

Lead-Safe Off-Grid Electrification

Understanding the Issues in Sub-Saharan Africa

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Abstract

Access to electricity is a cornerstone of sustainable development, and a basic prerequisite for modern agriculture and industry. Despite significant recent progress, 677 million people still lacked access to electricity in 2023, of which an estimated 87 percent live in sub-Saharan Africa, and most live in low-density rural, remote, or conflict-affected areas without functional electrical grids. In these contexts, rapid electrification—a political and development imperative, and current focus of the World Bank-led Mission 300 initiative—relies heavily on off-grid solar systems, which are favored for their quick and flexible deployment, zero recurrent costs, and low-carbon footprint. Most off-grid solar systems in sub-Saharan Africa use lead-acid batteries for energy storage, which can create severe risks of environmental lead pollution and human lead exposure in the absence of safe disposal and recycling. Unsafe used lead-acid battery (ULAB) recycling is thought to be one of several important sources driving high rates of lead poisoning in sub-Saharan Africa. This paper investigates the role of lead in off-grid electrification across sub-Saharan Africa, including trends in off-grid technologies; the health and safety risks associated with ULAB recycling within sub-Saharan Africa; and a deep-dive market analysis of the off-grid solar sector. While there is high uncertainty, we estimate that the off-grid solar sector generates between 250,000 and 1.5 million tonnes of ULAB waste per year, accounting for 13 to 47 percent of total ULAB waste volumes in the region. We conclude with a discussion of findings and actionable recommendations to improve collection and recycling practices within sub-Saharan Africa.

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The authors are grateful to Coefficient Giving and Founders Pledge for their financial support of this work, and to Chris Kinally, Andreas Manhart, and Oliver Reynolds for their extraordinarily helpful comments and suggestions.

Rachel Bonnifield and Caroline Mallory. 2026. "Lead-Safe Off-Grid Electrification: Understanding the Issues in Sub-Saharan Africa." CGD Policy Paper 383. Washington, DC: Center for Global Development. <https://www.cgdev.org/publication/lead-safe-off-grid-electrification-understanding-issues-sub-saharan-africa>

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Abbreviations

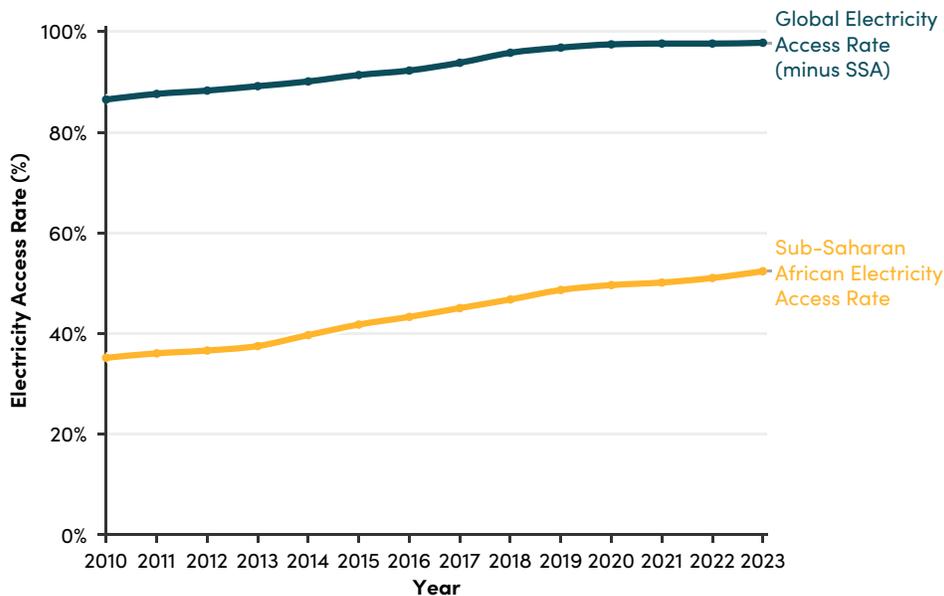
AfDB	African Development Bank
BLL	Blood Lead Levels
CDC	Centers for Disease Control
EDF	Electricité de France
EIB	European Investment Bank
EoL	End-of-Life
GONGLA	Global Association for the Off-Grid Solar Energy Industry
LEAP	Lighting and Energy Access Partnership
LEIA	Low Energy Inclusive Appliances
PAYG	Pay As You Go
PPE	Personal Protective Equipment
SEKs	Solar Energy Kits
SHS	Solar Home Systems
SOPs	Standard Operating Procedures
ULAB	Used Lead Acid Batteries

1. Introduction

The United Nations recognizes “access to affordable, reliable, sustainable and modern energy”—and access to electricity, specifically—as a cornerstone of sustainable development.¹ At the macroeconomic level, electricity access is a basic prerequisite for modern agriculture, industry, services, and participation in the international digital economy. At the community and household levels, electricity powers essential appliances for health, comfort, safety, learning, communication, and economic participation—including but not limited to modern lighting; cooling to preserve food and medicine; cell phones, radios, computers, and televisions; and fans and air conditioners to protect against extreme climactic conditions.

In recent decades, global access to electricity has expanded dramatically, from 83 percent of the global population in 2010, to 92 percent in 2023. Yet progress is incomplete and uneven (Figure 1). As of 2023, 677 million people still lacked access to electricity. Around 87 percent of them live in sub-Saharan Africa, where electricity access lags far behind global trends—and where the absolute number of people without electricity has hardly budged during this period, from 596 to 589 million, as the rate of electrification in the region has struggled to keep pace with population growth.² The remaining unelectrified households are challenging to reach: 82 percent are estimated to be in low-density rural, remote, or conflict-affected contexts.³

FIGURE 1. Percent of the population with access to electricity, global and sub-Saharan Africa, 2010–2023



Source: World Bank, Population—total, World Bank, Access to electricity (% of population).

1 Sustain. Dev., “Transforming Our World: The 2030 Agenda for Sustainable Development.”
2 “Access to Electricity (% of Population).”; Population, Total—Sub-Saharan Africa.
3 *Off-Grid Solar Market Trends Report 2024*.

Expansion of electrical grids yields significant benefits, offering the high throughput and reliability required for industrial development and more intensive electricity usage. Agricultural and manufacturing activities require dependable, consistent, and ample electricity access, typically exceeding the capacity generation of off-grid systems, which are broadly defined to include mini-grids, small-scale electricity generation and storage networks, off-grid solar products (including solar home systems (SHS) and pico solar), and generators powered by fossil fuels.⁴ Grids can collect and distribute electricity generated from diverse sources, including natural gas, coal, oil, solar, hydropower, and wind, which increases resilience and energy security. There is extensive research on the link between the development of the electric grid and economic development including its role in growing the labor market, diversifying the economy, improving education and health outcomes, and elevating overall welfare.⁵

However, given the preponderance of unelectrified households in fragile and conflict-affected situations, as well as rural and remote regions of sub-Saharan Africa beyond the reach of existing grid networks, rapid electrification implies heavy reliance on more flexible off-grid solutions. This stylized fact is reflected in recent trends; between 2020–2022, of the 67 million new people who gained access to electricity in sub-Saharan Africa, ⁶ 55 percent were connected via off-grid solar, while the remaining 45 percent came through new grid and mini-grid expansions.⁷

Broadly, there are two potential energy sources for such off-grid systems. The first category includes traditional fossil fuel-based generators, running on diesel, gasoline, propane, or natural gas. These are widely used across energy-insecure regions but are highly polluting and reliant on expensive fuel, which can become inaccessible during geopolitical and macroeconomic shocks.⁸ A second category captures energy from renewable sources: solar, wind, and hydroelectric power. Renewable systems require expensive capital investments but incur very low to zero marginal costs. They are typically favored by development banks and international donors due to their low carbon footprint and more sustainable profile.

Both categories share a common feature: reliance on batteries for their continuous operation. Much like traditional automobiles, fossil-fuel based generators require a battery to spark their motors. For renewable energy systems, batteries allow consistent energy output in the face of intermittent energy input, for example when the sun is down or winds are calm.⁹

While there are several competing battery technologies—and a long-term modal shift toward technically superior lithium-ion technologies—lead-acid batteries are currently the most common

4 Ortega-Arriaga et al., “Grid versus Off-Grid Electricity Access Options: A Review on the Economic and Environmental Impacts.”

5 Foster et al., *The Impact of Infrastructure on Development Outcomes*.

6 “Access to Electricity (% of Population)—Sub-Saharan Africa.”; “Population, Total—Sub-Saharan Africa.”

7 *Off-Grid Solar Market Trends Report 2024*.

8 “Why Do Oil Prices Matter to the Global Economy? An Expert Explains.”

9 *Batteries and Secure Energy Transitions*.

energy storage solution for off-grid systems in sub-Saharan Africa.¹⁰ Lead-acid batteries have several practical advantages. Most importantly, they are relatively inexpensive and recyclable; they are also standard equipment in traditional cars and motorbikes in all world regions and present few to zero safety risks during their actual use and deployment. However, lead-acid batteries have a shorter lifespan than other battery chemistries—generally ranging from six months¹¹ to five years¹²—and need sophisticated end-of-life (EoL) collection and recycling systems to ensure safe disposal and efficient reuse.

Safe recycling of used lead-acid batteries (ULABs) requires high capital investment to extract the greatest amount of recoverable lead while safeguarding employees, the environment, and the neighboring community from lead toxins. Comprehensive Standard Operating Procedures (SOPs) for ULAB recycling have been developed by Sustainable Recycling Industries, which suggest high investment costs and moderate operational costs yield a lead recovery rate of >98 percent, with an environmentally sound record. In such high-quality facilities, residual lead emissions are captured, contained, and fed back into the recycling process. There are inevitable losses of lead particulates with the generation of smelting slags, which are disposed of in controlled hazardous waste sites. Such recycling facilities are integrated such that all steps from recycling to refinement to waste management are conducted under one roof with battery breaking and lead smelting done in automated and enclosed systems. For workers, safe recycling requires additional measures such as adequate personal protective equipment (PPE) and blood lead level (BLL) monitoring.

