METHODOLOGY – SUPPLEMENTARY INFORMATION

GS4GG PAA M400-13 SI

SDG 13

POWERING UNIVERSAL LIGHTING VIA SOLAR ENERGY (PULSE)

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SECTION 1: BASELINE KEROSENE CONSUMPTION AND SUPPRESSED DEMAND THRESHOLDS

EXECUTIVE SUMMARY

This assessment evaluates peer-reviewed literature and institutional reports to determine the scientific and economic validity of the proposed methodological parameters. The principal findings and recommendations for the methodology draft are as follows:

a. **Baseline Fuel Consumption:** Empirical evidence confirms that a kerosene burn rate of 0.03 Liters/hour and a utilization rate of 3.5 hours/day represent highly conservative, lower-bound averages for traditional wick and hurricane lamps. It is recommended that the methodology adopt these as standard defaults to minimize transaction costs while ensuring environmental integrity.
b. **Lumen Output and Tier 1 Minimum Service Level (MSL):** Literature indicates that standard kerosene lamps deliver significantly less than 200 lumen-hours/day. Adopting 200 lumen-hours/day as the baseline denominator for suppressed demand calculations is therefore mathematically conservative. Furthermore, the World Bank's Multi-Tier Framework (MTF) robustly justifies setting the project target MSL at 1,000 lumen-hours/day (Tier 1) to ensure basic human needs are met.
c. **The Service Level Ratio Cap (SLR_{cap}):** To prevent over-crediting high-capacity solar systems under the suppressed demand approach, an absolute cap shall be applied. Economic energy-burden data indicates that operating more than 5 kerosene lamps simultaneously would consume 20–30% of a low-income household's monthly income, representing an absolute affordability ceiling. Therefore, it is recommended that the methodology strictly cap the baseline service equivalence at 5.0 (i.e., a maximum of 5 baseline lamps).

1| BASELINE FUEL USE RATES AND UTILIZATION

1.1 | Context for Methodology Design

To calculate baseline emissions without requiring every project to conduct invasive, long-term fuel weighing surveys, the methodology requires a standard default for kerosene fuel consumption per lamp. The UNFCCC CDM methodology (AMS-III.AR) utilized a default of 0.03 L/hour and 3.5 hours/day. This review assesses whether these values remain accurate and conservative for the current methodology.

1.2 |Literature Findings on Fuel Consumption Rates

The fuel consumption of a kerosene lamp depends heavily on its design:

a. **Simple Wick Lamps:** The most ubiquitous and inefficient devices (simple wick lamps constructed from tin cans or glass jars) typically consume between 0.005 and 0.02 L/h, depending on wick thickness and fuel quality (Mills, 2005; Lam et al., 2012).

b. **Hurricane Lamps:** Glass-chimney hurricane lamps, which provide slightly better combustion and wind protection, consume between 0.02 and 0.045

Liters/hour, with some poorly maintained models reaching up to 0.06 L/h (Alstone et al., 2014; Apple et al., 2010).

A Conservative Aggregate: The 0.03 L/h value is adopted to maintain continuity with the established UNFCCC AMS-III.AR precedent and because it sits within — and toward the lower-to-mid part of — the empirically observed hurricane-lamp range (0.02–0.045 L/h).

1.3 | Literature Findings on Daily Utilisation

Observational studies and survey data from Sub-Saharan Africa and South Asia consistently report that primary household lighting is used for 3 to 4.5 hours per night, primarily clustered between 6:00 PM and 10:00 PM (Bhatia & Angelou, 2015). A utilization rate of 3.5 hours/day aligns perfectly with the lower-bound median of these empirical observations.

1.4 | Recommendation for Methodology

The legacy parameters of 0.03 L/hour and 3.5 hours/day yield a daily consumption of 0.105 Liters/lamp/day. Generating approximately 0.000252 tCO_2e per day (assuming an IPCC default EF of 2.4 $kgCO_2e/L$), this represents a conservative lower bound for baseline emissions. It is recommended that the PULSE methodology adopts these values into the baseline emission equations to ensure baseline emissions are systematically estimated conservatively.

2| LUMEN OUTPUT AND THE TIER 1 MINIMUM SERVICE LEVEL (MSL)

2.1 | Context for Methodology Design

Under the "Suppressed Demand" approach, the methodology shall translate the clean energy service provided by the project (e.g., a 250-lumen solar lamp) into the number of baseline devices (kerosene lamps) that would have been required to achieve the same service. This requires establishing two distinct values – which shall not be conflated:

- **The baseline-lamp service denominator (Lbaseline = 200 lm-hr/day):** the assumed service of a single baseline kerosene lamp, used as the denominator in the service-equivalence ratio.
- **The Tier 1 Minimum Service Level (MSL = 1,000 lm-hr/day):** the project eligibility threshold a device must verifiably meet to use the suppressed-demand baseline option.

2.2 | Photometric Output of Baseline Lighting

Kerosene combustion is notoriously inefficient at producing visible light. The luminous efficacy of a simple wick lamp is approximately 0.1 to 0.2 lumens per Watt of thermal energy (Mills, 2005). In practical terms, a standard wick lamp produces 8 to 15 lumens, and a hurricane lantern produces 30 to 45 lumens (Lam et al., 2012). Assuming a high-end hurricane lamp producing 40 lumens, operated for 3.5 hours, the daily service delivered is 140 lumen-hours. For a simple wick lamp producing 10 lumens, it is 35 lumen-hours. Because actual output is far below the 200 lm-hr/day

denominator, the resulting equivalence ratio is mathematically shrunk, ensuring the project is under-credited rather than over-credited.

2.3 |Defining the Minimum Service Level

Historically, energy access was defined as a binary "connected or not connected" to the grid. In 2015, the World Bank's Energy Sector Management Assistance Program (ESMAP) introduced the Multi-Tier Framework (MTF) to define access based on the *quality* and *quantity* of service. The MTF explicitly defines the absolute minimum threshold for basic human lighting needs (Tier 1)—allowing for basic evening study and domestic tasks safely—as 1,000 lumen-hours per day per household (Bhatia & Angelou, 2015).

2.4 |Recommendation for Methodology

Baseline Denominator: To ensure maximum conservativeness in the suppressed demand ratio, the methodology should establish the baseline service level ($L_{baseline}$) at 200 lumen-hours/day. Because actual kerosene lamps produce closer to 35–140 lumen-hours, using a denominator of 200 mathematically *shrinks* the resulting equivalence ratio, ensuring the project is under-credited rather than over-credited.

Tier 1 Threshold: The methodology should formally adopt the MTF Tier 1 metric (1,000 lumen-hours/day) as the Minimum Service Level (MSL). Solar devices that cannot verifiably meet this threshold through independent testing should be barred from utilizing the Suppressed Demand baseline option.

3| EXPENDITURE CAP (SLR_{cap})

3.1 |Risk of Unbounded Suppressed Demand

A mathematical vulnerability in suppressed demand accounting is the risk of unbounded ratios. For example, if a developer distributes a large 5,000 lumen-hour/day Solar Home System, divided by the 200 lumen-hour baseline yields a ratio of 25. Claiming that a low-income household would have realistically purchased and burned fuel for 25 kerosene lamps simultaneously is economically absurd and violates environmental integrity. An absolute cap on the Service Level Ratio (SLR_{cap}) shall be established based on the economic realities of Tier 0 households.

3.2 |Expenditure Ceiling

To establish a rigorous cap, the economic limits of the "Business-as-Usual" scenario for Tier 0 households should be established.

a. Studies indicate that off-grid households in Sub-Saharan Africa and rural Asia typically spend between 3% and 10% of their monthly income on lighting fuels and dry-cell batteries (Grimm et al., 2020).

b. At the established burn rate of 0.03 L/h and 3.5 h/day, a single kerosene lamp consumes approximately 3.15 Liters of kerosene per month.

c. Operating 5 kerosene lamps would require approximately 15.75 Liters of kerosene per month. At typical rural kerosene prices ($1.00 - $1.50/Liter), this equates to roughly $15 to $23 per month.

d. Energy economics dictate an "energy burden" ceiling. When energy costs exceed 15-20% of income, households curtail use or exist in darkness rather than continuing to purchase fuel.

4| Recommendation for Methodology

A strict cap is mathematically and economically necessary to preserve the environmental integrity. Allowing an uncapped Suppressed Demand multiplier carry a risk of over-estimation of carbon credits.

It is strictly recommended that the methodology formally institutes a Service Level Ratio Cap (SLR_{cap}) of 5.0. Regardless of how powerful a distributed solar system is, the baseline emissions attributed to a single household premise shall never exceed the equivalent emissions of 5 baseline kerosene lamps. This allows suppressed-demand alleviation up to the Tier 1 boundary while introducing a rigorous safeguard against over-crediting.

