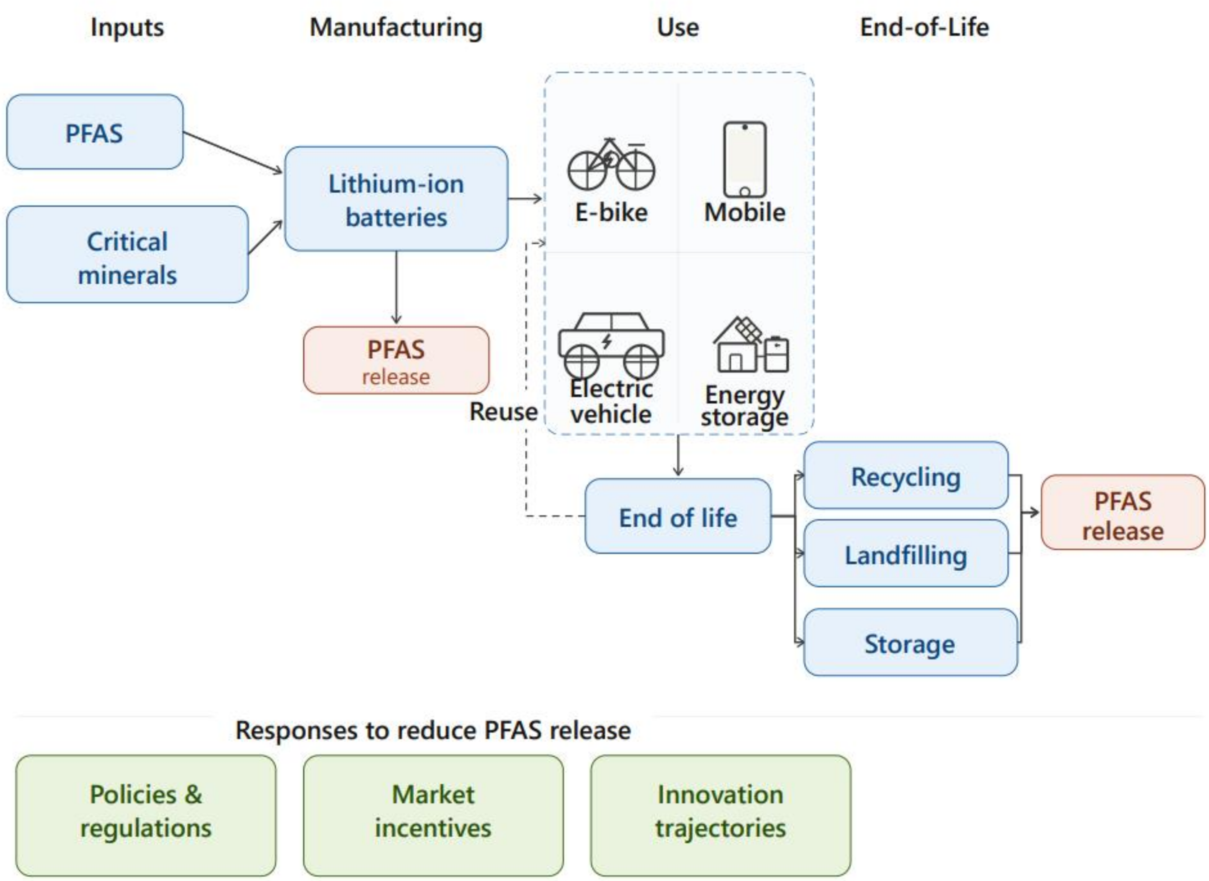


Figure 2. Inputs, manufacturing, use and end-of-life aspects of Lithium-Ion Batteries (LIBs). This illustrates points of PFAS release (brown boxes) along with responses to reduce PFAS release (green boxes). The uses shown in the figure are illustrative of the many uses of LIBs. Note that re-use of LIBs is possible, particularly for electric vehicle LIBs used for residential energy storage. Responses to reduce PFAS release are also illustrative with a more complete discussion contained in Section 3.4.