Unsafe ULAB recycling operations lack sufficient health and safety measures, creating risks of severe occupational and environmental lead exposure. At its most primitive, unsafe recycling occurs in open-air suburban backyards by an individual or small groups of workers. Recyclers are not formally trained and lack smelting equipment, which causes lead losses to the environment of up to 50 percent.¹³ Such operations expose neighbors and household members to extremely high concentrations of toxic lead emissions.¹⁴ Larger-scale unsafe recycling may occur in formal facilities, sometimes processing several thousand tonnes of ULABs per month.¹⁵ While these facilities may look legitimate, in many cases they lack features such as flooring, proper storage of slag and ash, ventilation, and employee BLL monitoring.¹⁶ Pollution from unsafe ULAB recycling is exacerbated by the proliferation of inexpensive, low-quality batteries, often manufactured in China, which have shorter lifespans and thus require disposal and recycling at shorter intervals, increasing overall volume.¹⁷

10 *Techno-Economic Analysis of Battery Energy Storage for Reducing Fossil Fuel Use in Sub-Saharan Africa.*

11 Kinally et al., "Solar Home Systems in Malawi: Commercialisation, Use and Informal Waste Management."

12 Manhart et al., *End-of-Life Management of Batteries in the Off-Grid Solar Sector.*

13 Wilson and Manhart, *Standard Operating Procedures for Environmentally Sound Management of Used Lead-Acid Batteries.*

14 Pearce, "Getting the Lead Out: Why Battery Recycling Is a Global Health Hazard."

15 *Closing the Loop on Energy Access in Africa.*

16 Wilson and Manhart, *Standard Operating Procedures for Environmentally Sound Management of Used Lead-Acid Batteries.*

17 Kinally et al., "Solar Home Systems in Malawi: Commercialisation, Use and Informal Waste Management."

Substandard ULAB recycling creates severe environmental and health hazards. Lead is a neurotoxin, which is very dangerous to humans when ingested or inhaled. Even at low levels, lead exposure impedes normal cognitive development¹⁸ and significantly increases risks of cardiovascular disease,¹⁹ among other impacts. At high levels of exposure—which are typically driven by occupational exposure or contaminated sites,²⁰ including those associated with unsafe battery recycling²¹—lead poisoning can cause colic, seizures, paralysis, coma, and even death.²² Lead exposure due to unsafe recycling is not merely an abstract concern, but highly relevant to health and educational outcomes in sub-Saharan Africa. In the region, almost four in ten children are estimated to have BLLs above 5 µg/dL,²³ the level at which the World Health Organization recommends clinical intervention.²⁴ Each year, lead exposure is estimated to cause 1.54²⁵ to 5.5²⁶ million deaths globally, with exposure driving about a fifth of the learning gap between wealthy and poor countries.²⁷ The exact contribution of ULAB recycling to overall lead exposure is unknown, but many studies find severe and widespread impacts.²⁸

Expanded electrification efforts across sub-Saharan Africa are therefore likely to result in increased demand for lead-acid batteries. Yet for good reason, given extensive economic implications and high political salience, electrification in sub-Saharan Africa is currently an urgent priority for African governments and development banks. Most prominently, the World Bank and African Development Bank (AfDB) are spearheading a new initiative, Mission 300, which aims to expand energy access to an additional 300 million sub-Saharan Africans by 2030.²⁹

In this paper, we consider how to constructively reconcile these two essential imperatives: first, achieving rapid electrification, which will necessarily require increased usage of lead-acid batteries; and second, protecting individuals, populations, and economies from the severe consequences of lead poisoning. Importantly, there is no inherent contradiction between these two objectives. It is entirely possible to safely use and recycle lead-acid batteries; further, the existence of strong systems for EoL management can in fact *facilitate* faster and more efficient roll-out of off-grid

18 Lidsky and Schneider, "Lead Neurotoxicity in Children: Basic Mechanisms and Clinical Correlates."

19 Lamas et al., "Contaminant Metals as Cardiovascular Risk Factors: A Scientific Statement From the American Heart Association."

20 Rees and Fuller, *The Toxic Truth: Children's Exposure to Lead Pollution Undermines a Generation of Future Potential*.

21 Gottesfeld, "The Lead Battery: A Growing Global Public Health Challenge."

22 Cent. Dis. Control, "What Are Possible Health Effects from Lead Exposure?"

23 Rees and Fuller, *The Toxic Truth: Children's Exposure to Lead Pollution Undermines a Generation of Future Potential*; "World Population Prospects 2024."

24 WHO *Guideline for Clinical Management of Exposure to Lead*.

25 Inst. Health Metr. Eval., "Global Health Metrics."

26 Larsen and Sánchez Triana, "Global Health Burden and Cost of Lead Exposure in Children and Adults: A Health Impact and Economic Modelling Analysis."

27 Crawford et al., *How Much Would Reducing Lead Exposure Improve Children's Learning in the Developing World?*

28 Haefliger et al., "Mass Lead Intoxication from Informal Used Lead-Acid Battery Recycling in Dakar, Senegal.;" Chowdhury et al., "Child Lead Exposure near Abandoned Lead Acid Battery Recycling Sites in a Residential Community in Bangladesh: Risk Factors and the Impact of Soil Remediation on Blood Lead Levels.;" Gottesfeld and Pokhrel, "Review: Lead Exposure in Battery Manufacturing and Recycling in Developing Countries and Among Children in Nearby Communities.;" Ericson et al., "The Global Burden of Lead Toxicity Attributable to Informal Used Lead-Acid Battery Sites."

29 World Bank, "Mission 300: Overview."

systems by easing the burden on suppliers to set up their own bespoke collection and recycling mechanisms. However, achieving lead-safe off-grid electrification will require targeted investments, regulatory strengthening, and careful planning from all stakeholders.

We propose that a better understanding of these issues—and, in turn, better systems for EoL battery management—must be integrated into electrification strategies in sub-Saharan Africa, including Mission 300. To that end, this paper proceeds as follows. First, we discuss the role of lead in electrification across sub-Saharan Africa, including trends in off-grid technologies, as well as the market share of lead-acid batteries across different electrification modalities. Next, we turn specifically to the health and safety risks associated with ULAB recycling within sub-Saharan Africa, including evidence on current collection and recycling practices and their associated harms. We then offer a deep-dive market analysis of the off-grid solar sector, providing a case study in the role of lead-acid batteries as well as illustrating the mix of private sector, non-profit, philanthropic, governmental, and development bank stakeholders that help shape the market. We conclude with a discussion of findings and actionable recommendations to improve collection and recycling practices within sub-Saharan Africa.

2. The role of lead in off-grid electrification

2.1 Low and unreliable electricity access constrains sub-Saharan Africa's development

Sub-Saharan Africa is rich in energy resources, including fossil fuels,³⁰ solar, wind, and hydro power potential,³¹ and the critical minerals required for green energy capture and storage.³² Yet despite the local availability of these resources—and even after accounting for recent progress—energy access continues to lag significantly behind global levels. Across the region, just 53.3 percent of individuals had access to electricity in 2023³³—about 45 percentage points lower than the rest of the world's average.³⁴ Existing grids are also vulnerable to frequent blackouts and loadshedding,³⁵ and overall consumption rates are low—about 0.62 MWh per capita as of 2023,³⁶ compared to 6.5 MWh per capita in China³⁷ (a 10-fold difference) and 13.0 MWh per capita in the United States (a 20-fold difference).³⁸ In the 20 most populous sub-Saharan African countries, just 35 and 17 percent of households own

30 "Statistical Review of World Energy"; US Energy Inf. Adm., "Frequently Asked Questions (FAQs)."

31 *The Renewable Energy Transition in Africa*.

32 Chen et al., *Digging for Opportunity: Harnessing Sub-Saharan Africa's Wealth in Critical Minerals*.

33 "Access to Electricity (% of Population)—Sub-Saharan Africa."

34 "Access to Electricity (% of Population)."

35 Mpako and Moyo-Nyede, *Zimbabweans Grow Increasingly Dissatisfied with Government's Provision of Electricity*; Nakayiza et al., *Despite Government Efforts, Most Ugandans Still Lack Reliable Electricity*; Onishi, "Weak Power Grids in Africa Stunt Economies and Fire Up Tempers."

36 Int. Energy Agency, "Countries & Regions: Africa—Sources of Electricity Generation."

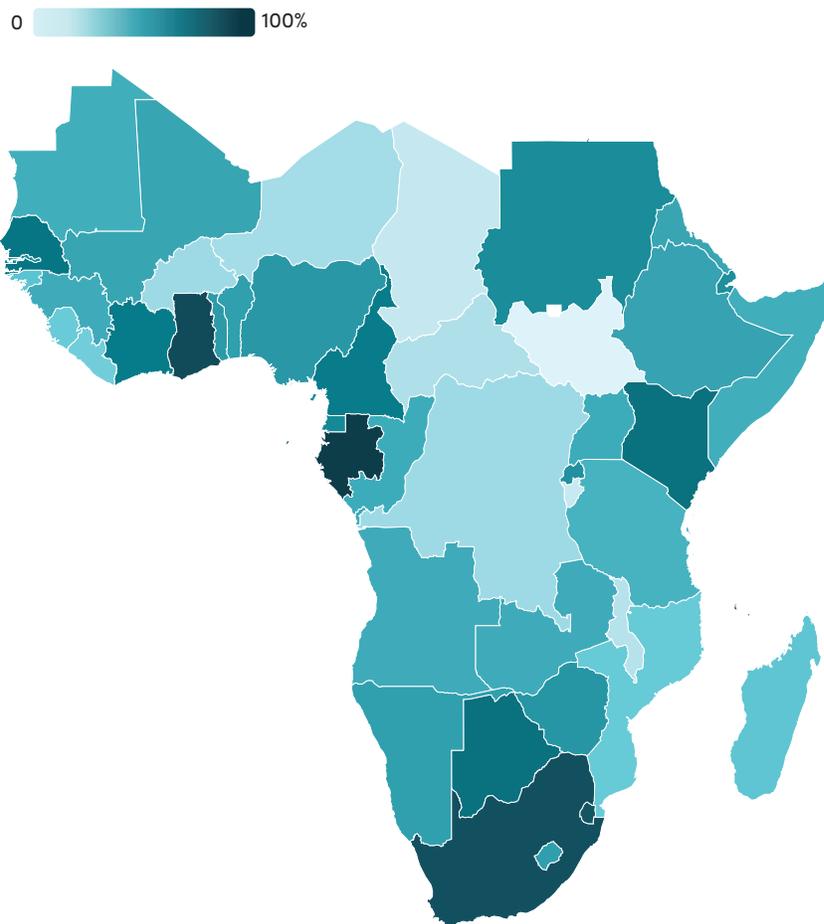
37 Int. Energy Agency, "Countries & Regions: China."

38 Int. Energy Agency, "Countries & Regions: United States."

televisions and refrigerators, respectively, with even lower ownership rates in rural contexts.³⁹ Underlying these cross-regional figures is significant variation in access levels across countries.⁴⁰

To date, sub-Saharan Africa's low rates of access to electricity and weak economic growth have driven a negative feedback loop, wherein greater electricity access is needed to drive economic growth, but countries currently cannot afford the requisite investments to secure sufficient energy access.⁴¹ This challenge will be exacerbated by rapid population growth, with the overall population expected to reach over two billion by 2050⁴² (from 1.29 billion in 2024).⁴³ In total, demand for electricity is expected to grow by three percent per year through 2050.⁴⁴

FIGURE 2. Sub-Saharan African electricity access rate (%), 2023



Source: World Bank (boundaries), Access to electricity (% of population)-Sub-Saharan Africa.