5| ANNOTATED BIBLIOGRAPHY

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Mills, E. (2005). The specter of fuel-based lighting. Science, 308(5726), 1263-1264. https://www.researchgate.net/publication/7821814_The_Specter_of_Fuel-Based_Lighting

SECTION 2: ASSESSMENT OF EMBODIED EMISSIONS FOR PICO-SOLAR AND SOLAR HOME SYSTEMS

EXECUTIVE SUMMARY

This assessment was executed to ensure the methodology's strict compliance with the GS4GG Methodology Standard: Requirements for Addressing Leakage in Methodologies (PAA MS400-05), which mandates the systematic quantification and deduction of indirect upstream greenhouse gas (GHG) emissions for material-intensive project inputs.

To avoid the prohibitive transaction costs of requiring every micro- and small-scale project developer to commission bespoke, ISO-compliant Life Cycle Assessments (LCAs) for every product model distributed, the standard permits the use of "conservative, sector-specific default deductions."

This pre-implementation review synthesizes peer-reviewed LCA literature and Environmental Product Declarations (EPDs) from 2014 to 2024 to evaluate the cradle-to-gate emissions of Pico-solar lanterns and Solar Home Systems (SHS). The objective was to determine default factors that are scientifically valid and conservative.

The principal findings and recommendations for the methodology draft are as follows:

1. **Pico-Solar Lanterns (<10 Wp):** Peer-reviewed LCAs indicate that the cradle-to-gate footprint of standard Pico-solar devices ranges from 2.6 to 4.8 kg CO_2e. The proposed methodology default of 5.0 kg CO_2e per Pico-solar unit represents a robust, conservative upper-bound suitable for mandatory deduction.
2. **Solar Home Systems (10–30 Wp):** verified SSA-specific LCAs support a flat default of 20.0 kg CO2e/unit as conservative for entry-level Tier 1 systems up to 30 Wp.
3. **Larger systems (>30 Wp):** because embodied emissions scale with PV wattage and battery mass, the 20 kg default is capped at 30 Wp. Larger systems apply a transparent capacity-based build-up or submit a model-specific EPD.

Capacity Cap Recommendation: Because SHS embodied emissions scale linearly with photovoltaic (PV) wattage and battery mass, the 20 kg CO_2e default shall be strictly capped for systems up to **30 Wp**. To prevent the under-accounting of leakage, the methodology shall require systems larger than 30 Wp to apply a scalable capacity-based penalty (e.g., 1.5 kg CO_2e per Wp) or submit specific EPDs.

1| CRADLE-TO-GATE EMISSIONS

1.1 |Cradle-to-Gate Boundary

To align with GS4GG PAA MS400-05, the analytical boundary for this assessment is restricted to "cradle-to-gate." In ISO 14040/14044 terms, this encompasses all emissions from raw material extraction (e.g., mining of lithium, cobalt, bauxite, and silica), refinement, component manufacturing (PV cell fabrication, battery synthesis,

injection moulding), final assembly, and primary packaging prior to distribution. Use-phase emissions are zero (solar charging), and End-of-Life (EoL) impacts are addressed operationally via the methodology's mandatory Waste Management Plan safeguard.

1.2 |Pico-Solar Lanterns (Integrated PV < 10 Wp)

Pico-solar products are highly integrated, portable units designed to meet basic Tier 1 lighting needs. They generally consist of a small polycrystalline or amorphous silicon PV panel (1 Wp to 8 Wp), a compact energy storage unit (1,000 mAh to 4,000 mAh), a printed circuit board (PCB), LED diodes, and a polycarbonate or ABS plastic housing.

The carbon footprint of these devices is remarkably low and consistent across studies. Early foundational LCAs by Alstone et al. (2014) established a baseline of approximately 2.6 to 4.2 kg CO_2e for single-light lanterns. with larger multi-light pico systems at upper end of the pico range. Despite the embodied emissions, the energy payback time for Pico-solar displacing kerosene is achieved within 20 to 40 days of operation (Alstone et al., 2014).

1.3 |Solar Home Systems (SHS) (Separate PV ≥ 10 Wp)

Solar Home Systems provide decentralized, multi-room lighting and appliance charging (Tier 1 to Tier 2 access). They feature a separate roof-mounted PV panel (10 Wp to 50+ Wp), a heavier central battery/charge controller unit, extensive copper cabling, and multiple DC appliances. The embodied carbon scales significantly with these systems. The inclusion of aluminium framing for the PV module and the sheer mass of the battery are the primary drivers.

a. Studies evaluating standard 10 Wp to 15 Wp SHS report cradle-to-gate emissions around 12.4 to 16.5 kg CO_2e (Antonanzas-Torres et al., 2021; Kinally et al., 2024).
b. 20 Wp to 30 Wp Tier 1 standard: emissions range from 18.5 kg CO_2e to 23.1 kg CO_2e (Bensch et al., 2017; Badza et al., 2024).
c. For larger systems (**≥30 Wp**) values are derived through the component build-up in Section 3.0 rather than cited to a single source.

2| IDENTIFICATION OF EMISSION HOTSPOTS

2.1 |Photovoltaic (PV) Modules

Across all LCAs reviewed, the PV panel accounts for 30% to 50% of the total cradle-to-gate emissions. The primary driver is the electricity-intensive Czochralski process used to pull monocrystalline silicon ingots. Because the vast majority of off-grid solar panels are manufactured in Asian hubs with high grid carbon intensities, the upstream Scope 3 emissions remain substantial (approximately 1.0 to 1.5 kg CO_2e per Watt-peak). Furthermore, for SHS (≥10 Wp), the anodized aluminium frame used to protect the PV glass adds a massive emissions penalty, as aluminum smelting is incredibly carbon-intensive.

Per-Wp module factor — conservative envelope: for the purpose of the component build-up, a deliberately conservative envelope of up to ~1.0–1.5 kg CO2e

per Wp may be applied. This is higher than the central estimate in current module-level LCA literature (modern modules cluster nearer 0.4–0.6 kg CO2e/Wp). Because the figure is used to compute a leakage deduction, an overstatement is conservative: it increases the deduction and reduces the risk of over-crediting. The factor is therefore presented as a conservative envelope, not a literature central estimate.

2.2 |Battery Chemistries: Lead-Acid vs. Lithium-Ion (LFP/NMC)

Batteries account for **25% to 40%** of the cradle-to-gate footprint, varying wildly by chemistry:

a. Lead-Acid (SLA): Historically the standard for SHS, SLA batteries have a relatively low embodied carbon footprint per kilogram of mass. However, their poor energy density requires a massive, heavy battery to provide sufficient storage. Furthermore, their field lifespan is notoriously short (1-2 years under deep discharge), requiring constant replacements that compound their lifecycle emissions (Kinally et al., 2024).

b. Lithium-Ion (NMC) and LFP: Modern off-grid lighting has aggressively shifted to Lithium Iron Phosphate (LFP). The cradle-to-gate manufacturing of lithium batteries is highly energy-intensive (ranging from 100 to 150 kg CO_2e per kWh of capacity) due to active material synthesis and refining (Peters et al., 2017).

c. Net Impact: While Lithium-ion batteries have a higher carbon footprint per kg, their lightweight nature means the per system manufacturing carbon footprint is comparable to legacy Lead-Acid systems. Crucially, their superior cycle life (3 to 5 years) means this emissions cost is incurred only once during a typical 5-year crediting period.

2.3 |Balance of System (BoS)

Printed Circuit Boards (PCBs) and copper cabling account for 10% to 15% of emissions, largely due to the mining and refining of copper, gold, and tin. Plastic casings (polycarbonate/ABS) constitute a minimal fraction of the total GHG footprint (<5%), despite being the most visible physical component of the device.

3| METHODOLOGY DEFAULTS AND THE LARGE-SYSTEM BUILD-UP

3.1 |Pico-Solar Default (5 kg CO_2e)

The literature indicates the true average for modern pico-solar units is between 2.6 and 4.2 kgCO2e, with extreme multi-light edge cases reaching 4.8 kgCO2e. The 5.0 kg CO2e default is scientifically robust. It provides a comfortable margin of error that satisfies the GS4GG requirement for a "conservative upper-bound" deduction, ensuring that projects will not over-credit regardless of their specific manufacturing supply chain.

3.2 | SHS Default (20 kg CO_2e) and the Scalability Gap (20.0 kg CO2e, capped at 30 Wp)

A flat 20 kg CO_2e default is conservative for standard 10–30 Wp systems (verified values 12.4 to 23.1 kg CO2e). It is, however, insufficiently conservative for larger systems, because embodied emissions scale with PV wattage and battery mass. The flat default is therefore capped at 30 Wp.

3.3 | Large-SHS safeguard (>30 Wp) — transparent build-up

For systems exceeding 30 Wp, the default may not be used. The developer shall either (a) submit an ISO 14025-compliant Environmental Product Declaration or verified model-specific LCA, or (b) apply the following auditable component build-up, each term traceable to a verifiable factor:

EE(total) = EE(PV) + EE(battery) + EE(BoS)

EE(PV) = rated PV capacity (Wp) × conservative per-Wp module factor (≤1.5 kg CO2e/Wp).

