SUNNY

DELIVERABLE 2.2

Local value chains and circular approach

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DATA	Data sets, microdata, etc.	
OTHER	Software, technical diagram, etc.	

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TABLE OF CONTENTS

This project has received funding from the European Union’s Horizon Europe Research and Innovation programme under Grant Agreement No. 101147546

This project has received funding from the European Union's Horizon Europe Research and Innovation programme under Grant Agreement No. 101147546

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS

List of acronyms will be added after the deliverable has been reviewed and finalised.

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EXECUTIVE SUMMARY

To be added.

I. INTRODUCTION

1. General Background

Deliverable 2.2 contributes to Work Package 2 of the SUNNY project, which focuses on the co-development of local value chains, training, and capacity building to ensure that renewable energy solutions deployed in refugee and host-community settings are socially embedded, technically viable, and economically sustainable. The overarching ambition of SUNNY is to demonstrate how off-grid renewable energy technologies, which cover clean cooking, electrification, agricultural production, and cold storage, can be adapted to the specific needs, constraints, and opportunities present in displacement contexts in Rwanda and Uganda. Achieving this ambition requires understanding not only the performance of the technologies themselves, but also the broader socio-economic and institutional ecosystem that enables their uptake, long-term operability, and replicability.

Within this broader framework, the development of local value chains and circular approaches is central. In displacement settings, market systems are often fragmented, dominated by short-term humanitarian provisioning, or only partially connected to surrounding host-community economies. SUNNY seeks to move beyond the traditional "procure-and-provide" model by supporting context-appropriate supply chains, workforce development, and the emergence of locally anchored installation, operation, maintenance, repair, and end-of-life pathways. Strengthening these functions is essential for moving from technology demonstration to sustainable energy service provision with enduring socio-economic benefits.

Deliverable 2.2 (covering Tasks 2.3.1 and 2.3.2) therefore contributes directly to SUNNY's objective of creating service-oriented, circular, and socially embedded value chains that are suitable for long-term use in humanitarian and host-community environments. It

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provides an analytical foundation for localising technology lifecycles, from procurement to waste management, while identifying opportunities for community participation and economic inclusion.

2. Deliverable objectives

This deliverable documents the results of Task 2.3, which consists of two closely connected subtasks. Together, these tasks support SUNNY's aim to create long-term sustainable energy systems, rooted in local capacities and aligned with both environmental and socio-economic considerations

a. Task 2.3.1 – Definition of local value chains

T2.3.1 focuses on developing local value chains for each of the five SUNNY technologies through a structured application of the International Labour Organization's Value Chain Development (ILO VCD) approach. The aim is to understand how each solution—hydrogen cooking, solar home systems, solar irrigation, solar-powered cold storage, and biogas for cooking—can be embedded within local service ecosystems throughout their full lifecycle. This includes:

- identifying procurement pathways and local sourcing potential;
- mapping actors involved in installation, operation, maintenance, and governance;
- assessing opportunities for community participation and skill development;
- identifying constraints, risks, and systemic bottlenecks; and
- outlining viable routes for strengthening local economic linkages.

b. Task 2.3.2 – Definition of technological waste repair and recycling solutions

T2.3.2 complements the local value chain analysis by assessing the circularity, reparability, and end-of-life management of the SUNNY technologies. This includes identifying:

- repair and maintenance opportunities that can be carried out locally;
- existing or potential waste collection, recycling, and reuse pathways;
- material characteristics relevant to circularity; and
- actors who may participate in emerging circular value chains.

3. Deliverable structure

The deliverable is structured into two main parts, reflecting the two subtasks. The first part presents the methodology and findings of the local value chain analysis, including:

1. **Introduction** – situating local value chain development within the broader SUNNY framework.
2. **Methods** – applying the International Labour Organisation's value chain

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development approach (mapping, research, and analysis).

3. **Results** – technology-specific local value chains for all five SUNNY solutions, each covering procurement, installation, operation, maintenance, circularity considerations, regulatory requirements, and associated strengths-weaknesses-opportunities-threats analyses.
4. **Discussion** – cross-cutting observations on localisation potential, opportunities, risks, and systemic enabling conditions.
5. **Summary and Outlook** – synthesising implications for subsequent project phases.

The second part examines the circularity dimension of the SUNNY technologies and includes:

1. **Introduction and Objective** – situating circularity within the SUNNY project.
2. **Methods** – combined person-centred and system-centred approaches as well as multi-actor learning labs for waste assessment.
3. **Results** – findings on existing waste flows, recycling structures, repair practices, and opportunities across the two demonstration sites.
4. **Analysis** – strengths, weaknesses, and potential for circular value chains.
5. **Discussion and Implications** – how circularity considerations support broader SUNNY goals.
6. **Summary and Outlook** – conclusions and next steps for integrating circular approaches.

Together, the two parts provide a comprehensive analysis of how SUNNY's technologies can be embedded in local economies, supported by circular practices, and operated sustainably beyond the demonstration period.

II. T2.3.1 DEFINITION OF LOCAL VALUE CHAINS

1. INTRODUCTION

The second work package (WP2) of the SUNNY project focuses on the collaborative development of local value chains, training, and capacity building. Its overarching goal is to ensure that SUNNY solutions are aligned with user needs through the active engagement of local stakeholders, thereby supporting high adoption rates and long-term sustainability. Within WP2, Task 2.3 concentrates on co-developing and defining local value chains using a circular approach. Specifically, T2.3.1 addresses local value chain development, while T2.3.2 examines opportunities for circularity, including technological waste repair and recycling pathways.