39 *The State of the Off-Grid Appliance Market.*

40 "Access to Electricity (% of Population)."

41 Bogmans et al., *Energy, Efficiency Gains and Economic Development: When Will Global Energy Demand Saturate?*

42 United Nations, Department of Economic and Social Affairs, Population Division, "Probabilistic Population Projections Based on the World Population Prospects 2024."

43 "Population, Total—Sub-Saharan Africa."

44 Schwerhoff and Sy, "Where the Sun Shines."

Low rates of electrification and unreliability stifle sub-Saharan Africa's human, labor, and economic development. Unreliable electricity lowers GDP growth⁴⁵ and impedes development of micro, small, and medium enterprises, with negative implications for the labor force, productivity, operational efficiency, and supply chain resilience.⁴⁶ Lack of reliable electricity is also a major constraint for individual welfare and health outcomes; as just one example, only half of hospitals in sub-Saharan Africa have reliable electricity, and 15 percent lack any access at all.⁴⁷ About a third of children live nearest to schools that are not served by electricity, negatively affecting attendance, quality of education, and future incomes.⁴⁸

2.2 Expanding electricity access is a significant political priority for African citizens, governments, and their development partners

Expanding electricity access is a shared priority for development institutions, African governments, and individual citizens. Public opinion polling suggests electricity access is a second-tier concern to citizens—not as high as unemployment or health but nevertheless ranking in the top 10. Across 39 African countries, roughly one in eight people list “electricity access” as a top-3 political priority, with prioritization concentrated in poor, rural, and no-electricity households⁴⁹—and less than half of respondents are satisfied with their government’s performance in electricity provision.⁵⁰ Governments and political leaders are responsive to this demand; for example, Nigerian President Bola Ahmed Tinubu campaigned on reliable “24/7” electricity access⁵¹ and reiterated his pledge shortly after inauguration,⁵² while Kenyan President William Ruto has promised to extend last-mile electricity access to all Kenyans.⁵³

At the international level, Sustainable Development Goal 7 presents a call to action to “ensure access to affordable, reliable, sustainable and modern energy for all,” including electricity (target 7.1.1).⁵⁴ African electricity access, specifically, has also been the focal point of targeted development initiatives, including the U.S.-led Power Africa public-private partnership (cancelled in 2025). Energy development in Africa received a cumulative \$345.76 billion from MDBs and G20 countries between 2012–2021.⁵⁵

45 Andersen and Dalgaard, “Power Outages and Economic Growth in Africa.”

46 Avordeh et al., “Impact of Power Outages: Unveiling Their Influence on Micro, Small, and Medium-Sized Enterprises and Poverty in Sub-Saharan Africa—An in-Depth Literature Review.”

47 *Energizing Health: Accelerating Electricity Access in Health-Care Facilities.*

48 Moner-Girona et al., “Empowering Quality Education through Sustainable and Equitable Electricity Access in African Schools.”

49 Najib Ben Saad and Logan, *Keeping up with the People's Agenda: Popular Priorities for Government Action, and How They Are Evolving.*

50 *Energy Gaps: Slight, Uneven Progress Still Leaves Many Africans without Electricity, Afrobarometer Survey Shows.*

51 Ibeh, “Year in Review: Top Political Promises Made By Presidential Candidates Ahead of 2023 Elections.”

52 Okonkwo, “President Tinubu Promises Affordable Electricity to All Nigerians.”

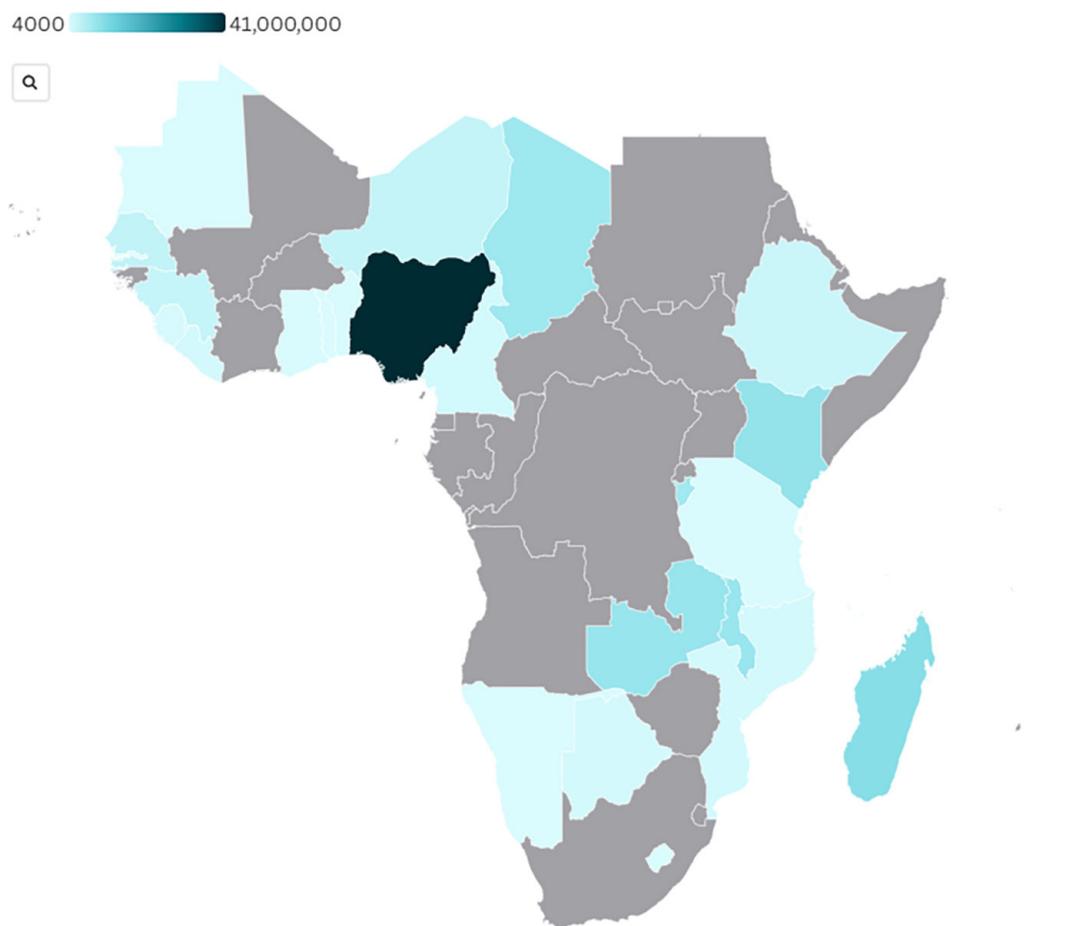
53 Kamau, “Ruto Pledges to Fulfill All Promises Made to Kenyans.”

54 U. N. Dep. Econ. Soc. Aff. Sustain. Dev., “Sustainable Development Goals.”

55 Moses, “Who Finances Energy Projects in Africa?”

Most recently, in April 2024 the World Bank and AfDB jointly launched Mission 300 in partnership with the African Union and several African governments.⁵⁶ Mission 300 is an ambitious \$98 billion effort to connect an additional 300 million people in sub-Saharan Africa to electricity by 2030 via both grid expansion and off-grid solutions. Thus far the World Bank, AfDB, and their partners have collectively committed about \$54 billion toward the initiative's total price tag.⁵⁷ As of writing, 29 African countries had either published or were in the process of producing “National Energy Compacts” under the Mission 300 umbrella⁵⁸—voluntary, country-led plans which lay out the individual goals of each participating country (Figure 3).⁵⁹

FIGURE 3. Estimated Mission 300 expansions in electricity access via off-grid electricity



Source: World Bank (boundaries), M300 Compacts.

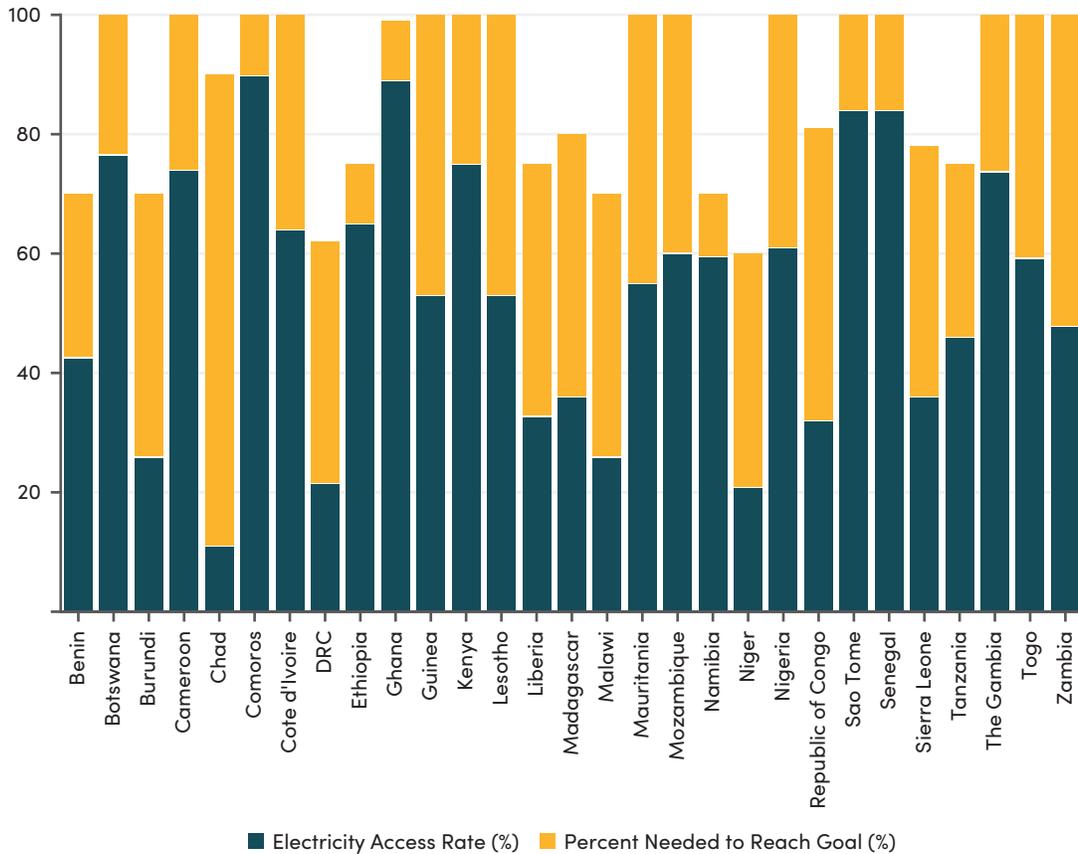
56 World Bank Group, “New Partnership Aims to Connect 300 Million to Electricity by 2030.”