EE(battery) = battery capacity (kWh) × per-kWh factor (100–150 kg CO2e/kWh, Peters et al., 2017).

EE(BoS) = a balance-of-system allowance for cabling, charge controller and housing (10–15% of EE(PV) + EE(battery)).

Stating the build-up explicitly makes the deduction auditable by the VVB, removes reliance on unverifiable single-point citations for systems at and above 30 Wp.

4| Recommendations

To balance simplicity with rigorous environmental accounting, the methodology shall adopt a capacity-capped default system. It is formally recommended that the methodology incorporates the following normative requirements in the Embodied Emissions Leakage section:

Mandatory Application: The deduction of embodied emissions shall be a non-negotiable requirement for all *new* Project Devices distributed.

Adoption of Tiered Defaults:

a. **Pico-Solar** (<10 Wp): Mandatory default deduction of 5.0 kgCO_2e / unit.

b. **Small SHS** (10 Wp to ≤ 30 Wp): Mandatory default deduction of 20.0 kgCO_2e / unit.

The Large SHS Safeguard (>30 Wp): The 20 kg default cannot be used for systems exceeding 30 Wp. Activity developers deploying large systems shall either:

- Apply a conservative scalable factor: 20.0 kgCO_2e + [1.5 kgCO_2e × (System Wp - 30 Wp)]; OR
- Submit an ISO 14025 compliant Environmental Product Declaration (EPD) or verified LCA specific to their model to override the default.

5| SUMMARY DATA TABLE OF LCA FINDINGS

The following table synthesizes specific cradle-to-gate (embodied) GHG emissions values extracted from peer-reviewed LCAs and institutional reports for off-grid lighting products.

Table 1. Cradle-to-Gate Emissions of Off-Grid Solar Lighting Devices

Source / Study	Device Category	System Specifications (PV Wp, Battery)	LCA Boundary	Calculated Cradle-to-Gate Emissions (kg CO_2e)
Alstone et al. (2014)	Pico-Solar	1.5 Wp PV, 1000 mAh Li-ion	Cradle-to-Gate	2.6
Alstone et al. (2014)	Pico-Solar	3.0 Wp PV, 2500 mAh Li-ion	Cradle-to-Gate	4.2
Pico (multi-light) range	Pico-Solar	5-8 Wp Central gub	Cradle-to-Gate	≤4.8
Antonanzas-Torres (2021)	Small SHS	10.0 Wp PV, Lead-Acid	Cradle-to-Gate	12.4
Kinally et al. (2024)	Small SHS	~15.0 Wp SHS	Cradle-to-Gate	~16.5
Bensch et al. (2017)	Standard SHS	20.0 Wp, Lead-Acid	Cradle-to-Gate	18.5
Badza et al. (2024)	Standard SHS	Stand-alone PV+Storage	Cradle-to-Gate	~23.1
Section 3.0 build up	Large SHS	50.0 Wp	Derived	derive
Section 3.0 build up	Large SHS (Tier 2/3)	>50.0 Wp	Derived	derive

5.1 |ANNOTATED BIBLIOGRAPHY

Alstone, P., Lai, P., Mills, E., & Jacobson, A. (2014). High Life Cycle Efficacy Explains Fast Energy Payback for Improved Off-Grid Lighting Products. *Journal of Industrial Ecology*, 18(5), 722–733. https://doi.org/10.1111/jiec.12117

Contribution: A foundational text in the LCA of off-grid solar. The authors utilized empirical teardowns of pico-solar lanterns to conduct detailed life-cycle material inventories. The study concludes that the energy payback time for pico-solar displacing kerosene is incredibly short (measured in weeks or months). This study provides the robust baseline proof that while embodied emissions must be accounted for (as per PAA

rules), they are small enough for Pico-solar that a 5.0 kg CO_2e default represents a safe, highly conservative upper limit.

Antonanzas-Torres, F., Antonanzas, J., & Blanco-Fernandez, J. (2021). Environmental impact of solar home systems in Sub-Saharan Africa. Sustainability, 13(17), 9708. https://doi.org/10.3390/su13179708

Contribution: Rigorous LCA of SHS deployed in Sub-Saharan Africa; identifies PV-module manufacturing and copper wiring as hotspots and reports ~12.4 kg CO2e for a 10 Wp system, anchoring the lower bound of the SHS category..

Antonanzas-Torres, F., Antonanzas, J., & Blanco-Fernandez, J. (2021). Environmental life cycle impact of off-grid rural electrification with mini grids in West Africa. Sustainable Energy Technologies and Assessments, 47, 101471. https://doi.org/10.1016/j.seta.2021.101471

Contribution: Companion West-Africa study providing component-level off-grid PV inventories and SSA manufacturing and transport assumptions used in the build-up.

Badza, K., Sawadogo, M., & Soro, Y. M. (2024). Environmental impacts of a stand-alone photovoltaic system in sub-Saharan Africa: a case study in Burkina Faso. Heliyon, 10(19), e38954. https://doi.org/10.1016/j.heliyon.2024.e38954

Contribution: SSA stand-alone PV-with-storage LCA (ISO 14040/44) comparing lead-acid and lithium-ion chemistries and end-of-life options; supports the 20–30 Wp standard-SHS range and battery-chemistry sensitivity.

Bensch, G., Peters, J., & Sievert, M. (2017). The lighting transition in Africa - from kerosene to LEDs and the emerging disposal problem. Energy for Sustainable Development, 39, 13-20. https://doi.org/10.1016/j.esd.2017.03.004

Contribution: Documents the kerosene-to-LED transition and the emerging disposal problem; corroborates the ~18–20 kg CO2e footprint of legacy 20 Wp lead-acid systems, validating the 20 kg default for small SHS.

Kinally, C., Antonanzas-Torres, F., Podd, F., & Gallego-Schmid, A. (2024). Life cycle assessment of solar home system informal waste management practices in Malawi. Applied Energy, 364, 123135. https://doi.org/10.1016/j.apenergy.2024.123135

Contribution: Recent SSA LCA showing that short-lived lead-acid batteries can drive lifecycle emissions above those of diesel generators, justifying both the battery-defined technical life and the mandatory Waste Management Plan.

Peters, J. F., Baumann, M., Zimmermann, B., Braun, J., & Weil, M. (2017). The environmental impact of Li-Ion batteries and the role of key parameters - a review. Renewable and Sustainable Energy Reviews, 67, 491-506. https://doi.org/10.1016/j.rser.2016.08.039

Contribution: Detailed review establishing the 100–150 kg CO2e/kWh embodied-carbon range for Li-ion batteries, providing the per-kWh factor for the large-system component build-up.

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SECTION 3: ASSESSMENT OF MARKET LEAKAGE, "LIGHTING STACKING," AND BASELINE EQUIPMENT TRANSFER

EXECUTIVE SUMMARY

Under the *GS4GG Methodology Standard: Requirements for Addressing Leakage in Methodologies (PAA MS400-05)*, methodologies shall rigorously account for the risk that displaced baseline equipment (e.g., kerosene lanterns) might continue to be used within the household (a phenomenon known as "stacking") or transferred to non-project households ("baseline equipment transfer"), thereby negating a portion of the claimed emission reductions.

To address this, the methodology introduces a strict requirement: project developers must either physically scrap and destroy the baseline lamps (yielding 0% leakage) or accept a mandatory default deduction. This assessment reviews Randomized Controlled Trials (RCTs) and longitudinal field studies to assessment represents an empirically justifiable, conservative deductions. The principal findings and recommendations for the methodology draft are as follows:

1. **"Lighting Stacking" is Minimal but Present:** Unlike "stove stacking" in clean cooking (where traditional stoves are often retained indefinitely for specific culinary tasks or cultural preferences), "lighting stacking" is far less prevalent. Solar lighting acts as a near-perfect substitute for kerosene. RCTs consistently demonstrate that the introduction of a quality solar product reduces household kerosene consumption by 85% to 95% almost immediately. The residual 5% to 15% of use is typically reserved for backup during heavy monsoon seasons, secondary rooms, or for mobile outdoor use.
2. **Baseline Equipment Transfer Risk is Functionally Negligible:** The primary baseline devices (simple tin-can wick lamps) possess near-zero economic resale value. Field observations confirm they are rarely "sold" to neighbours. When hurricane lanterns are given away, they typically displace other highly inefficient biomass/kerosene combustion rather than displacing less GHG-intensive technologies, thereby neutralizing the net-atmospheric leakage risk.
3. **Validation of the 5% Default Deduction:** Given that empirical data shows solar adoption achieves an average ~90% displacement of fossil fuel lighting, applying a flat **5% deduction** to the total Crediting Baseline Emissions (when physical scrapping is not verified) provides a robust, scientifically backed conservative buffer. It safely accounts for both residual stacking and any marginal equipment transfer, avoiding the prohibitive transaction costs of collecting valueless tin lamps in remote areas.