### 3.3 How PFAS use in LIBs is relevant to GEF's goals

#### The growing use of PFASs in LIBs is relevant to several GEF focal areas

- Under the **Climate change focal areas,** LIBs are central to decarbonization, enabling renewable energy integration and low-emission transport. However, the rapid scaling of these technologies, with their reliance on PFAS, risks embedding persistent chemical pollution within the energy transition.
- Within the **Chemicals and Waste focal area**, PFASs in LIBs represent an emerging and largely unaddressed source of persistent pollutants. PFASs are resistant to degradation, accumulate in environmental media and organisms, and are linked to adverse health outcomes, including immune and endocrine effects.[129] Risks arise throughout the battery life cycle, particularly at EoL, where recycling and waste management systems are not designed to manage PFASs.
- In **International Waters**, the high mobility and persistence of PFASs enable their transport through hydrological systems, resulting in widespread contamination of rivers, lakes, and coastal waters.[130] Monitoring data shows that PFAS contamination is already extensive, with many water bodies exceeding environmental safety thresholds.[131] This transboundary nature of contamination makes PFASs a clear concern for shared water systems.
- PFAS contamination is also relevant to **Land Degradation**, as these substances accumulate in soils and groundwater and are difficult and often costly to remediate.[132] Soil contamination can lead to uptake into crops and food systems, affecting agricultural production and resulting in human exposure.
- For the **Biodiversity focal area**, several PFASs have been shown to bioaccumulate in wildlife and move through food webs, with documented impacts on animal health and ecosystem functioning.[133] Their persistence and biomagnification raise concerns about long-term ecological effects across terrestrial and aquatic ecosystems.

### 3.4. GEF entry points for addressing lock-in of PFAS use in LIBs

The challenge posed by PFAS use in LIBs is similar to that of the historical use of polychlorinated biphenyls (PCBs) in electrical equipment, where widespread adoption of a high-performing but hazardous chemical led to global contamination and costly remediation. Unlike PCBs, which were largely concentrated in identifiable equipment, PFASs in LIBs are embedded in rapidly expanding and highly dispersed products, from EVs to consumer electronics, making monitoring, recovery, and control difficult. This combination of persistence, mobility, rapid growth in use, and diffuse

[129] First Sentier MUFG Sustainable Investment Institute (2024).
[130] Ackerman Grunfeld et al. (2024).
[131] European Environment Agency (2024).
[132] European Environment Agency (2025).
[133] Ferretti et al. (2026); Lukić Bilela et al. (2023)

distribution underscores the importance of early intervention and aligns with the GEF's mandate to generate global environmental benefits across multiple focal areas.

Practical entry points are available to act on this issue in a way that is consistent with the GEF's role as a financing mechanism for MEAs. **The strongest rationale is not to treat PFASs in LIBs as a narrow waste issue, but as an emerging systems problem at the intersection of clean energy, chemicals and waste management, circular economy, and pollution prevention**. Such a framing is consistent with GEF's emphasis on tackling the drivers of environmental degradation and preventing lock-in of unsustainable production and consumption pathways, as noted in the GEF-8[134] and GEF-9[135] Programming Directions.

The most immediate entry point lies in the *chemicals and waste agenda under the Stockholm Convention and GFC*. Several PFASs and PFAS groups are listed under the Stockholm Convention, including PFOS, PFOA, PFHxS, long-chain perfluoroalkyl acids (LC-PFCAs), and related substances,[136] which establishes a clear treaty-based basis for GEF support to strengthen inventories, policy frameworks, development and adoption of safer alternatives, monitoring, and control measures relevant to PFAS-containing battery materials and wastes. While not all PFAS used in LIBs are currently listed, the Convention's architecture provides a ready platform for countries to build institutional capacity, identify uses and releases, and develop regulatory and technical responses before additional PFASs become further entrenched in battery value chains. As a subset of e-waste, PFAS use in LIBs also falls under the "hazardous substance within the life cycle of electrical and electronic products" issue of concern under SAICM (now subsumed by the *Global Framework on Chemicals)*.[137]

Another entry point is the GEF climate mitigation portfolio, where the GEF can help ensure that battery expansion does not embed persistent chemical risks into the low-carbon transition. The GEF-9 climate change strategy[138] notes support for policies and local capacity to advance recycling of LIBs and other critical materials; however, this objective needs to explicitly consider PFAS risks. Although PFAS-free battery designs are not yet commercially available, their technical feasibility[139] creates an upstream opportunity for the GEF to support demonstration, de-risking, including through blended finance, and early deployment of safer battery materials and designs in emerging markets. In practice, this means linking climate finance more directly to safer materials innovation, design for recycling, and life-cycle assessment, including through existing GEF climate mitigation investments, such as the UNEP-led e-mobility program (see Box 4).