57 World Bank Group, “Heads of State Commit to Concrete Plans to Transform Africa’s Energy Sector, with Strong Backing from Global Partners.”

58 Afr. Dev. Bank, “Mission 300 Gains Momentum as More African Countries Submit Transformative National Energy Compacts to Connect More People to Electricity by 2030.”

59 Mission 300 Afr., “Compacts.”

FIGURE 4. Country compact electrification goals, Mission 300



Source: M300 Compacts.

2.3 Rapid electrification will rely heavily on off-grid solutions

Given the characteristics and spatial distribution of the population in need; the limited coverage and unreliability of existing grids; and the high cost of new grid connections, most experts acknowledge that grid expansion alone cannot feasibly serve 300 million additional people by 2030. As discussed in the introduction, sub-Saharan Africa’s electricity access shortfall is heavily concentrated in rural, fragile, and conflict-affected settings. Even in urban areas where grids are in place, new connection costs are among the highest in the world—ranging between \$50 and \$400 in most sub-Saharan African countries—and therefore unaffordable to large swaths of the population, even before ongoing usage fees for energy consumption.⁶⁰ In rural areas, the costs of grid expansion would be far higher given the need to extend the grid to entirely new and sparsely populated geographic areas.

Instead, experts estimate that off-grid solar would be the least-cost method of electrification for about 55 percent of unelectrified households.⁶¹ This figure is roughly aligned to the Mission 300 plans,

60 Golumbeanu and Barnes, *Connection Charges and Electricity Access in Sub-Saharan Africa*.

61 *Off-Grid Solar Market Trends Report 2022: State of the Sector*.

which anticipates a 45 percent contribution of off-grid and mini-grid connections to overall access gains, reaching 135 million people total; see Figure 4 for estimated new off-grid connections in the first 29 country compacts.⁶² Off-grid solar systems require significant but typically lower up-front capital costs (discussed further in following sections) but do not subsequently incur marginal consumption costs. However, there is often a trade-off between the lower cost of off-grid solar and level of power generation, which depends on the size (and cost) of the system, but which in practice is often quite low. Almost half of existing solar systems are categorized as “solar lanterns”—meaning they produce just enough electricity to provide a single light or charge a phone, and therefore do not meet the minimum criteria for electricity “access” set out by ESMAP.⁶³ Less than a quarter of SHS are Tier 2 or above,⁶⁴ which would power a few small appliances for 4 hours a day—and even here, the power output is typically insufficient for large household appliances like refrigerators, or industrial processes like grain milling.

2.4 Off-grid solar systems require battery storage—with lead-acid batteries still dominating the market

Most renewable energy sources, including solar, provide only intermittent energy generation; they therefore require energy storage (e.g. batteries) to hold the energy until desired use. A typical off-grid solar system, therefore, will necessarily include at least one battery alongside the solar panels and inverter.

There are two primary battery chemistries in wide use across sub-Saharan Africa: lithium-ion and lead-acid. Lithium batteries are technically superior: they have higher energy densities, need less maintenance, charge faster, last longer,⁶⁵ and perform better in hot environments than lead-acid batteries, which makes them more adaptable to climate change.⁶⁶ Lead-acid batteries are less performant than lithium-ion chemistries and generally cost more per unit of energy over their lifetimes.⁶⁷ However, lead-acid batteries have a far lower up-front cost, are safer during use, and are almost entirely recyclable. Lithium-based batteries are generally not recycled, as the process for doing so is too complicated to be widely profitable.⁶⁸

62 *A Sustainable Off-Grid Industry Is Crucial to Achieving Mission 300.*

63 ESMAP’s Multi-Tier Framework defines energy access as “the ability to avail energy that is adequate, available when needed, reliable, of good quality, convenient, affordable, legal, healthy and safe for all required energy services.” According to their standards, minimum energy access is achieved at Tier 1, with a minimum daily capacity of 12 watt hours, OR lighting of 1,000 lumen-hours per day and phone charging.

64 *Off-Grid Solar Market Trends Report 2024.*

65 *Handbook on Battery Energy Storage System.*

66 Lockhart et al., *Comparative Study of Techno-Economics of Lithium-Ion and Lead-Acid Batteries in Micro-Grids in Sub-Saharan Africa.*

67 Ayeng’o et al., “Comparison of Off-Grid Power Supply Systems Using Lead-Acid and Lithium-Ion Batteries.”

68 Yu et al., “Current Challenges in Efficient Lithium-Ion Batteries’ Recycling: A Perspective.”

Details of their respective performance and characteristics can be found in Table 1.

TABLE 1. Comparing performance and characteristics of lithium-ion and lead-acid batteries

Parameters	Lead-Acid	Lithium-Ion
Safety	High	Medium
Cycle Life	500–1,000	2,000–6,000
Energy Density (Wh/kg)	40–60	80–150
LCOE (\$/kWh)	0.480	0.395
CAPEX (\$/kWh)	80–150	250–350

Notes: LCOE = Levelized Cost of Electricity (per unit cost of electricity generated over 20 year lifetime), CAPEX = Capital Expenditure. Note that LCOE does not include potential EoL value of ULABs.

Source: ESMAP, Ayeng'o et al.

Globally, lithium-ion batteries are rapidly gaining market share given rapid price reductions, their lower life-time costs and superior performance; in the long-term, it is likely that lithium batteries will continue to crowd out lead-acid batteries for energy storage. Between 2022 and 2030, the global market for lithium-ion batteries is anticipated to soar almost seven-fold, from 700 to 4,700 gigawatt-hours;⁶⁹ in contrast, demand for lead-acid batteries is projected to see a more modest rise of 31 percent over the same period.⁷⁰ Already, the vast majority of quality assured SHS—making up about a third of the market in sub-Saharan Africa—use lithium-ion battery chemistries. For example, the World Bank will only purchase VeraSol quality-certified off-grid solar products;⁷¹ there are 193 eligible solar energy kits with this designation, of which only two use lead-acid chemistries and the majority are lithium-ion.⁷²

However, at present, lead-acid batteries still dominate the energy storage market in sub-Saharan Africa and will likely continue to do so for the foreseeable future.⁷³ While there is no reliable data on the precise breakdown, anecdotal reports suggest that most of the non-quality-assured market runs on lead-acid batteries, suggesting a roughly 70 percent overall market share globally. Consumer preference for lead-acid batteries is due to their lower capital cost: indicatively, in one setting a lead-acid battery costs \$45 USD, whereas an equivalent lithium-ion battery cost \$160 USD.⁷⁴ For poor consumers, the upfront cost of quality-verified lithium-ion batteries can be prohibitive, and suitable financing models are rarely accessible.⁷⁵ Further, component-based systems are often the only affordable option for the most economically insecure customers, who piece together batteries, panels, controllers, and an appliance to create their own off-market alternatives. In many settings,

69 Fleischmann et al., “Battery 2030: Resilient, Sustainable, and Circular.”

70 Consort. Battery Innov., “Lead Battery Market Data.”

71 Author’s conversations with Mission 300 World Bank procurement team.

72 “Products—SEK.”

73 Kinally et al., “Off-Grid Solar Waste in Sub-Saharan Africa: Market Dynamics, Barriers to Sustainability, and Circular Economy Solutions.”

74 Zubi et al., “Lithium-Ion Battery-Packs for Solar Home Systems: Layout, Cost and Implementation Perspectives.”

75 World Bank Group, “Off-Grid Solar Could Provide First-Time Electricity Access to Almost 400 Million People Globally by 2030.”

component-based systems are the *only* available option at any price, given incomplete penetration of the affiliated market across sub-Saharan Africa.⁷⁶

According to data from the Global Association for the Off-Grid Solar Energy Industry (GOGLA), 37.8 million “quality-assured” off-grid solar products were sold in sub-Saharan African regions between 2019–2024.⁷⁷ Worldwide, quality-assured products are estimated to comprise about 30 percent of the total off-grid solar market;⁷⁸ this would (roughly) imply total regional sales of 126 million off-grid solar systems during this period, including 88 million units within the unaffiliated/non-quality-assured market segment. Technically, this is a low-end estimate because some units would have been sold before 2019 or after 2024. Mini-grids also require battery storage and are considered separately (Box 1).

BOX 1. The role of lead-acid batteries in mini-grids

Mini-grids are standalone, decentralized energy systems which generate and distribute electricity—detached from the primary electric grid—and can be used to power individual household units as well as more energy-intensive facilities, including industrial systems, schools, and businesses. Mini-grids may be a preferred option for primary energy access in remote or rural regions; they can also be used for back-up energy supply in settings with unreliable primary grids.⁷⁹ At present, almost all planned mini-grids use solar photovoltaic (PV) to capture energy, replacing diesel powered systems.⁸⁰ Most mini-grids require batteries for energy storage.

As of 2022, there were 3,100 operational mini-grids in Africa, with 9,000 additional projects in the pipeline.⁸¹ Rapid expansion plans reflect increasing affordability; ESMAP projects that the LCOE for mini-grids may fall to \$0.20/kWh by 2030—a steep decline from the \$0.38/kWh cost in 2020, reflecting significant savings over current average national grid costs in the region (\$0.27).⁸²

Lithium batteries are now the favored battery chemistry for mini-grids, replacing lead-acid chemistries. Until 2017, 97 percent of surveyed grids used lead-acid batteries, but between 2018 and 2021 lithium-based batteries attained 69 percent market share in new mini-grid installations.⁸³ Lithium-ion batteries have far longer cycle lives (3,000 compared to 800 for lead-acid), lowering maintenance and replacement costs.⁸⁴

The modal shift to lithium-ion batteries in mini-grids is likely to continue in parallel to their scale-up. In the short-term, absolute use of lead-acid batteries may increase, but over a longer time-horizon the volume of ULABs should fall.

76 *Off-Grid Solar Market Trends Report 2024*.

77 Sales data provided directly by GOGLA.

78 *Off-Grid Solar Market Trends Report 2024*.