1| BEHAVIOURAL ECONOMICS OF "LIGHTING STACKING"

1.1 | The Concept of Stacking in Energy Transitions

In development and energy economics, the traditional "Energy Ladder" model posited that as households gain income or access to modern energy, they completely and

linearly abandon traditional, inferior fuels. However, modern behavioural economics has largely replaced this with the "Energy Stacking" (or multiple fuel) model, wherein new technologies do not immediately displace old ones; rather, they are added to a household's portfolio to maximize energy security, flexibility, and economic utility.

In carbon accounting, stacking represents a major risk: if a household acquires a solar lamp but continues to burn kerosene at 50% of its historical rate, the actual emission reduction is halved, and crediting 100% of the baseline would violate environmental integrity.

2| Divergence Between Cooking and Lighting Behaviours

A critical finding in the literature is that the behavioural dynamics of cooking and lighting transitions are fundamentally different:

a. **Cooking (High Stacking):** Cooking is deeply tied to cultural practices, taste profiles, and the physical shape of local cookware. Improved cookstoves often fail to meet all user needs (e.g., space heating, roasting specific foods), leading to high rates of stacking.

b. **Lighting (High Substitution):** Lighting is a highly fungible utility; "a lumen is a lumen." However, solar LEDs produce significantly more lumens, emit no noxious smoke (eliminating respiratory and eye irritation), present no fire hazard, and cost nothing to operate after the initial capital purchase. Consequently, RCTs demonstrate that households exhibit a profound preference for solar lighting over kerosene, treating it as an absolute "superior good."

3| Empirical Evidence on Kerosene Displacement

Extensive field studies and RCTs conducted over the past decade in Sub-Saharan Africa and South Asia demonstrate that lighting substitution is highly efficient, approaching near-perfect displacement:

a. Near-Complete Substitution: An RCT in rural Rwanda (Grimm et al., 2020) found that the introduction of simple Pico-solar kits led to a near-immediate cessation of kerosene use, reducing weekly lighting expenditures by over 80%. A field experiment in India (Aklin et al., 2017) tracking 1,400 households found kerosene use for lighting dropped by over 80% following solar access.
b. The Economic Imperative: The primary driver of this rapid substitution is the elimination of recurring fuel costs. For households in extreme poverty (Tier 0), spending up to 10% of their income on kerosene is a crippling burden. The behavioural drive to maximize the economic return on the solar investment leads to the rapid abandonment of kerosene purchases.
c. Residual Use Cases (The Rebound): When stacking does occur, studies indicate it is driven by technological constraints rather than preference:
    i. **Capacity Limits:** A 1-bulb solar lamp cannot illuminate a 3-room household simultaneously. If the household cannot afford a multi-light

Solar Home System (SHS), they may retain a kerosene wick for secondary rooms (Rom et al., 2017, Lay et al., 2013).

ii. **Weather Reliance:** During prolonged rainy seasons where solar charging is sub-optimal, households may keep a kerosene lamp as an emergency backup.

iii. **Mobility:** If the solar system is fixed (SHS), households may retain a cheap battery torch or hurricane lamp for walking outside at night.

The empirical literature proves that "lighting stacking" is predominantly a symptom of capacity constraints rather than behavioural preference. By capping the Suppressed Demand claims (via the SLRcap) and applying a dedicated leakage penalty, the methodology can safely internalize this limited stacking effect without requiring highly invasive, continuous fuel-weighing surveys.

4| BASELINE EQUIPMENT TRANSFER (MARKET LEAKAGE)

4.1 |The GS4GG Definition of Equipment Transfer Leakage

According to GS4GG PAA MS400-05 (Section 6.2.2), "Baseline Equipment Transfer" occurs when functional baseline equipment is displaced by the project, retains economic value, and is transferred to another user outside the project boundary to displace a process with lower GHG intensity (or simply prolongs fossil fuel use that would have otherwise ceased).

For off-grid lighting, the scenario involves a household receiving a Solar Home System and subsequently selling or giving their old kerosene hurricane or wick lamp to a neighbour.

4.2 |Economic Value and Transferability of Baseline Lamps

To assess this risk, the economic nature of the baseline equipment must be understood:

a. Simple Wick Lamps (Tin Cans/Jars): These constitute the vast majority of baseline lighting in Tier 0 households. They are typically constructed informally from discarded tomato paste cans or glass bottles. They have zero residual market value. Literature on transition behaviour notes that these devices are almost universally discarded, crushed, or left to rust when solar is adopted (Bensch et al., 2017). They are not "transferred" because anyone who needs one can build one for free.
b. Hurricane Lanterns (Glass/Metal): These have marginal residual capital value (typically $2 to $5 new). However, field studies show that rather than selling them, risk-averse households tend to clean them and put them in long-term storage as a contingency asset in the event of solar battery failure, rarely fuelling them.(Lay et al., 2013)
c. The Fuel Constraint on Leakage: The true constraint on lighting access in Tier 0 communities is the high recurring cost of kerosene fuel, not the cost of the lamp. Transferring a free, used wick lamp to a neighbour does not meaningfully increase that neighbour’s fuel consumption, as their

consumption is rigidly constrained by their low income. Transferring the physical hardware does not induce them to burn more kerosene than they already were.

Methodological Implication: Unlike transferring a functioning diesel generator or a high-value industrial asset, transferring a rudimentary kerosene lamp does not mathematically generate significant *new* additive emissions. The theoretical market leakage is functionally close to 0%.

5| DEFAULT DEDUCTION

5.1 |Regulatory Context and the Scrapping Challenge

Despite the economic evidence that market leakage from kerosene lamp transfer is negligible, carbon standard governance requires conservative safeguards. Under Paris Agreement Alignment, methodologies cannot simply waive leakage without robust, verifiable evidence.

The methodology may propose a two-tiered approach to Market Leakage ($LE_{market,y}$):

a. Avoidance (0% Deduction): Implement a verifiable "Take-Back and Scrapping" program (collecting and destroying old lamps).
b. Quantification (5% Deduction): Accept a mandatory 5% default deduction from the total Crediting Baseline Emissions if scrapping cannot be verified.

5.2 |Justification of Conservativeness

Given the extreme logistical difficulties and high transaction costs of collecting zero-value tin cans from highly dispersed, off-grid rural households, the 5% default deduction pathway will be the standard for the vast majority of developers. We must ensure this penalty is scientifically conservative.

a. As established above, empirical field data shows that solar adoption reduces kerosene consumption by 85% to 95%. This means the *maximum possible uncaptured emissions* (due to stacking or transfer) range from 5% to 15%.

b. However, the methodology calculates the baseline using conservative lower-bound fuel use defaults (0.03 L/h at 3.5 hours/day) and tightly caps Suppressed Demand (via the $SLRcap$). Furthermore, the methodology inherently applies an annual Downward Adjustment Factor (DAF).

c. Applying an *additional* 5% flat deduction to the final baseline emission calculation provides a robust safety net. Consider a project distributing 10,000 Pico-solar lanterns. A 5% penalty assumes that the equivalent of 500 households *completely* maintained their historical kerosene consumption at full baseline levels—a scenario that is behaviourally impossible given the economic imperative to eliminate fuel spending.

d. Mandating physical collection and destruction of zero-value tin-can lamps imposes massive logistical costs on small-scale project developers for negligible environmental gain. The 5% deduction provides a scientifically sound, conservative alternative that protects the integrity of the carbon

ledger while maintaining the financial viability of rural electrification projects.

6| Recommendation for Methodology

The **5% Default Market Leakage Deduction** ($LEmarket = BEy \times 0.05$) is empirically robust, highly conservative, and behaviourally sound. It is formally recommended that this provision be permanently integrated into the PULSE methodology. It successfully addresses the leakage for projects that do not implement physical scrapping while acknowledging the real-world near-complete substitution rates of solar lighting.

7| ANNOTATED BIBLIOGRAPHY

Aklin, M., Bayer, P., Harish, S. P., & Urpelainen, J. (2017). Does basic energy access generate socioeconomic benefits? A field experiment with off-grid solar power in India. *Science Advances*, 3(5), e1602153.
DOI: 10.1126/sciadv.1602153

Contribution: A rigorous Randomized Controlled Trial (RCT) involving 1,400 off-grid households in Uttar Pradesh, India, evaluating the impact of providing solar micro-grids and standalone solar lighting. The study meticulously tracked household fuel expenditures. It empirically demonstrated that while total household energy spending decreased significantly, kerosene use dropped dramatically (by over 80%), virtually eliminating kerosene for lighting, though some minimal fuel was retained for other household uses. This supports the conclusion that lighting stacking is minimal and well-contained by a 5% leakage margin.