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[134] GEF (2022).
[135] GEF (2026).
[136] In 2025, the Conference of the Parties listed long-chain PFCAs, their salts, and related compounds in Annex A to the Convention (decision SC-12/12). https://www.pops.int/Implementation/IndustrialPOPs/PFAS/Overview/tabid/5221/Default.aspx.
[137] The Global Framework on Chemicals will decide on the SAICM's issue of concern at the first international conference based on resolution V/5. See: https://www.unep.org/global-framework-chemicals/implementation/issues-concern.
[138] See paragraph 358; the climate change section of the GEF-9 Programming Directions (GEF, 2026).
[139] Savvidou et al. (2024)

Through its investments across the chemicals and waste, and the Climate Change Mitigation focal area, the GEF could support monitoring systems and demonstration of environmentally sound EoL management in countries likely to receive used batteries or second-hand electric vehicles, particularly where institutional capacity remains limited. UNEP has already indicated that the transition to electric vehicles could create growing EoL pressures in LMICs that lack adequate repair and recycling systems, which strengthens the case for anticipatory action.[140] The GEF could also help strengthen inventories of battery flows, improve technical standards for collection and recycling, and build capacity for environmentally sound management before diffuse PFAS contamination becomes harder and more expensive to address. Investments in other focal areas (Biodiversity, Land Degradation, and International Waters) could also include risk screening that considers how the flow of LIBs can impact objectives in those focal areas.

The GEF Integrated Programs could also provide useful entry points for addressing PFAS use in LIBs:

- **Eliminating Hazardous Chemicals from Supply Chains:[141]** This may be the most direct IP entry point. The program is explicitly designed to prevent chemical pollution in priority supply chains by promoting safer alternatives, innovation, and enabling policies. In practice, this program could support upstream action on PFAS-containing battery materials through alternatives assessment, demonstration of safer substitutes, supply-chain transparency, and policy frameworks for reducing hazardous chemical use in battery manufacturing and EoL management.
- **Sustainable Cities:[142]** The Sustainable Cities Integrated Program is relevant because cities are major demand centers for electric mobility, stationary storage, electronics, and municipal waste management. This program could therefore address PFAS lock-in indirectly by supporting urban circular economy strategies for batteries, environmentally sound collection and recycling systems, and city-level planning that integrates climate, waste, and pollution objectives.
- **Greening Transportation Infrastructure Development:[143]** Transport electrification is one of the main drivers of LIB demand. The IP is intended to build sustainability into transport infrastructure planning from the outset. That upstream orientation provides an opportunity to incorporate battery sustainability criteria, not only carbon and mobility benefits, but also chemical safety, design-for-recycling, and EoL management.
- **Net-Zero Nature-Positive Accelerator:** This IP is a good entry point given that it seeks to accelerate nature-positive, net-zero pathways through investment in new technologies and enabling institutions. Since LIBs are central to electric mobility and

[140] Kendall et al. (2023).
[141] See: https://www.unep.org/topics/chemicals-and-pollution-action/circularity-sectors/eliminating-hazardous-chemicals-supply.
[142] https://www.thegef.org/what-we-do/topics/sustainable-cities.
[143] https://gridip.org/.

energy storage, this program offers a practical route for ensuring that decarbonization does not lock-in countries to PFAS-dependent battery systems.