79 O’Callaghan and Kennedy, *Mini Grids For Half A Billion People*.

80 O’Callaghan and Kennedy, *Mini Grids For Half A Billion People*.

81 O’Callaghan and Kennedy, *Mini Grids For Half A Billion People*.

82 O’Callaghan and Kennedy, *Mini Grids For Half A Billion People*.

83 O’Callaghan and Kennedy, *Mini Grids For Half A Billion People*.

84 O’Callaghan and Kennedy, *Mini Grids For Half A Billion People*.

The total volume of ULAB waste associated with off-grid solar nevertheless remains highly uncertain due to several unknown parameters—specifically, the battery size associated with each unit and average battery life. A high estimate would assume a full-size car battery (18.15 kg) per unit with a one-year battery life; this would imply roughly 1.5 million tonnes of ULAB waste associated with off-grid solar per year in sub-Saharan Africa. A low estimate would assume a smaller average battery size (e.g. a 6 kg motorcycle battery) with a two-year battery life; this would in turn imply about 250,000 tonnes of ULAB waste associated with off-grid solar per year. The lower-end estimate is probably unrealistically conservative, given the documented use of full-size car batteries in anecdotal reporting.⁸⁵

To contextualize these figures within a rough order of magnitude, we crudely update the Tür et al. (2016)⁸⁶ estimates of ULAB waste volume in sub-Saharan Africa through 2025; we assume that vehicle and uninterruptible power supply use will have increased at a rate equivalent to annual economic growth.⁸⁷ For 2025, this yields an annual estimate of 1.4 million tonnes of ULAB waste associated with passenger and commercial vehicles; 100,000 tonnes of ULAB waste associated with motorbikes; and 230,000 tonnes of ULAB waste associated with uninterruptible power supplies. Our high-end estimate, therefore, is roughly equivalent to estimated waste ULAB volume generated by automobiles; it would imply that total ULAB waste volumes are roughly 3.27 million tonnes per year, of which off-grid solar is a plurality (47 percent). Our low-end estimate is more comparable to ULAB waste generated by uninterruptible power supply systems; it would imply that total ULAB waste volumes are roughly 1.98 million tonnes per year, of which off-grid solar is a minority contributor (13 percent) to overall volumes.

TABLE 2. Off-grid solar ULAB waste generation estimates

Estimate	Battery Mass (Kg)	Recycling Rate (Years)	ULAB Waste (t/a)	Off-Grid Solar Units	LAB-Powered Solar Units
Off-Grid Solar Low End	6.00	2	254,181	125,978,330	84,726,996
Off-Grid Solar High End	18.15	1	1,537,795	125,978,330	84,726,996

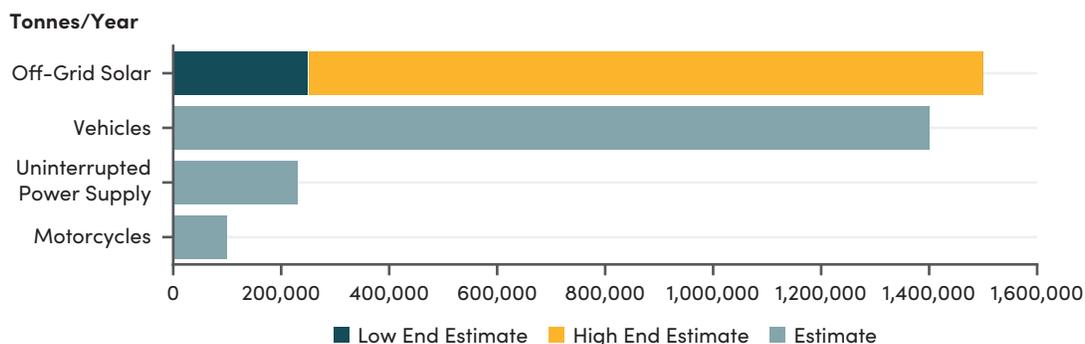
Source: See details in appendix.

85 Kinally et al., “Solar Home Systems in Malawi: Commercialisation, Use and Informal Waste Management.”

86 Tür et al., *Generation of Used Lead-Acid Batteries in Africa—Estimating the Volumes*.

87 International Monetary Fund, “Real GDP Growth.”

FIGURE 5. ULAB volume generation in sub-Saharan Africa
Estimates of ULAB waste generated by source



Source: See details in appendix.

3. Addressing safety risks from lead acid batteries

3.1 Without appropriate EoL management, lead acid batteries create severe health and safety risks

Rechargeable lead-acid batteries were first developed in the mid-1800s and remain a highly dependable technology. Unlike lithium batteries—which can experience overheating and explosion⁸⁸—lead-acid batteries are stable, presenting minimal safety risk while in use.⁸⁹ As an essential component for all gas-powered vehicles, lead-acid batteries are also a familiar technology to African technicians, which can be serviced by the local repair economy.⁹⁰ Due to their relatively heavy weight, lead-acid batteries are most appropriately used in stationary contexts and to power machinery that can support their weight (i.e. cars).

The components of a lead-acid battery—lead, plastic, and acid—are entirely recyclable, making lead-acid batteries a sustainable and circular option. In the United States, a typical lead-acid battery contains about 80 percent recycled material.⁹¹ Annual lead mining is in gradual decline from its 2013 peak, in part due to highly performant ULAB recycling networks across many high-income countries and lead’s suitability for repeat recycling without degradation.⁹²

ULAB recycling also occurs in LMICs, but its quality and recovery rates are highly variable. Quality levels of ULAB recycling in LMICs can be defined via the SOPs issued by Sustainable Recycling Industries, which identify three tiers in a sub-Saharan African context: high standard industrial, low standard industrial, and backyard recycling. Industrial recycling is formal, meaning it is privy

88 Bugryniec et al., “Review of Gas Emissions from Lithium-Ion Battery Thermal Runaway Failure—Considering Toxic and Flammable Compounds.”

89 Battery Counc. Int., “Reliable & Proven Track Record.”

90 Kinally, “Research Brief: How Are Malawi’s Rural Solar Energy Systems and Lead Poisoning Connected?”

91 *National Recycling Rate Study*.

92 *Lead Data Sheet—Mineral Commodity Summaries 2020*; *The World Lead Factbook 2023*.

to government oversight and taxes, while informal recycling is unregistered and unaccountable to these checks.

Formal, high-quality ULAB recycling yields high lead recovery rates without compromising human and environmental safety to lead exposure. High-quality recycling requires both expensive equipment and sophisticated occupational safety procedures. Plants considered high-quality maintain equipment that traps lead from leaking to the environment, such as automated battery breaking, suitable furnace design and operation, off-gas treatment systems, technologies capturing and recycling lead particles, as well as the safe disposal of generated slags. Further, high quality plants ensure the provision of proper PPE and health monitoring, including a respirator, work clothing, head gear, gloves, footwear, goggles, a sealed face visor, and ear defenders for workers, as well as routine blood lead monitoring and dedicated facilities where workers can eat and wash, which mitigates the direct consumption and take-home risk of toxic lead dust.⁹³

Identifying a high-quality recycling facility is relatively straightforward—facilities either follow the SOPs, or they do not. Low-quality recycling operations, in contrast, have more variable levels of quality, with differing implications for occupational lead exposure and environmental contamination.

Formal but low-quality operations are registered as taxable entities, may employ a large workforce, and may have some expensive, efficient equipment. In practice, these operations commonly see some lead losses to the environment, which can make up several percentages of the total lead throughput.⁹⁴ In many cases, such facilities operate in the absence of strong regulatory oversight, which can lead them to cut corners on safety. Lead exposure to workers in these facilities and their families can be significant; in Serbia, for example, having a parent employed by such a facility was associated a 5.2 µg/dL increase in children's BLL.⁹⁵

Informal, highly polluting recycling facilities—also called backyard recycling—lose between 40 to 50 percent of recoverable lead to the environment.⁹⁶ These ULAB recycling operations are typically located in urban and suburban areas, capitalizing on the high supply and density of ULAB waste. Backyard operations are not held to any human or environmental safety standards and can create severe contamination. In one notable incident in Dakar, Senegal, from 2007 to 2008, 18 children died from lead poisoning traced to a nearby recycling operation. Later testing demonstrated BLLs ranging from 39.8 µg/dL to 613.9 µg/dL among neighbors and worker's family members.⁹⁷ Informal recycling operations can continue to pose a health threat even after they cease operations. Proximity to these

93 Wilson and Manhart, *Standard Operating Procedures for Environmentally Sound Management of Used Lead-Acid Batteries*.

94 *Closing the Loop on Energy Access in Africa*.

95 Mandić-Rajcević et al., "Environmental and Take-Home Lead Exposure in Children Living in the Vicinity of a Lead Battery Smelter in Serbia."

96 *Closing the Loop on Energy Access in Africa*.

97 Haefliger et al., "Mass Lead Intoxication from Informal Used Lead-Acid Battery Recycling in Dakar, Senegal."

so-called “ghost plants”—those which are no longer active but have not been remediated—was found to be the strongest predictor of childhood BLL in one study from Bangladesh.⁹⁸

3.2 Actual recycling practices in Sub-Saharan Africa are enormously polluting and unsafe

Sub-Saharan Africa has several factories which manufacture lead-acid batteries.⁹⁹ The region also hosts notable smelting capacity to produce recycled lead for export. Once smelted, recycled lead is transported as ingots to overseas manufacturers, likely in Europe or Asia, to be manufactured into new lead-acid batteries.¹⁰⁰

Most recycling in the region is highly polluting. Ericson (2016) estimates that there are between 1,167 to 7,217 informal ULAB recycling operations in sub-Saharan Africa, exposing anywhere from around 671,000 to 4,000,000 people to lead toxicity.¹⁰¹ New research estimates, albeit with significant uncertainty, that up to 162 million people in sub-Saharan Africa face some level of toxic lead exposure from ULAB recycling.¹⁰² Exposure can occur while breaking the battery, draining its acid, and through other forms of tactical contact.¹⁰³ Recycling employees therefore face the highest risk of lead exposure. Across developing countries, the average battery industry worker in manufacturing and recycling facilities has a BLL of 47 µg/dL and 64 µg/dL respectively¹⁰⁴—about 13 and 18 times the Center for Disease Control’s (CDC) reference value for lead poisoning of 3.5 µg/dL.¹⁰⁵

In sub-Saharan Africa, ULAB recycling operations are often located in urban and suburban areas, capitalizing on their high supply and density of ULAB waste.¹⁰⁶ Children are at particular risk in neighborhoods proximate to recycling facilities, in part due to behaviors such as pica and outdoor play.¹⁰⁷ Across all developing countries, one review found average BLLs of 19 µg/dL among children residing near battery plants.¹⁰⁸ Severe lead poisoning outbreaks traced to ULAB recycling have been documented in Senegal,¹⁰⁹ Republic of Congo,¹¹⁰ and Kenya.¹¹¹

98 Chowdhury et al., “Child Lead Exposure near Abandoned Lead Acid Battery Recycling Sites in a Residential Community in Bangladesh: Risk Factors and the Impact of Soil Remediation on Blood Lead Levels.”

99 Agese, *Challenges Facing the Battery Industry in Africa & Solutions*.

100 Manhart et al., *The Deadly Business—Findings from the Lead Recycling Africa Project*.

101 Ericson et al., “The Global Burden of Lead Toxicity Attributable to Informal Used Lead-Acid Battery Sites.”

102 Crawford et al., *Beyond Hot Spots: Estimating Population Lead Exposure from Battery Recycling*.

103 Wilson and Manhart, *Standard Operating Procedures for Environmentally Sound Management of Used Lead-Acid Batteries*.

104 Gottesfeld and Pokhrel, “Review: Lead Exposure in Battery Manufacturing and Recycling in Developing Countries and Among Children in Nearby Communities.”