Bensch, G., Peters, J., & Sievert, M. (2017). The lighting transition in Africa—From kerosene to LEDs and the emerging disposal problem. *Energy for Sustainable Development*, 39, 13-20.

https://doi.org/10.1016/j.esd.2017.03.004

Contribution: This study relies on extensive cross-sectional survey data from multiple Sub-Saharan African countries to track the transition from fuel-based to LED lighting. Crucially for this assessment, the authors investigate the fate of legacy lighting equipment. They confirm that rudimentary wick lamps are overwhelmingly discarded as trash or kept in un-fuelled storage rather than resold, providing direct empirical evidence that the "Baseline Equipment Transfer" leakage risk is functionally negligible in off-grid contexts.

Grimm, M., Munyehirwe, A., Peters, J., & Sievert, M. (2020). A first step up the energy ladder? Low cost solar kits and household's welfare in rural Rwanda. *The World Bank Economic Review*, 34(3), 631-649.

Contribution: This RCT analysed the rollout of Pico-solar kits to Tier 0 households in Rwanda. It provides high-resolution data on fuel substitution. The study found a near-100% displacement of kerosene and dry-cell battery use for lighting among households receiving the kits. The authors noted that lighting is an "all-or-nothing" substitution preference for these households, heavily validating the methodology's assumption that stacking is not a material driver of over-crediting, thus making a 5% penalty a safe, conservative upper bound.

Harrison, K., Scott, A., & Adams, C. (2020). *The Economic and Social Impacts of Off-Grid Solar*. GOGLA (Global Off-Grid Lighting Association). https://www.gogla.org/wp-content/uploads/2024/12/gogla_sales-and-impact-reporth1-2021_07.pdf

Contribution: While an industry report, this represents one of the largest aggregated field datasets available, covering surveys of tens of thousands of solar adopters across East Africa, West Africa, and South Asia. The data shows that while 70-80% of households report completely stopping the use of kerosene and candles, 20-30% engage in some degree of stacking (using both).

Lay, J., Ondraczek, J., & Stoever, J. (2013). Renewables in the energy transition: Evidence on solar home systems and lighting fuel choice in Kenya. *Energy Economics*, 40, 350-359. https://doi.org/10.1016/j.eneco.2013.07.024

Contribution: This study investigates fuel choices among households adopting Solar Home Systems (SHS) in Kenya. It specifically explores the dynamics of "energy stacking." The findings show that while households may physically retain hurricane lamps, they shift their function from "daily primary use" to "rare emergency backup" (e.g., during multi-day storms). This confirms that physical retention of baseline equipment does not equate to continued baseline emission levels, further validating that the 5% leakage deduction over-compensates for actual use.

Masera, O. R., Saatkamp, B. D., & Kammen, D. M. (2000). From linear fuel switching to multiple cooking strategies: A critique and alternative to the energy ladder model. *World Development*, 28(12), 2083-2103.

https://doi.org/10.1016/S0305-750X(00)00076-0

Contribution: The foundational behavioural economics paper that introduced the "Energy Stacking" model. While originally focused on cooking fuels, its theoretical framework is universally applied to off-grid lighting transitions. It provides the theoretical justification for why carbon standard setters must anticipate stacking behaviour and build quantitative deductions (like the 5% market leakage factor) into methodologies to maintain environmental integrity.

Obeng, G. Y., & Evers, H. D. (2010). Impacts of public solar PV electrification on rural micro-enterprises: A case study of Ghana. *Energy for Sustainable Development*, 14(3), 223-231.

https://doi.org/10.1016/j.esd.2010.07.005

Contribution: While focusing on micro-enterprises, this field study highlights the economic drivers of the lighting transition. It shows that commercial users abandon kerosene completely as soon as solar is available, driven entirely by the desire to eliminate the daily operational expenditure of fossil fuels to increase profit margins. This demonstrates that economic forces naturally prevent "lighting stacking" in commercial premises, rendering market leakage negligible in these contexts.

Rom, A., Günther, I., & Harrison, K. (2017). *The Economic Impact of Solar Lighting: Results from a randomised field experiment in rural Kenya*. ETH Zurich & GOGLA.

https://ethz.ch/content/dam/ethz/special-interest/gess/nadel-dam/documents/research/Solar%20Lighting/17.02.24_ETH%20report%20on%20economic%20impact%20of%20solar_summary_FINAL.pdf

Contribution: This field experiment explored both the economic impacts and the behavioural changes associated with off-grid solar. It documents the marginalization of the baseline lamp, noting that households retain them primarily for rare battery-depletion events or specific outdoor chores where a fixed SHS bulb cannot reach. It provides the behavioural context proving that retained baseline equipment does not operate at the baseline 3.5 hours/day, making a 5% leakage deduction more than sufficient to cover residual emissions.

SECTION 4: ASSESSMENT OF ASSET LIFESPANS, E-WASTE TOXICITY, AND ENVIRONMENTAL LOCK-IN RISK

EXECUTIVE SUMMARY

Under the GS4GG, mitigation activities must undergo a "Lock-In Risk" assessment to ensure they do not entrench carbon-intensive practices or cause severe environmental degradation that contradicts the "Do No Significant Harm" (DNSH) principle. While solar lighting is a zero-emission technology at the point of use (safely passing the GHG lock-in test), the rapid proliferation of decentralized, battery-powered devices across the Global South presents a massive, looming electronic waste (e-waste) crisis.

To prevent carbon finance from inadvertently subsidizing environmental contamination, the methodology requires strict operational guardrails. This pre-implementation assessment evaluates technical literature on battery durability and e-waste toxicity to establish defensible rules for crediting limits and environmental safeguards.

The principal findings and recommendations for the methodology draft are as follows:

a. The "Technical Life" : While Light Emitting Diodes (LEDs) boast lifespans of 50,000 hours (10+ years), the actual field lifespan of a solar lighting device is entirely dictated by its chemical battery. Field data shows off-grid batteries fail within 1 to 5 years depending on chemistry (Lead-Acid vs. Lithium-based). The methodology shall strictly limit the crediting period based on the Battery Cycle Life, explicitly prohibiting the use of LED lifespans to claim 10-year emission reductions for 3-year devices.
b. E-Waste Toxicity and the "Negative List": Improper disposal of off-grid solar batteries leads to severe heavy metal leaching (Lead, Cadmium) and toxic electrolyte contamination in soil and groundwater. The methodology shall establish a "Negative List" of prohibited battery chemistries (e.g., Nickel-Cadmium) to prevent the distribution of highly toxic, difficult-to-recycle materials.
c. Mandatory Waste Management Safeguard: The distribution of millions of solar lanterns without reverse logistics locks rural regions into an environmental toxicity pathway. To satisfy the GS4GG Lock-In Risk and DNSH requirements, the methodology shall mandate a formalized Waste Management Plan (WMP) covering collection, safe storage, and EoL processing as an absolute prerequisite for project eligibility and crediting renewal.

1|ASSET LIFESPANS AND CREDITING LIMITATIONS

1.1 |LED and Battery Lifespans

A persistent loophole in legacy carbon accounting methodologies for lighting has been the conflation of the luminaire's lifespan with the total system's lifespan. Manufacturers frequently market solar lanterns with claims of "50,000 hours of light" based on the degradation curve (L70) of the LED diode. If operating 4 hours a night, 50,000 hours translates to over 34 years.

However, off-grid solar devices are deeply constrained by their energy storage components. The system is only as durable as its battery. When the battery loses its ability to hold a charge, the 50,000-hour LED is rendered entirely useless, and the household will revert to baseline fossil fuels if the battery cannot be replaced.

1.2 |Field Durability of Battery Chemistries

A review of technical standards (e.g., IEC 62257-9-5 / VeraSol) and field evaluations reveals the true operational lifespans of off-grid solar energy storage:

a. **Sealed Lead-Acid (SLA):** Historically used in early Solar Home Systems (SHS). Due to frequent deep-discharging by users and poor temperature tolerance, SLA batteries in rural off-grid settings typically fail within **1.5 to 2.5 years** (Kinally et al., 2024).

b. **Lithium-Ion (NMC / LCO):** Common in first-generation Pico-solar lanterns. These generally offer 300 to 500 charge cycles before capacity degrades below 70%, yielding an effective field life of **2 to 3 years** (Alstone et al., 2014).

c. **Lithium Iron Phosphate (LiFePO4 / LFP):** The current premium standard for off-grid lighting. LFP batteries offer superior thermal stability and 1,500 to 2,000+ charge cycles, extending the effective field life to **3 to 5 years** (GOGLA, 2019).

1.3 |Recommendation for Methodology

Allowing an activity developer to claim a 10-year crediting period for a device with a 3-year battery risk of massive over-crediting.

The methodology shall explicitly define "Technical Life" as the *certified cycle life of the battery component*. The monitoring system must track the commissioning date of every unique device and automatically truncate emission reduction claims once the device exceeds its battery lifespan, unless verifiable evidence of a physical battery replacement/refurbishment is provided.