**The GEF's comparative advantage is catalytic rather than remedial**. It is well placed to support interventions that address the structural drivers of lock-in, including *innovation and demonstration* of PFAS-free LIBs, *knowledge generation (*for example, through monitoring and inventories of uses and releases, and life-cycle assessment,[144] subject to the availability of data), *policy coherence* linking battery deployment, chemicals management, circular economy, and waste regulation, and *international cooperation and technology transfer,* so that developing countries are not locked into problematic battery systems as markets expand. To be impactful, a GEF entry-point strategy should focus on shaping technology and policy trajectories now, before the combination of sunk investments, fragmented regulation, expanding waste flows, and diffuse contamination reproduces—at a much larger scale—the kind of long-tail legacy that MEAs have repeatedly had to address after the fact.

**Box 4. GEF investments and agency experience relevant to PFAS in lithium-ion batteries**

The GEF is already financing a growing portfolio of projects that expand the deployment of LIBs across transport and energy systems, creating entry points to address PFAS risks. In electric mobility, this includes the Global Electric Mobility Programme (GEF IDs 10114; GEF-7) and associated addendums, and regional/country projects such as South Africa energy transition and storage (GEF ID 11822; ), Senegal e-mobility (GEF ID 11080; GEF-8), Peru urban mobility (GEF ID 10286; GEF-8), and the Green Mobility Financing Facility for Africa (GEF ID 11671; GEF-8), all of which accelerate adoption of EVs and associated battery systems. In parallel, the GEF is supporting battery storage across both grid and off-grid applications, including projects such as the Burundi rural electrification (GEF ID 11888; GEF-8), Energy security project in Antigua and Barbuda (GEF ID 11474; GEF-8), and the Sustainable energy transition for decarbonization in India (GEF ID 11758; GEF-8). These investments collectively expand the scale and geographic footprint of LIB use, increasing the importance of upstream material choices and EoL management.

GEF Agencies are also active across the battery value chain. UNEP, through the Global Electric Mobility Program, supports over 60 LMICs in the shift to electric mobility and has begun to move "upstream" on circularity through work on EoL EVs and EV batteries.[145] The United Nations Industrial Development Organization (UNIDO) is supporting lithium-ion battery manufacturing and charging infrastructure in countries such as Tanzania, providing upstream opportunities to influence material choices.[146] UNDP has developed life-cycle and EoL analyses for EV batteries in Asia-Pacific countries, identifying policy and management gaps.[147]

[144] Note that current life-cycle assessments of LIBs and LIB recycling do not consider PFAS. Hanna et al. (2025), Paul et al. (2024).
[145] See: https://www.unep.org/gef/focal-areas/climate-change-mitigation/our-work/electric-mobility
[146] UNIDO (2025).
[147] UNDP (2024); World Bank Group (2024).

Among development banks, the World Bank Group supports electric mobility and battery storage in multiple countries and has financed EV battery recycling capacity[148] and has produced an analysis on the state of affairs regarding the reuse and recycling of LIBs.[149] The AfDB is advancing green mobility through facilities such as the Green Mobility Financing Facility for Africa (GEF ID 11671; GEF-8) and its Sustainable Energy Fund for Africa, which provides catalytic finance to unlock private investment in renewable energy and energy efficiency.[150]

These investments show that the GEF and its agencies are already engaged at key leverage points—deployment, manufacturing, and EoL—where PFAS risks may arise. However, PFASs are not yet systematically addressed. This creates an opportunity for the GEF to build on existing investments by partnering with its agencies to integrate PFAS considerations into project design and implementation, including safer-material screening, life-cycle assessment, strengthened monitoring, and support for PFAS-free battery technologies, thereby addressing an emerging risk before it becomes further entrenched.