105 Cent. Dis. Control, “CDC Updates Blood Lead Reference Value.”

106 Manhart et al., *Partnership for Responsible Battery and Metal Recycling (ProBaMet)—Project Summary Report*.

107 Rees and Fuller, *The Toxic Truth: Children’s Exposure to Lead Pollution Undermines a Generation of Future Potential*.

108 Gottesfeld and Pokhrel, “Review: Lead Exposure in Battery Manufacturing and Recycling in Developing Countries and Among Children in Nearby Communities.”

109 Haefliger et al., “Mass Lead Intoxication from Informal Used Lead-Acid Battery Recycling in Dakar, Senegal.”

110 Fitzgibbon, “Court Suspends Battery Recycling Plant in the Republic of Congo, Citing Lead Poisoning.”

111 Bloom, “The Woman Risking Her Life to Save a Village from Lead Poisoning.”

3.3 Economic incentives cut against safe recycling

Capital and maintenance costs for battery recycling vary dramatically depending on the operation's level of safety and quality. High-quality recycling operations require large capital investments, typically costing between \$4 and \$10 million, to trap lead waste, with additional recurrent expenditure to sustain adequate safety measures. The cost structure is substantially lower for substandard industrial smelting operations, which generally require between \$300,000 and \$2 million up-front. Backyard operations are far cheaper, costing just \$100 to \$5,000 in initial investments, with few maintenance expenditures. Though exhaustive surveying has not been conducted, there is confirmation of one identified plant in sub-Saharan Africa—Green Recycling Ltd, in Nigeria—operating at high environmental health and safety standards.¹¹² This plant has since shut down after being economically outcompeted in the market.¹¹³

ULAB recycling is a highly economically advantageous process; about 65 percent of a ULAB's weight is lead,¹¹⁴ which garners \$1,995.00 per tonne on the London Metals Exchange.¹¹⁵ Lead recovery rates are far higher in high-standard industrial smelting plants compared to backyard smelting, but some few percentage points higher than low-standard industrial operations—a relatively marginal (economic) difference relative to the significantly larger investment and operational costs required.

Recycling facilities in sub-Saharan Africa typically source their ULABs from informal collection networks, which transport ULABs from users to recyclers, and will in turn sell their stock to the highest bidder. Low-standard industrial operations typically have the greatest profit margins, so they can pay the most to collectors, edging out high-quality operations from market competitiveness.¹¹⁶ In the absence of robust regulation, low-standard industrial operations therefore represent the economically dominant option in most settings.

In developed countries, strict regulations force informal and sub-standard recyclers out of the market. The United States, for example, has a closed-loop recycling and manufacturing system that recovers 99 percent of used lead from batteries.¹¹⁷ Closed loop systems funnel recycled battery materials from recyclers directly to manufacturers, who use the raw material for new battery production. An effective “reverse logistics recycling system” has also been rolled out in Brazil—a middle-income-country—requiring retailers to collect spent lead-acid batteries and return them to distributors, who in turn send them onward to legal smelters and legal manufacturers.¹¹⁸ This process is largely overseen by a third-party organization—Instituto Brasileiro de Energia Reciclável—which as of 2022 managed 75 percent of the ULAB market.¹¹⁹ However, closed-loop collection systems are

112 Manhart and Adjei, *Responsible Lead-Acid Battery Recyclers in Low- and Middle-Income Countries*.

113 Goodman et al., “Recycling Lead for U.S. Car Batteries Is Poisoning People.”

114 Tür et al., *Generation of Used Lead-Acid Batteries in Africa—Estimating the Volumes*.

115 LME price 12/03/2025.

116 *Closing the Loop on Energy Access in Africa*.

117 Dooley et al., *Lead-Acid Battery Recycling Success: Policy + Reverse Supply Chains*.

118 Wilson et al., *Consequences of a Mobile Future: Creating an Environmentally Conscious Life Cycle for Lead-Acid Batteries*.

119 2022 RELATÓRIO ANUAL LOGÍSTICA REVERSA DE BATERIAS CHUMBO-ÁCIDO. (DeepL translated)

not, on their own, a panacea: pollution is only reduced if the smelters and manufacturing facilities included in the loop meet high safety and emissions standards. Successful EoL management in the United States and Brazil is thus necessarily enabled by domestic recycling and manufacturing capacity, strong regional agreements, and developed transportation networks.

4. Market deep-dive—the off-grid solar industry

4.1 The supply of off-grid solar products is vast, unorganized, diverse, and bifurcated

The off-grid solar sector in sub-Saharan Africa is bifurcated between regulated and unregulated markets. The regulated market is broadly defined by several (largely overlapping) standards and certifications, including GOGLA affiliation and certification via Lighting Global (now VeraSol) quality standards.¹²⁰ Regulated products account for about 30 percent of the total global market for off-grid solar products, albeit with significant regional variation (Table 2).¹²¹ Rwanda, for example, represents a clear outlier, with upwards of 97 percent market share for regulated products. Dominance of the regulated market in Rwanda is in part due to the World Bank-backed Rwanda Renewable Energy Fund project, which worked with the regulated private sector to connect two million people to off-grid technologies,¹²² including via credit lines to improve their financial accessibility.¹²³ In most other sub-Saharan African countries, the market for off-grid solar is dominated by non-regulated products.

TABLE 3. Unaffiliated market share in selected sub-Saharan African countries

Country	Market Share (0–10 Wp Product)	Market Share (11–100+ Wp Product)
Ethiopia	68%	99%
Kenya	58%	60%
Malawi	51%	43%
Niger	85%	99%
Nigeria	66%	85%
Rwanda	3%	2%
Tanzania	72%	60%
Togo	96%	79%
Uganda	47%	96%
Zambia	62%	44%

Notes: Watt-peak (Wp) measures the maximum potential power output from a photovoltaic panel; Market share represents the share of unaffiliated products sold in each Wp category.

120 Kinally et al., "Off-Grid Solar Waste in Sub-Saharan Africa: Market Dynamics, Barriers to Sustainability, and Circular Economy Solutions."

121 *Off-Grid Solar Market Trends Report 2024*.

122 "Implementation Status & Results Report Renewable Energy Fund (P160699)."

123 Heltberg, *RWANDA RENEWABLE ENERGY FUND PROJECT*.

The regulated sector is characterized by several key attributes:

- First, as of 2023, a significant plurality (39 percent) of GOGLA-affiliated off-grid solar systems are purchased via pay-as-you-go (PAYG) financing, which offers customers a lease-to-own pathway. PAYG financing is unique to the affiliated market business model, and is generally not available in the unregulated market. Since 2018, PAYG-financed sales have increased by 15 percentage points—but they are still cost-prohibitive for many (affordable to only 22 percent of households) and are not available in many sub-Saharan markets.¹²⁴
- Second, most regulated product (including 100 percent of VeraSol certified offerings) come as complete “plug and play” units (pre-assembled). Unregulated products may be sold as either “plug and play” or component-based systems, which require professional installation and consist of at least a battery, inverter, and panel.¹²⁵
- Third, regulated products typically offer a one- or two-year warranty. These warranties help companies maintain a relationship with customers, keep track of their products, and monitor their quality.
- Fourth, almost all batteries on the regulated market contain lithium-ion (versus lead-acid) chemistries.¹²⁶ VeraSol offers 193 different Solar Energy kits (SEKs), of which only two are powered by lead-acid batteries.¹²⁷

The regulated market is diverse in terms of product offering. In addition to basic solar lamps, chargers, and home systems, companies sell a variety of products for individual and industrial scale, including walk-in freezers, refrigerated trucks, televisions, radio, and water pumps.¹²⁸

Importantly, most development institutions, most notably the World Bank, *exclusively* purchase products from the regulated/quality-assured market. Given the extreme rarity of lead-acid batteries in the formal sector, this implies very limited direct financing of lead-acid batteries with donor funds, and a relatively limited role of lead-acid batteries in achieving Mission 300 targets.

The remainder of units are sold through the unregulated off-grid solar sector—comprising about 70 percent of the market¹²⁹—which is opaque and difficult to characterize. In many cases, unregulated SHS are sold as components¹³⁰—with batteries, panels, and the charge controller all purchased separately. (In Uganda, for example, the market share of component-based systems

124 *Off-Grid Solar Market Trends Report 2024*.

125 “Currently VeraSol-Certified and Tested Products (Solar Energy Kits).”

126 Kinally et al., “Off-Grid Solar Waste in Sub-Saharan Africa: Market Dynamics, Barriers to Sustainability, and Circular Economy Solutions.”

127 “Currently VeraSol-Certified and Tested Products (Solar Energy Kits).”

128 GOGLA, “GOGLA Members.”

129 *Off-Grid Solar Market Trends Report 2024*.

130 Kinally et al., “Off-Grid Solar Waste in Sub-Saharan Africa: Market Dynamics, Barriers to Sustainability, and Circular Economy Solutions.”

is 50–80 percent.)¹³¹ Component-based systems tend to be lower quality compared to complete systems,¹³² and most components have a variety of uses beyond inputs for off-grid solar, making it difficult to trace where they end up. Unregulated products are typically sold through informal dealers who do not report sales data.¹³³

Most unregulated off-grid solar systems use (cheaper) lead-acid batteries, in large part due to their lower cost.¹³⁴ Customers purchasing unregulated products are most likely more economically insecure, forcing them towards less costly and more accessible battery options.¹³⁵ Market research from Malawi found zero penetration of lithium batteries on the unregulated market.¹³⁶ More research and data is needed to better understand the volume of waste ULABs generated on the unregulated market, and the corresponding need for safe battery collection, repair, and recycling.

4.2 Demand is shaped by macroeconomic factors, price reductions, and development commitments

From 2018 to 2023, global annual off-grid solar demand increased by 37 percent, representing an additional 14 million products sold each year across both the regulated and unregulated markets.¹³⁷ Increased demand is attributable to several factors, including background macroeconomic forces (demographic and economic growth), but also rapid price reductions and significant international development commitments.

The price of renewable LCOE has dropped significantly in recent years - with one review finding a decrease of about 9 percent annually from 2016 to 2021.¹³⁸ Price reductions for specific input costs are even more dramatic—90 percent for solar photovoltaic in the last decade¹³⁹ and 97 percent for lithium batteries since 1991.¹⁴⁰ The falling cost curve has also induced additional suppliers to enter the market; in 2015 there were 26 GOGLA affiliate (manufacturing) companies,¹⁴¹ increasing to 58 by 2025.¹⁴² Greater supply and falling prices have in turn increased the accessibility and suitability of off-grid solar as an electrification solution in the sub-Saharan African context.

131 Groenewoudt et al., “From Fake Solar to Full Service: An Empirical Analysis of the Solar Home Systems Market in Uganda.”

132 Groenewoudt et al., “From Fake Solar to Full Service: An Empirical Analysis of the Solar Home Systems Market in Uganda.”