2| WASTE TOXICITY AND ENVIRONMENTAL RISKS

2.1 |Scale of Off-Grid E-Waste

The success of the off-grid solar sector has a dark ecological footprint. GOGLA (the Global Off-Grid Lighting Association) estimates that tens of millions of off-grid solar products are sold annually. Because these products are distributed to the "last mile"—remote, rural areas entirely lacking municipal solid waste infrastructure—the default end-of-life pathway is informal disposal. When devices die, they are typically thrown into pit latrines, buried in agricultural fields, dumped in rivers, or burned in open fires (Bensch et al., 2017).

2.2 |Chemical Toxicity and Leaching Risks

The informal disposal of these devices poses severe, localized environmental and human health risks:

a. **Lead-Acid Batteries:** Lead is a potent neurotoxin. When SLA batteries are broken open (often by informal scavengers seeking to melt and sell the lead), lead dust and sulfuric acid contaminate the immediate soil and water. Lead exposure in children causes irreversible cognitive impairment (UNEP, 2019).

b. **Nickel-Cadmium (NiCd):** While largely phased out of modern electronics, cheap, unregulated solar products occasionally use NiCd. Cadmium is a highly toxic, bio-accumulative carcinogen that readily leaches into groundwater when battery casings degrade in soil.

c. **Lithium-Ion (LCO/NMC/LFP):** While less acutely toxic than Lead or Cadmium, Lithium-ion batteries contain hazardous electrolytes (e.g., lithium hexafluorophosphate) which, when exposed to moisture, can form highly toxic hydrofluoric acid. Furthermore, the cobalt and nickel in NMC chemistries can leach into soil, disrupting local agriculture. Puncturing or burning Lithium batteries also poses a severe thermal runaway and fire hazard (Magalini et al., 2016).

d. **Printed Circuit Boards (PCBs) & Plastics:** Open-burning of the plastic solar housings and PCBs releases brominated flame retardants, dioxins, and furans into the air, posing acute respiratory and carcinogenic risks to the household.

3| LOCK-IN RISK AND MANDATORY SAFEGUARDS

3.1 |Environmental Lock-in

The GS4GG Requirements for Additionality Demonstration mandate an analysis of "path dependencies" and "existing infrastructure" to avoid locking host countries into unsustainable trajectories. While carbon finance for off-grid solar avoids *greenhouse gas* lock-in, financing the distribution of millions of toxic batteries into regions with zero recycling infrastructure creates an *environmental toxicity* lock-in. It externalizes the cost of pollution onto the poorest communities, directly violating the GS4GG Safeguarding Principles.

3.2 |Justification for the "Negative List"

To immediately mitigate the most acute toxicity risks, the methodology must restrict eligible technologies.

a. Methodological Rule: The methodology shall establish a strict "Negative List" prohibiting the use of Nickel-Cadmium (NiCd) batteries entirely, and strongly discouraging non-sealed Lead-Acid batteries.

3.3 |Mandatory Waste Management Plan (WMP)

Carbon markets cannot ethically finance the distribution of electronics without financing their retrieval.

a. Methodological Rule: To successfully pass the Lock-In Risk assessment, the methodology must require the Activity Developer to formulate, document, and

execute a formal Waste Management Plan (WMP) as a mandatory eligibility condition.

This WMP must include:

a. Collection Logistics: Establishing drop-off centres or incentive schemes (e.g., discounts on replacement lamps) to retrieve dead batteries.
b. Safe Storage: Protocols for safely storing collected lithium batteries (to prevent fire) and lead-acid batteries (to prevent acid leaks) at central hubs.
c. End-of-Life (EoL) Solution: Contracts with certified e-waste recyclers. Recognizing that many LDCs lack formal recycling facilities, the methodology must allow for "Acceptable LDC Context" alternatives, such as safe stabilization (encasement in concrete) or Basel Convention-compliant export, but absolutely prohibit informal landfilling or open burning.

The VVB shall audit the execution of this WMP at each crediting renewal to ensure it is not merely a paper promise.

4| ANNOTATED BIBLIOGRAPHY

Alstone, P., Lai, P., Mills, E., & Jacobson, A. (2014). High Life Cycle Efficacy Explains Fast Energy Payback for Improved Off-Grid Lighting Products. Journal of Industrial Ecology, 18(5), 722–733. https://doi.org/10.1111/jiec.12117

Contribution: Beyond carbon footprinting, this LCA details the material composition and functional lifespans of Pico-solar devices. It confirms that the limiting factor in the technology is the battery chemistry, establishing the baseline expectation that first-generation lithium batteries in off-grid applications last 2 to 3 years. This provides the technical justification for decoupling the crediting period from the LED lifespan.

Bensch, G., Peters, J., & Sievert, M. (2017). The lighting transition in Africa—From kerosene to LEDs and the emerging disposal problem. Energy for Sustainable Development, 39, 13-20. https://doi.org/10.1016/j.esd.2017.03.004

Contribution: This paper provides early and urgent empirical evidence of the e-waste crisis emerging from the off-grid solar boom. Through field surveys, the authors document that end-of-life solar lanterns are overwhelmingly discarded in pit latrines, buried, or burned, owing to the complete absence of reverse logistics or municipal waste management. This study is the primary justification for why a mandatory Waste Management Plan must be an eligibility requirement for carbon crediting.

Cross, J., & Murray, D. (2018). The afterlives of solar power: Waste and repair off the grid in Kenya. Energy Research & Social Science, 44, 100-109. https://doi.org/10.1016/j.erss.2018.04.034

Contribution: An in-depth socio-technical study of off-grid solar in Kenya. The authors highlight the "repair economy" but also document the inevitable accumulation of dead solar batteries and panels. It emphasizes that without formal, funded take-back schemes, toxic components invariably enter the local environment. This justifies the methodology's requirement for formalized collection logistics and the tracking of E-waste volumes during monitoring.

GOGLA. (2019). Global Off-Grid Solar E-Waste Toolkit. Global Off-Grid Lighting Association. Utrecht, Netherlands.

Contribution: The definitive industry standard report on e-waste in the off-grid sector. This toolkit provides comprehensive data on the volume of waste generated, the toxicity profiles of different battery chemistries (SLA vs. LFP vs. NMC), and the economics of reverse logistics. It serves as the primary technical foundation justifying the methodology's "Negative List" of prohibited chemistries (e.g., NiCd) and the structural requirements of the mandatory Waste Management Plan.

Kinally, C., et al. (2024). Life cycle assessment of solar home system informal waste management practices in Malawi. Applied Energy, 364, 123-135. https://doi.org/10.1016/j.apenergy.2024.123135

Contribution: A highly recent and critical LCA that specifically evaluates the environmental impacts of informal disposal (open burning, scavenging) of Solar Home Systems in an LDC context. The study proves that when SLA batteries are scavenged for lead and acid is dumped, the environmental toxicity impacts are catastrophic. This paper firmly cements the argument that failing to manage off-grid solar e-waste constitutes an "environmental lock-in," providing the scientific basis for the methodology's DNSH safeguards.

Magalini, F., Sinha-Khetriwal, D., Rochat, D., Huismann, J., Munyigwa, M., Oliech, J., & Nnorom, I. C. (2016). Electronic waste (e-waste) impacts and mitigation options in the off-grid renewable energy sector. Evidence on Demand. https://doi.org/10.12774/eod_cr.may2016.magalinietal

Contribution: A comprehensive report commissioned by the UK Department for International Development (DFID). It models the vast tonnages of electronic waste generated by the off-grid solar sector and details the specific heavy metal leaching risks (Lead, Cadmium) associated with poor disposal. It serves as the primary literature backing the methodology's "Negative List," justifying the absolute prohibition of NiCd batteries in project activities.

United Nations Environment Programme (UNEP). (2019). Technical guidelines for the environmentally sound management of waste lead-acid batteries. Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal.

Contribution: The premier international regulatory document on the hazards of lead-acid batteries. The guidelines detail the severe neurotoxicity of lead exposure and the soil/water contamination pathways associated with informal smelting and dumping. This report provides the definitive toxicological justification for classifying improper battery disposal as a violation of the "Do No Significant Harm" principle, thereby mandating strict regulatory safeguards within the carbon crediting framework.

SECTION 5: ASSESSMENT OF COMMON PRACTICE PENETRATION, MARKET BARRIERS, AND ADDITIONALITY THRESHOLDS

EXECUTIVE SUMMARY

Under the GS4GG *Requirements for Additionality Demonstration*, mitigation activities must not be "Common Practice" in their target sector and applicable geographical area. A critical challenge is addressing the common narrative that off-grid solar has become fully commercialized and ubiquitous. While the global off-grid solar sector has undeniably scaled over the past decade, an extensive, highly granular review of regional market penetration and persistent socioeconomic barriers reveals a deeply fragmented reality. The "low-hanging fruit"—peri-urban, middle-income households—has largely been served, however, the poorest, most remote populations (Tier 0) remain heavily reliant on fossil fuels due to acute affordability constraints, infrastructure deficits, and macroeconomic shocks.