### 3.4 How GEF can promote breaking lock-in of EoL LIBs

LIBs are now firmly embedded in global energy and transport systems and will remain central to decarbonization pathways for the foreseeable future. The climate change strategy in the draft GEF-9 programming directions recognized the importance of power systems and energy access (Strategy 1.3) and integrated and zero-emission mobility (Strategy 1.4), both of which will rely heavily on battery technologies to deliver climate mitigation outcomes.[151] Ensuring that these are implemented in an environmentally sustainable manner is therefore essential. Within its mandate as a financing mechanism for chemicals and waste and climate change MEAs, and in alignment with its catalytic role, the GEF can act at a limited number of high-leverage intervention points to help break PFAS lock-in in LIBs:

- **Redirect innovation trajectories toward safer battery chemistries to break technology lock-in.** The GEF can support demonstration and early deployment of PFAS-free battery materials (e.g., alternative binders, electrolytes, and separator technologies), particularly in emerging manufacturing ecosystems.
- **Strengthen the evidence base and transparency across the battery life cycle to address data and knowledge gaps.** Improved data availability and transparency can enable regulatory action by strengthening the evidence base, while also supporting market shifts by reducing uncertainty and facilitating substitution decisions across supply chains.[152] Establishing harmonized metrics for comparing PFAS-containing and PFAS-free technologies would also support informed decision-making by policymakers and industry.

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148 World Bank Group (2024).
149 World Bank Group (2020).
150 African Development Bank (n.d.)
151 GEF (2025).
152 OECD (2025); European Chemicals Agency (2020).

- **Promote policy coherence across climate, chemicals, and circular economy agendas.** The GEF can support integrated policy frameworks that align agendas, for example, by embedding PFAS considerations into national battery strategies, e-mobility policies, and circular economy roadmaps. This is consistent with calls for lifecycle-based governance of chemicals and waste under the Global Framework on Chemicals.[153] Under the Stockholm Convention, the GEF can further support countries to strengthen regulatory controls, inventories, and risk management approaches for PFAS groups relevant to LIBs.
- **Create market incentives that internalize environmental and health costs.** The GEF can support enabling conditions for economic instruments, such as extended producer responsibility (EPR), eco-design standards, and pollution pricing, that shift incentives toward safer materials and improved EoL management. Evidence from chemicals management shows that internalizing lifecycle costs is essential for driving substitution and innovation.[154] By linking such instruments to private sector engagement and blended finance, the GEF can help overcome investment inertia associated with existing production systems.
- **Build capacity for environmentally sound management and circularity of LIBs to break infrastructure and supply chain lock-in.** The GEF can support the development of collection, reuse, and recycling systems that can manage PFAS risks alongside metal recovery. This includes investments in design-for-recycling approaches, safe dismantling and treatment technologies, and reverse logistics systems, particularly in LMICs at risk of becoming recipients of EoL batteries. Building such capacity can also facilitate the second use of LIBs, as EV batteries that no longer meet vehicle performance requirements often retain substantial residual capacity and can be repurposed for less demanding stationary applications, including residential energy storage systems.[155]
- **Anticipate and prevent burden shifting across regions.** Given the transboundary nature of LIB value chains and PFAS pollution, the GEF can support early action in countries where battery demand and waste flows are expected to grow most rapidly. This includes strengthening controls on transboundary movements of used batteries, improving traceability of materials, and supporting regional cooperation through regional programs.

These actions would reflect a strategic shift from managing the consequences of PFAS use in LIBs to addressing its underlying drivers. By targeting innovation systems, market incentives, policy coherence, and knowledge gaps, the GEF can help steer the rapidly expanding battery economy toward safer and more sustainable pathways.

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[153] See: https://wedocs.unep.org/rest/api/core/bitstreams/3b1a4570-a9a8-46f1-b172-40efa8a988ab/content.
[154] European Environment Agency (2019); OECD (2016).
[155] Bobba et al. (2019); American Council for an Energy-Efficient Economy (2025); Nazim & Elavarasan (2026).

## 4. Conclusions

The persistence of harmful environmental and technological practices, as illustrated by both AMR and PFAS use in LIBs, reflects the influence of systemic lock-in. These cases demonstrate that unsustainable outcomes may not be simply the result of individual choices or isolated market failures but can arise from lock-in which results from reinforcing interactions among economic incentives, technological infrastructures, governance arrangements, and social conditions.

**Applying a lock-in lens can provide a practical and strategic framework for identifying leverage points where GEF interventions can catalyze system transformation**. The GEF's comparative advantage lies in its ability to operate across focal areas, support integrated and country-driven solutions, and convene diverse stakeholders to address complex, transboundary challenges.

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