133 Kinally et al., “Off-Grid Solar Waste in Sub-Saharan Africa: Market Dynamics, Barriers to Sustainability, and Circular Economy Solutions.”; Groenewoudt et al., “From Fake Solar to Full Service: An Empirical Analysis of the Solar Home Systems Market in Uganda.”

134 Kinally et al., “Off-Grid Solar Waste in Sub-Saharan Africa: Market Dynamics, Barriers to Sustainability, and Circular Economy Solutions.”

135 Kinally et al., “Life Cycle Assessment of Solar Home System Informal Waste Management Practices in Malawi.”

136 Kinally et al., “Solar Home Systems in Malawi: Commercialisation, Use and Informal Waste Management.”

137 *Off-Grid Solar Market Trends Report 2024*.

138 Weinand et al., Global LCOEs of Decentralized Off-Grid Renewable Energy Systems.

139 Ritchie, “Solar Panel Prices Have Fallen by around 20% Every Time Global Capacity Doubled.”

140 Ritchie, “The Price of Batteries Has Declined by 97% in the Last Three Decades.”

141 *Global Solar Off-Grid Semi-Annual Market Report*.

142 GOGLA, “GOGLA Members.”

Demand for off-grid products has also increased due to specific commitments from bilateral donors and multilateral development banks. Power Africa, a 2013 USAID-led initiative to increase electricity access in sub-Saharan Africa, used \$1.2 billion in direct bilateral funding to mobilize \$29 billion in power project finance from other sources.¹⁴³ By end 2023, Power Africa support reported that it had helped connect an additional 200 million people to electricity.¹⁴⁴ A 2019 Inspector General report suggesting most that most additional connections by 2017 (80 percent) had been achieved via small-capacity solar lanterns.¹⁴⁵ The World Bank and IFC have also supported the “Lighting Africa” initiative since 2009, which has since evolved into the “Lighting Global” project. Efforts supported under this umbrella include a range of market-building activities in the off-grid energy space, including market intelligence, quality assurance, access to finance, consumer education, policy engagement, and capacity building.¹⁴⁶ Mission 300—described in previous sections—intends to build on this foundation.

4.3 The off-grid solar sector includes diverse stakeholders and interest groups

The off-grid solar market is influenced by a diverse range of stakeholders and interest groups including development finance institutions; climate and green energy non-profits and related philanthropies; and many different private sector providers, including industry bodies.

Multinational, regional and national development institutions play a significant role in off-grid electrification in sub-Saharan Africa. Mission 300, led by the World Bank and AfDB, is the largest ongoing electrification project in sub-Saharan Africa. Other significant current investments include the European Investment Bank (EIB)-financed Electricite de France (EDF) Off-Grid Africa project (€35 million);¹⁴⁷ and the United Kingdom-supported Transforming Energy Access platform,¹⁴⁸ among many others. Both Germany and the United Kingdom have supported efforts to promote responsible ULAB recycling.¹⁴⁹

The private sector itself is large and diverse. Currently, there are 106 different industry members affiliated with GOGLA and many more unaffiliated companies.¹⁵⁰ The majority of affiliated members are operating in sub-Saharan Africa. Almost half (52) of the industry members are headquartered in sub-Saharan Africa. Most industry members are either manufacturers or distributors, but there is

143 Lee, “What We’re Losing: Energy, Growth, and Power Africa.”

144 *Power Africa Annual Report 2023*.

145 *Power Africa Coalesced Energy Efforts but Lacked Portfolio-Wide Risk Management and Consistent Measures of Progress*.

146 Light. Glob., “How We Work.”

147 Eur. Invest. Bank Group, “EDF OFF-GRID AFRICA.”

148 UK AID, “Transforming Energy Access.”

149 Bankole, “UK Plans \$5m Lithium Battery Recycling Plant in Ogun”; “Partnership for Responsible Battery and Metal Recycling (ProBaMet).”

150 GOGLA, “GOGLA Members.”

also a smaller contingent among GOGLA Industry Members of investors, software platforms, donors/ implementors, and a research consultancy. Some of these organizations also have multiple roles.

TABLE 4. GOGLA industry members

Role	GOGLA Industry Members
Distributor	34
Manufacturer	37
Manufacturer–Distributor	20
Software Platform–Provider	15
Donor–Project Implementor	1
Investor	2
Research Organization–Consultancy	1

Source: GOGLA. Some members have multiple roles.

Several industry bodies help facilitate the market for off-grid solar, including via market intelligence, coordination and quality standards. Key actors in this space are GOGLA, a global membership association for the off-grid solar industry;¹⁵¹ the VeraSol quality assurance program;¹⁵² and Efficiency for Access, which hosts (1) the Lighting and Energy Access Partnership (LEAP) Awards for up-and-coming off-grid solar products;¹⁵³ and (2) the Low Energy Inclusive Appliances (LEIA) program for research and development. These bodies send powerful market signals about product quality through their respective membership and certification processes.

Finally, battery recycling and repair operations are themselves important stakeholders in the sector, as off-grid solar products comprise a relatively low but significant and growing portion of ULAB waste in sub-Saharan Africa.¹⁵⁴

5. Discussion and conclusion

While data is sparse, this investigation points to a significant and growing volume of ULAB waste associated with off-grid solar systems in sub-Saharan Africa, comprising a 13 to 47 percent share of total ULAB waste. At the high-end estimate, off-grid solar would be the single leading driver of ULAB waste in sub-Saharan Africa. However, off-grid solar is nevertheless a minority share of *overall* ULAB waste; over a longer time horizon, the share of ULABs associated with off-grid systems will likely contract given the modal shift to more performant (and increasingly cost-effective) lithium-ion batteries.

151 GOGLA, "About Us."

152 VerSol, "VeraSol."

153 Effic. Access, "Global LEAP Awards."

154 Kinally, "Research Brief: How Are Malawi's Rural Solar Energy Systems and Lead Poisoning Connected?"

In the interim, development institutions must take care to “do no harm” in their efforts to increase electricity access, including by ensuring appropriate EoL management for the products which they finance. We find that development institutions bear limited direct responsibility for existing challenges with ULAB waste generated by off-grid solar systems. Most development institutions, including the World Bank, exclusively finance quality-assured products from the regulated sector—which are overwhelmingly powered by lithium-ion batteries. (Findings are slightly different for mini-grids, where a third of World Bank-financed investments between 2020–2021 relied on lead-acid batteries, though the Bank increasingly prefers lithium-ion).¹⁵⁵ However, development institutions may cause *indirect* uptake of lead-acid battery-powered off-grid systems—for example, by promoting VAT exemptions for off-grid solar which could apply equally to regulated and unregulated plug-and-play products. Development institutions also enjoy close partnerships with national governments in the energy sector, providing an important entry point to improve regulatory and physical infrastructure for safe ULAB recycling, including waste from both off-grid systems and more traditional sources (e.g. automobiles).

Further, we find that unsafe ULAB recycling is driven by deep structural forces, confounding hopes for quick-fix solutions. Previous research, reviewed in this paper, suggests market failures that create major economic disincentives to safe battery recycling. In the absence of government intervention, low-quality formal plants are most economically advantageous, offering relatively low costs and reasonably high yields (~90 percent) compared to those achieved in informal, backyard operations (~50 percent). High-quality, safer plants are significantly more expensive to capitalize and operate but offer only marginally higher recovery rates (~98 percent).

Safer recycling could theoretically be incentivized via per-unit subsidies to compensate for the cost difference; realistically, however, doing so is unlikely to be affordable given the magnitude of the capital and marginal cost financing gaps, alongside the very large scale of recycling. Forthcoming research from Manhart and Adjei estimates a \$212/tonne cost disparity between high- and low-standard ULAB recycling, requiring a recurrent subsidy of roughly \$420 to \$693 million per year across the roughly 1.98–3.27 million tonnes of ULAB waste in sub-Saharan Africa.¹⁵⁶ The requisite amount is very large in context, equivalent to roughly two to three percent of the International Development Association’s *total* annual commitments on the African continent,¹⁵⁷ but quite small compared to estimates of the economic burden from lead exposure (productivity losses alone have been estimated at between \$46 to \$76 billion per year.¹⁵⁸) Development partners or governments could also subsidize standalone facility construction or upgrades; however, this would be insufficient in the absence of other intervention, as safe recycling facilities also incur significantly higher *marginal* operating costs when compared to their lower-quality competitors.

155 O’Callaghan and Kennedy, *Mini Grids For Half A Billion People*.

156 Manhart and Adjei, *Lead-Acid Battery Recycling in Selected African Settings: Status Quo and Considerations for Sector Policies*.

157 Int. Dev. Assoc., “What Is IDA?”

158 Ericson and Brown, “Lead-Attributable Productivity Losses in Low- and Middle-Income Countries.”

Regulatory solutions offer a more cost-effective and sustainable path forward in the long run. Severe penalties for lead pollution, coupled with robust and consistent enforcement, can counteract and eventually outweigh the current economic incentives that favor unsafe recycling operations. There is no simple shortcut here, but instead a need for long-term investment in increasing governmental and citizen awareness of lead’s dangers; strengthening regulatory frameworks; and building and deploying enforcement capacity. Recent developments in Nigeria—in which the National Environmental Standards and Regulations Enforcement Agency raided and shut down 29 noncompliant industrial operations, including several battery recycling plants¹⁵⁹—offer an optimistic portrait about potential for regulatory action to address this challenge, though consistency and follow-through will be needed to fundamentally change the underlying economic incentives. Several other countries in sub-Saharan Africa have also signaled significant political will to tackle ULAB pollution, including Malawi (which included significant content on battery EoL management in its Mission 300 compact), and the dozen sub-Saharan African countries who have joined the Partnership for a Lead-Free Future.¹⁶⁰

In parallel, governments and development partners can take constructive steps to encourage a relative market shift to regulated systems—offering better long-term value for money to customers and reducing ULAB waste volumes. National governments can directly regulate the quality of off-grid solar systems available for domestic purchase, including quality controls on imports, though doing so requires substantial regulatory capacity. Subsidies for PAYG businesses and customers can also improve affordability of high-quality regulated products and help deepen their market penetration. In Rwanda, for example, government policies and donor investments—including quality standards for off-grid solar systems, credit lines for qualified off-grid solar providers, and consumer subsidies to purchase solar systems—have helped regulated products achieve a 95 percent-plus market share.¹⁶¹

Overall, our findings suggest that off-grid electrification is a highly significant of ULAB pollution in the sub-Saharan Africa context—with most associated ULAB use occurring in the unregulated off-grid solar market. While the World Bank and other development institutions deserve little direct blame for the problem, they have the opportunity to be part of the solution aligned with their own respective commitments to a Lead-Free Future.¹⁶² Through Mission 300, we urge the World Bank and other development partners to raise the salience of this issue with partner governments and thereafter support them to develop an effective regulatory framework for economically productive and lead-safe ULAB recycling.