To ensure the methodology accurately targets carbon finance toward truly additional activities while maintaining regulatory clarity, this assessment evaluated regional market penetration statistics and structural barriers in exhaustive detail.

The principal findings and methodological recommendations are as follows:

1. **Market Penetration of Quality-Verified Devices is deeply stratified:** While the global market is flooded with cheap, unverified, and short-lived generic solar products, the penetration of *quality-verified* (QV) Tier 1 solar systems (the standard required by this methodology to ensure permanent climate impact) remains low in target demographics. Across Sub-Saharan African LDCs, quality-verified penetration ranges from 2% to 22%, leaving hundreds of millions in energy poverty.
2. **Persistent Barriers Restrict Commercial Expansion:** The autonomous expansion of commercial solar has plateaued in the poorest regions. Persistent barriers—specifically the "affordability gap" for end-users, prohibitive last-mile distribution/servicing costs, market spoilage by counterfeiters, and severe local currency devaluation (forex risks)—make it impossible to serve these communities without concessional funding or carbon revenues.
3. **Justification of TMC-3 and Thresholds:** Based on the market maturity of the technology itself, off-grid solar is correctly classified as **Technology Maturity Category 3 (TMC-3: Early Majority)**. However, considering the severe contextual barriers, it was recommended that the methodology establish differentiated Common Practice Thresholds (Fmax): **25% for LDCs/SIDS/LLDCs** and **16% for other countries**. These thresholds safely ensure that carbon finance intervenes precisely where autonomous commercial markets fail.

1| CURRENT MARKET PENETRATION STATISTICS

To accurately determine the Common Practice Factor (F), penetration must be measured against the *target addressable market*—which consists strictly of

households lacking reliable grid access, not the entire national population. Furthermore, the analysis must isolate **Quality-Verified (QV) products** (e.g., Global certified systems that meet the 1,000 lumen-hour Minimum Service Level and battery lifespan rules required by the methodology) from the broader influx of non-verified, generic products that do not yield permanent climate mitigation.

1.1 |Global Overview

According to the World Bank's Energy Sector Management Assistance Program (ESMAP) and the Global Off-Grid Lighting Association (GOGLA) *Off-Grid Solar Market Trends Report*:

- Over **685 million people** globally remain completely without access to electricity, with approximately **1 billion more** suffering from highly unreliable, weak-grid connections (Tier 1 or below).
- While the OGS sector has reached over 400-500 million people historically, the active, operational stock of quality-verified systems at any given moment is significantly lower due to product lifespans and battery degradation.
- QV products account for only **25% to 30%** of total global sales, with the remaining 70% consisting of non-affiliated, often substandard generic products.
- Global autonomous market penetration of QV products in the target off-grid demographic remains below **15% to 20%**, heavily clustered in specific geographic pockets.

1.2 |Sub-Saharan Africa (SSA)

Sub-Saharan Africa accounts for over 80% of the world's unelectrified population. Market penetration is acutely bifurcated by sub-region.

- **East Africa (The Mature Hubs):** Kenya, Rwanda, Uganda, and Tanzania are often cited as the "success stories" of off-grid solar. This was catalysed by the early proliferation of mobile money (e.g., M-Pesa), which enabled the PAYG business model. In Kenya, the penetration of solar lighting in off-grid areas approaches **20% to 28%**. Despite this maturity, growth has largely plateaued. Commercial operators report struggling to push past this penetration cap because the remaining unserved populations live in deep rural or pastoralist areas (e.g., Turkana, Samburu) where Customer Acquisition Costs (CAC) outstrip potential profits.
- **West Africa (The High-Volume, High-Grid-Deficit Market):** Markets like Nigeria, Senegal, Côte d'Ivoire, and Ghana possess massive populations, but their dynamics differ from East Africa. The issue here is frequently a mix of pure off-grid populations and massive "unreliable grid" populations. Penetration of QV SHS and Pico-solar in rural West Africa ranges from **8% to 15%**. The region historically suffered from lower mobile money interoperability, complex import logistics, and severe macroeconomic instability. The market is also heavily distorted by cheap, non-verified products crossing porous borders, eroding consumer trust.

- **Central and Southern Africa (The Nascent Frontier):** In LDCs such as the Democratic Republic of Congo (DRC), Malawi, Madagascar, Zambia, and Angola, the market is profoundly underdeveloped. These nations contain some of the largest un-electrified populations on earth. Penetration of QV solar products remains stubbornly low, typically **between 2% and 5%**. Extreme systemic poverty, lack of mobile network infrastructure, lack of paved roads, and political instability render autonomous commercial PAYG models virtually unviable outside of capital cities without heavy donor subsidy or carbon finance intervention.

1.3 |South Asia

- **India:** India achieved near-universal village electrification under the *Saubhagya* scheme, drastically shrinking the purely "off-grid" population. However, the "Unreliable Grid" remains a massive issue. In states like Bihar, Uttar Pradesh, and Jharkhand, grid power is often available for less than 12 hours a day, missing the evening peak. Penetration of QV OGS in these specific unreliable-grid segments is estimated at **10% to 15%**, acting primarily as backup to grid failures or diesel generators.
- **Bangladesh & Pakistan:** Bangladesh historically operated a massive, state-subsidized SHS program (IDCOL). However, with grid expansion, the *new* autonomous addressable market has shrunk to extreme remote areas (e.g., riverine *chars* in Bangladesh or mountainous regions in Pakistan) where penetration of modern Tier 1 systems remains **below 15%**.

1.4 |Southeast Asia, Pacific SIDS, and Latin America

- **Archipelagic Nations (Indonesia, Philippines, Papua New Guinea, Vanuatu):** SIDS and archipelagos face extreme topographical and logistical barriers. Extending the grid across thousands of islands is economically impossible. In Papua New Guinea, electricity access is below 20%. The cost of inter-island shipping effectively doubles the retail price of a Solar Home System. Penetration of QV systems often hovers around **5% to 12%**, entirely dependent on targeted carbon finance to offset crippling supply chain costs.
- **Latin America & Caribbean:** In regions like the Amazon basin or SIDS like Haiti, extreme geographical isolation and/or socio-economic collapse have kept QV solar penetration in the single digits (**<10%**), largely reliant on sporadic state tenders rather than autonomous commercial retail markets.

2| BARRIERS FACING OFF-GRID SOLAR ADOPTION

If OGS technology is proven and lifecycle costs are cheaper than burning kerosene, classical economics suggests adoption should be universal. The fact that it stalls below 20% globally highlights profound, persistent market failures. Carbon finance under the PULSE methodology is specifically designed to dismantle these exact barriers.

2.1 |Economic and Affordability Barriers (The "Affordability Gap")

The most insurmountable barrier is the upfront capital cost relative to the purchasing power of Tier 0 households.

- **The Cash Flow Mismatch:** A Tier 0 household may comfortably spend $0.30 to $0.50 a day on kerosene (affordable on a daily wage). However, a high-quality Pico-solar lantern costs $25-$40, and a basic SHS costs $100+. Without access to formal banking, acquiring this upfront capital is impossible for households living below the poverty line.
- **The Limits of PAYG:** PAYG financing was hailed as a silver bullet, allowing users to pay in micro-installments. However, literature shows that commercial PAYG currently only serves the "upper tier of the bottom of the pyramid." Default rates on PAYG loans frequently reach 15-20% when deployed to extreme poverty segments due to erratic agricultural incomes. The World Bank explicitly identifies an "Affordability Gap" of over 200 million people who are too poor to afford even the cheapest Tier 1 PAYG solar lantern on commercial terms.
- *Role of Carbon Finance:* Carbon revenues allow developers to lower the upfront deposit, reduce the daily tariff, or deploy Results-Based Financing (RBF), effectively subsidizing the technology down to a price point accessible to the extreme poor.

2.2 |Supply Chain, O&M, and Last-Mile Distribution Barriers

Serving remote, off-grid communities is structurally unprofitable for pure commercial capital.

- **The CapEx of the Last Mile:** Distributing hardware, establishing rural retail kiosks, training local agents, and managing cash/mobile payments in deep rural areas without paved roads imposes massive operational expenditures (OpEx). Often, the cost of delivering a solar lamp to a remote village exceeds the manufacturing cost of the lamp itself.
- **Operations and Maintenance (O&M) and Reverse Logistics:** Quality-verified products require a warranty. Sending a technician to a remote village to replace a defective $30 Pico-solar lantern destroys commercial margins. Furthermore, as highlighted in the E-Waste assessment (Section 4), establishing reverse logistics for safe battery recycling is a total market failure; no commercial entity will autonomously pay to travel to a remote village to collect a dead battery.
- *Role of Carbon Finance:* Carbon credits provide the continuous, multi-year revenue stream required to fund these mandatory "Last-Mile O&M" and waste management networks.

2.3 |Macroeconomic and Institutional Barriers

Particularly in LDCs, distributors face systemic macroeconomic risks that stifle investment.

- **Foreign Exchange (FX) Risk and Inflation:** Solar components are manufactured in Asia and purchased in USD, but sold to customers via PAYG contracts in local, highly volatile currencies (e.g., Nigerian Naira, Kenyan Shilling, Malawian Kwacha). Recent severe currency devaluations have caused

the local-currency retail price of solar systems to double or triple, pushing the technology further out of reach and rendering local distributors insolvent.

- *Role of Carbon Finance:* Carbon credits are typically denominated and sold in hard currencies (USD/EUR). They act as a vital currency hedge, allowing distributors to absorb local currency shocks without passing the full cost onto the vulnerable end-user.
- **Fossil Fuel Subsidies:** In many developing nations, kerosene and diesel are heavily subsidized by the state to protect the poor. This creates an artificially distorted baseline where the "dirty" fuel is cheaper than the true market cost of the clean alternative, requiring carbon finance to level the economic playing field.

2.4 |Socio-Cultural and Trust Barriers (Market Spoilage)

In many developing nations, institutional frameworks for enforcing quality standards at ports of entry are weak.

- **Problem:** Markets are frequently flooded with cheap, counterfeit, and unverified generic solar products. These products use substandard components and typically fail within 3 to 6 months.
- **Erosion of Trust:** When a poor household sacrifices a month's wages for a generic solar lamp that rapidly breaks, their trust in solar technology is destroyed. They revert to kerosene and become highly resistant to future solar adoption.
- *Role of Carbon Finance:* Quality-verified products (which undergo rigorous IEC/VeraSol testing) are fundamentally more expensive to manufacture than generic copycats. Carbon finance provides the financial premium necessary for high-quality distributors to compete on price against disposable counterfeits, thus rescuing spoiled markets.

3| JUSTIFICATION OF COMMON PRACTICE THRESHOLDS

Under the GS4GG *Methodology Tool: Common Practice Analysis*, establishing the maximum penetration threshold (Fmax) is critical to determining additionality. Based on the penetration statistics and persistent barriers detailed above, the PULSE methodology establishes the following parameters:

3.1 |Justification for TMC-3 (Early Majority) Classification

Off-grid solar is no longer an experimental, unproven prototype (TMC-1), nor is it limited only to early-adopter innovators (TMC-2). Supply chains exist, and the technology is commercially available. However, it is not "Mature" (TMC-4) because its adoption is severely restricted by the persistent financial and infrastructural barriers detailed above. It is accurately classified as **TMC-3 (Early Majority)**—a technology ready to scale but requiring external catalytic intervention (carbon finance) to cross the chasm to the poorer, harder-to-reach majority.

3.2 |Justification for the 25% Threshold in LDCs and SIDS

- **The Threshold:** For Least Developed Countries (LDCs), Small Island Developing States (SIDS), and Landlocked Developing Countries (LLDCs), the methodology sets the Common Practice Threshold at **25%** (based on stock of the target population).
- **Rationale:** LDCs and SIDS suffer from the most acute convergence of barriers—extreme end-user poverty, lack of mobile money infrastructure, exorbitant logistical costs, and severe macroeconomic instability. The data shows that quality-verified penetration in these regions currently ranges from 2% to 15%.
- Setting the threshold at 25% provides the necessary "runway" for carbon finance to sustainably scale operations, build last-mile supply chains, and establish the mandatory Waste Management networks without being prematurely disqualified. Disqualifying projects at 10% or 15% in a country like the DRC or Vanuatu would effectively abandon the poorest populations to perpetual fossil fuel reliance.

3.3 |Justification for the 16% Threshold in Non-LDCs

- **The Threshold:** For all other non-LDC developing nations (e.g., lower-middle-income countries like India, Indonesia), the threshold is set at **16%**.
- **Rationale:** In non-LDCs, commercial markets are more mature, banking access is higher, and state-led grid expansion is moving faster. According to Everett Rogers' foundational *Diffusion of Innovations* theory, the boundary separating "Innovators/Early Adopters" from the "Early Majority" is exactly 16% (2.5% + 13.5%).
- Setting a tighter 16% threshold acknowledges the higher baseline commercial maturity of the host country. Once adoption passes 16% in these markets, the technology is demonstrating autonomous commercial viability. This lower threshold ensures that carbon finance is strictly targeted at the difficult early-adoption phase and the stubborn, hard-to-reach pockets of energy poverty that commercial forces continue to bypass, preventing the crediting of purely commercial market expansion.

4| ANNOTATED BIBLIOGRAPHY

Akerlof, G. A. (1970). The market for "lemons": Quality uncertainty and the market mechanism. The Quarterly Journal of Economics, 84(3), 488-500. https://doi.org/10.2307/1879431

Contribution: The foundational economic theory explaining market failure due to asymmetric information. In the context of this SI, it perfectly describes the "market spoilage" barrier in the off-grid solar sector. The influx of cheap, counterfeit, non-verified products destroys consumer trust, preventing the adoption of higher-priced, quality-verified solar systems. It provides the academic backing for classifying market spoilage as a severe institutional barrier requiring carbon finance to overcome.

Bhatia, M., & Angelou, N. (2015). Beyond Connections: Energy Access Redefined. Energy Sector Management Assistance Program (ESMAP). Washington, DC: World Bank.

https://www.worldbank.org/content/dam/Worldbank/Topics/Energy%20and%20Extract/Beyond_Connections_Energy_Access_Redefined_Exec_ESMAP_2015.pdf

Contribution: Establishes the foundational Multi-Tier Framework (MTF) for energy access. It highlights the vast difference between basic electrification (e.g., owning a generic flashlight) and meaningful, reliable access. The report's data underscores that while basic lighting products have proliferated, true Tier 1 access (which the methodology demands) remains stubbornly low in rural demographics, justifying the methodology's focus on quality-verified, high-capacity systems as non-common practice.

Bridle, R., Sharma, S., Mostafa, M., & Geddes, A. (2019). Fossil Fuel to Clean Energy Subsidy Swaps: How to pay for an energy revolution. International Institute for Sustainable Development (IISD).

https://www.iisd.org/system/files/publications/fossil-fuel-clean-energy-subsidy-swap.pdf

Contribution: This policy report provides a detailed economic analysis of how institutional fossil fuel subsidies (specifically for kerosene and diesel) artificially suppress the adoption of decentralized renewable energy. It provides the macroeconomic justification for why off-grid solar requires external subsidization (such as carbon finance) to overcome entrenched institutional barriers, supporting the Additionality claims of the methodology.

GOGLA, ESMAP, & Lighting Global. (2024). Off-Grid Solar Market Trends Report 2024: State of the Sector. World Bank Group.

https://www.esmap.org/Off-Grid_Solar_Market_Trends_Report_2024

Contribution: The definitive biennial market intelligence report for the sector. This report provides the quantitative data underpinning Section 1 of this SI. It details the massive disparity in market penetration—showing high saturation in certain East African hubs while detailing the near-zero penetration of quality-verified products in Central and West African LDCs. Crucially, the 2024 report highlights the crippling effects of FX volatility and inflation on distributors, confirming the ongoing, absolute need for hard-currency carbon finance to sustain market growth. It explicitly notes the "Affordability Gap" affecting over 200 million people.

Moore, G. A. (1991). Crossing the Chasm: Marketing and Selling High-Tech Products to Mainstream Customers. New York: HarperBusiness.

http://soloway.pbworks.com/w/file/fetch/46715502/Crossing-The-Chasm.pdf

Contribution: The foundational text on technology adoption lifecycles. It provides the theoretical framework for the 16% and 25% thresholds. By explaining why technologies stall after reaching the Early Adopters (16%), it provides the academic rationale for classifying off-grid solar as TMC-3 and justifying a higher threshold

(25%) in LDCs where the "chasm" is exacerbated by extreme poverty and lack of infrastructure.

Sotiriou, C., Scott, A., & Ockwell, D. (2021). The limits of the "Pay-As-You-Go" model for rural electrification in Sub-Saharan Africa. Energy Research & Social Science, 81, 102275.

Contribution: A critical academic evaluation of the PAYG financing mechanism. The authors demonstrate that PAYG inherently excludes the poorest demographics due to their irregular income streams and lack of mobile money access. This directly challenges the assumption that the off-grid solar market can solve energy access purely through commercial debt financing, providing robust justification for why carbon-financed interventions remain strictly additional for reaching the extreme poor.

Waldron, D., & Pearce, J. M. (2019). The economics of Pay-As-You-Go solar home systems. Energy for Sustainable Development, 53, 137-148.

Contribution: A rigorous financial analysis of the unit economics of solar distributors. Waldron and Pearce demonstrate the high capital costs, default risks, and operational expenditures associated with last-mile distribution. The study shows that without concessional capital or carbon revenues, serving Tier 0 households is fundamentally unprofitable. This provides the mathematical baseline for the methodology's "Ongoing Financial Need" (OFN) requirement at the renewal of the crediting period.