159 Adejoro, “NESREA Seals 29 Facilities in S’West for Environmental Pollution.”

160 Partnership. Lead-Free Future, “Partners.”

161 “Rwanda.” *GOGLA*.

162 World Bank Group, “How the World Bank Is Addressing Lead Pollution.”

Appendix: Estimating ULAB volumes

To generate a rough estimate of total ULAB volumes; ULAB volumes associated with off-grid solar; and the share of off-grid solar-associated ULABs as a percent of all ULAB waste, we make the following assumptions:

1. Using estimates from GOGLA reported in the 2024 Off-Grid Solar Market Trends Report, we assume that the affiliated market (A) captures 30 percent of total off-grid solar sales and stock; the unaffiliated (U) sector, therefore, captures the remaining of 70 percent share of off-grid solar sales and stock.¹⁶³
2. We sum GOGLA sales data from 2019–2024 to estimate the total “stock” of affiliated off-grid solar units currently in use in sub-Saharan Africa. We assume that the GOGLA reported sales data captures the entirety of the affiliated (A) market in sub-Saharan Africa, and that all units sold during this period remain functional and in use.
3. There is limited evidence on the share of lead-acid batteries used in the unaffiliated market. The best indicative evidence is provided by market research from Kinally (2023), which found *exclusive* use of lead-acid batteries in the unaffiliated (U) sector. To be conservative, we assume a low but non-zero penetration of alternative battery chemistries in the unaffiliated sector, e.g. 95 percent market share for lead-acid batteries.¹⁶⁴ We also assume the market share of lead-acid batteries in the unaffiliated (U) sector is constant across off-grid solar systems of varying capacity (by Wp).
4. We conducted a portfolio review of all VeraSol quality-assured products; we found that only two (out of 193) VeraSol-qualified products use lead-acid batteries, with the remainder relying on alternative battery chemistries. GOGLA sales data for the affiliated (A) sector, provided on request, shows a three percent market share for lead-acid batteries in systems with <11Wp; zero percent market share in the 11Wp–49Wp segment; and two percent market share in the 50Wp+ market segment.¹⁶⁵ We assume these figures offer an accurate representation of lead-acid battery use in the formal sector.
5. GOGLA reports sales by capacity market segment, e.g. by Wp band. We assume the distribution of off-grid solar sales by capacity band is equivalent in both the affiliated (A) and unaffiliated (U) sectors.
6. We were unable to find reliable, up-to-date estimates of ULAB waste volumes associated with non-off-grid solar sources. Instead, we crudely update 2016 estimates by

¹⁶³ *Off-Grid Solar Market Trends Report 2024*.

¹⁶⁴ Market research from Kinally 2023, which is the best we have to go on suggest 100% of the unregulated market uses lead-acid batteries. As data and documentation is sparse, we reconcile this as 95%.

¹⁶⁵ Correspondence with GOGLA.

Tür et al. (2016)¹⁶⁶ estimates of ULAB waste volume in sub-Saharan Africa through 2025; we assume that vehicle and uninterruptible power supply use will have increased at a rate equivalent to annual economic growth (IMF).¹⁶⁷ See Part 3 for further details of the calculation.

Part 1: Calculating total volumes of off-grid solar products and usage of lead-acid batteries

PART 1. Calculating total lead-powered off-grid solar products (based on GOGLA sales data 2019–2024)

Capacity (Wp)	Sales (A)	Sales (U)	Total Sales	Lead Share (A)	Lead Share (U)	Lead Products (A)	Lead Products (U)	Total Lead
0–1.5	12,007,250	28,016,917	40,024,167	3%	95%	360,218	26,616,071	26,976,288
1.5 to 3	10,083,794	23,528,853	33,612,647	3%	95%	302,514	22,352,410	22,654,924
3 to 10	7,797,031	18,193,072	25,990,103	3%	95%	233,911	17,283,419	17,517,330
11 to 20	2,840,881	6,628,722	9,469,603	0%	95%	-	6,297,286	6,297,286
21 to 49	2,326,350	5,428,150	7,754,500	0%	95%	-	5,156,743	5,156,743
50 to 100	2,449,302	5,715,038	8,164,340	2%	95%	48,986	5,429,286	5,478,272
100 +	288,891	674,079	962,970	2%	95%	5,778	640,375	646,153
	37,793,499	88,184,831	125,978,330			951,406	83,775,589	84,726,996

We first use these assumptions to calculate total stock of off-grid solar systems in the affiliated and unaffiliated sectors (Table 1). We use GOGLA reported cumulative sales data (units sold) by capacity band for 2019 to 2024 (“Sales (A)”). We assume their reported sales data in each band comprise 30 percent of the full market for that band during the 2019–2024 period and therefore extrapolate the total market size (“Total Sales”) and share of sales in the unaffiliated market (“Sales (U)”) for the same period. We assume all sold units are still functional and in-service, yielding an estimated 37.8 million units in the affiliated sector and 88.2 million units in the unaffiliated sector, totaling 126 million off-grid solar units in use.

We next estimate total usage of lead-acid batteries within those 126 million units. For the affiliated sector (A), we use the share of lead-acid batteries from actual GOGLA reported sales data (“Lead share (A)”) to calculate the number of units using lead-acid batteries in each band (“Lead products (A)”)—summing to 951,000 across all capacity bands. For the unaffiliated sector (U), we assume 95 percent usage of lead-acid batteries in each capacity band (“Lead share (U)”), summing to 83.8 million off-grid solar units powered by lead-acid batteries. Summing the unaffiliated and affiliated volumes together yields an estimated 84.7 million off-grid solar units powered by lead-acid batteries.

166 Tür et al., *Generation of Used Lead-Acid Batteries in Africa—Estimating the Volumes*.

167 International Monetary Fund, “Real GDP Growth.”

Part 2: Estimating ULAB waste associated with off-grid solar

Next, we apply the Part 1 estimate to generate high- and low-end estimates of ULAB waste volume associated with off-grid solar. We bound our high- and low-end estimates based on two criteria: (1) size of lead-acid batteries; and (2) battery lifespan.

Size of Lead-Acid Batteries: Market research from Kinally (correspondence) suggests that there are two types of lead-acid batteries in use to power off-grid solar systems. Smaller systems may be powered by motorcycle batteries, weighing approximately 6 kilograms each. More typically, Kinally observed usage of full-size car batteries, weighing approximately 18.15 kilograms each. We use these two weights as the upper- and lower-bounds for our estimates; however, we note that the low-end estimate is unrealistically low given the widespread documented usage of full-size car batteries.

Battery Lifespan: Lead-acid battery lifespan can vary significantly due to intensity of usage, climactic conditions, and inappropriate usage, among other factors. In the sub-Saharan African context, estimates reported in the literature range between six months¹⁶⁸ and five years.¹⁶⁹ We use the intermediate ends of this range—one year and two years—to bound our high- and low-end estimates, respectively.

Applying these parameters, we calculate a low-end estimate of 254,000 ULAB tonnes per annum, and a high-end estimate of 1.54 million ULAB tonnes per annum.

PART 2. Calculating low- and high-end estimates

High end

Capacity Band (Wp)	Total Lead	Mass (Kg)	Tonnes	Year	ULAB t/a
TOTAL	84,726,996	18.15	1000	1	1,537,795

Low end

Capacity Band (Wp)	Total Lead	Mass (Kg)	Tonnes	Year	ULAB t/a
TOTAL	84,726,996	6	1000	2	254,181

Part 3: Calculating off-grid solar-associated ULAB waste as a proportion of all ULAB waste

To offer an order-of-magnitude contextualization of the off-grid solar share of overall ULAB waste, we provide a very rough estimate of overall volumes of ULAB waste from three other notable sources: automobiles, uninterruptible power supply (UPS) systems, and motorbikes. For automobiles and UPS systems, we update estimates from Tür et al. (2016).¹⁷⁰

168 Kinally et al., "Solar Home Systems in Malawi: Commercialisation, Use and Informal Waste Management."

169 Manhart et al., *End-of-Life Management of Batteries in the Off-Grid Solar Sector*.

170 Tür et al., *Generation of Used Lead-Acid Batteries in Africa—Estimating the Volumes*.

Vehicles: Using data from the International Organization of Motor Vehicles (IOMV), Tür et al. (2016) estimate total registered cars on the road in sub-Saharan Africa, and subsequently back out total ULAB waste volumes given rough assumptions about ULAB weight, lead content, and battery life. They estimate 1,060,996 tonnes per annum of ULAB waste generated in 2016. We update this figure by applying the real GDP growth rate as reported by the IMF¹⁷¹ for 2017–2025; this yields an estimated total of 1,398,798 tonnes per annum for 2025.

UPS: Tür et al. (2016) estimate UPS volumes based on market share data from the Industrial Technology Research Institute. We use the same method as above (e.g. application of IMF growth rates for 2017–2025) to update this figure, estimating 229,311 ULAB tonnes per annum in 2025.

Motos: We use data from the FIA Foundation, which reported 27 million motorbikes in use in sub-Saharan Africa for 2022.¹⁷² We note that this figure, as with vehicles above, is likely to be highly conservative, as it reports only *registered* motos and does not consider potential waste volumes from unregistered motorbikes. We assume a lead-acid battery in a motorbike weighs 6 kg and lasts two years. We apply the same method as above to update the 2022 figure to 2025, e.g. applying IMF growth rates for 2023–2025. We estimate 101,477 tonnes of ULABs were generated by motorbikes in 2025.

Calculating off-grid solar-associated ULAB waste as a proportion of all ULAB waste

	2017	2018	2019	2020	2021	2022	2023	2024	2025
SSA GDP growth rate	3.00%	3.30%	3.20%	-1.50%	4.70%	4.10%	3.60%	4.00%	3.80%
Motos (units)						27,000,000	27,972,000	29,090,880	30,196,333
Vehicle growth (ULAB t/a)	1,092,826	1,128,889	1,165,014	1,147,538	1,201,473	1,250,733	1,295,759	1,347,590	1,398,798
UPS growth (ULAB t/a)	179,152	185,064	190,986	188,121	196,963	205,038	212,420	220,917	229,311
Motos growth (ULAB t/a)						90,589	93,850	97,604	101,313

Together, these three sources total to 1.73 million tonnes of ULAB waste per annum. By adding our low- and high-end estimates of OGS-associated ULAB waste—254,000 and 1.54 million ULAB tonnes per annum, respectively—we calculate a total ULAB waste range between 1.98 million to 3.27 million tonnes per annum, of which OGS-associated ULAB waste accounts for a 13 to 47 percent share.

171 International Monetary Fund, "Real GDP Growth."

172 Bishop and Courtright, *Wheels of Change: Safe and Sustainable Motorcycles in Sub-Saharan Africa*.

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