As a reminder, the SUNNY project aims to implement five off-grid energy solutions to improve energy access in refugee settings in Rwanda and Uganda. Two solutions—solar

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home systems and clean hydrogen cooking—will be demonstrated in the Mahama refugee and host communities in Rwanda. The remaining three solutions—smart solar irrigation, refrigerated food storage, and biogas production and cooking—will be implemented in the Bidibidi refugee and host communities in Uganda.

Against this backdrop, the purpose of T2.3.1 is to identify the most suitable value chains for the SUNNY solutions in each demonstration site. This involves a comprehensive assessment of the strengths, weaknesses, and opportunities associated with each value chain, as well as an evaluation of the potential for local sourcing of materials, components, and skilled labour. By doing so, the task aims to maximize the local share of each value chain and contribute to local economic development.

The following sections describe the methodology used to develop and analyse local value chains, present the key findings, and discuss their implications for the SUNNY solutions across both demonstration sites.

2. Methods

The International Labour Organization's (ILO) Value Chain Development (VCD) approach provides a structured methodology for strengthening market systems in ways that support decent work, competitiveness, and sustainable economic development. At its core, the approach views value chains not merely as linear sequences of economic activities, but as systems embedded within a wider network of supporting functions, institutions, and rules that collectively shape how products and services flow from conception to end use. Strengthening a value chain therefore requires understanding not only the actors involved but also the incentives guiding them, the systemic constraints they face, and the opportunities that exist for scalable and sustainable change. This systemic perspective is particularly relevant when working in refugee-hosting areas, where markets are dynamic, often informal, and influenced by humanitarian actors, regulatory frameworks, and the socio-economic realities of displaced and host populations.

In the context of the SUNNY project, which seeks to deploy a set of off grid energy solutions in Rwanda and Uganda, the VCD methodology supports the design of local value chains capable of expanding energy access while fostering local economic, social, and environmental development. Although the project's technologies differ in their functions and target user groups, they all depend on multi actor systems of supply, distribution, maintenance, training, financing, and governance. The VCD approach provides a common framework through which these systems can be examined, strengthened, and adapted to local conditions.

The ILO's VCD approach is organised into five interconnected steps that support systemic and sustainable market improvements. The process begins with sector selection. In this step, practitioners identify priority sectors based on clear criteria such

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as relevance to the target group, employment creation potential, and feasibility of intervention, ensuring that efforts focus on areas with the greatest opportunity for impact. This is followed by market system analysis (MSA). This step comprises value chain mapping, in-depth research, and analysis to understand how a sector functions, where constraints originate, and what systemic factors shape market performance. Insights from this analysis feed into intervention design. In this third step, tailored strategies are developed to address underlying constraints and enable long-term change, with an emphasis on solutions that can be sustained and scaled by market actors. The fourth step, implementation, focuses on facilitating these solutions within the market via strengthening business models, building capacities, and supporting institutions so that improvements can continue beyond project support. Finally, monitoring and results measurement ensures that progress is systematically tracked, outcomes are assessed against objectives, and learning is fed back into the process. This enables ongoing adaptation and ensures alignment with the overarching goals of decent work, inclusion, and market sustainability.

In the context of the SUNNY project, the sector selection step has already been predefined through the choice of five off-grid energy solutions to be demonstrated across the two project sites. As a result, the focus of this task lies squarely on the second step, which is MSA. This step provides the analytical foundation for understanding how local value chains for these technologies function and where opportunities exist for strengthening them. The rest of this section describes the market system analysis process in detail and outlines how it is applied within the SUNNY project.

Within the VCD cycle, three analytical components form the core of MSA: value chain mapping, value chain research, and value chain analysis. Together, they enable the development of a deep and realistic understanding of how each value chain operates, where constraints arise, and how interventions can be designed to generate long-term improvements. The ILO emphasises that these components are not sequential in a rigid sense; each stage can be revisited and refined as new insights emerge, and analysis is strengthened through participatory engagement with market actors.

a. Value Chain Mapping

Value chain mapping is the first step of MSA and serves as a practical tool for illustrating how a product or service moves from its initial conception to the final user. According to the ILO, mapping begins by developing a simple flowchart that traces the core transactions within the chain. These transactions span the sourcing of raw materials or components, production, installation, distribution, and post-sales support, up to the end consumer. To keep the map clear and functional, related activities are grouped under consolidated value chain levels. This simplification is particularly useful when examining complex systems such as those surrounding off-grid energy technologies, where multiple actors and processes may overlap.

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Once the basic flow of the chain is established, the next step involves creating an inventory of market players positioned at each value chain level. This includes the businesses directly involved in supplying, distributing, installing, or servicing the product, as well as the wider set of supporting organisations that contribute indirectly, such as government agencies, training institutions, worker organisations, NGOs, and informal networks. Mapping these actors helps clarify not only who participates in the chain but also how responsibilities, incentives, and relationships are distributed across the system.

As the map takes shape, it becomes possible to layer in an initial illustration of opportunities and constraints at each stage of the chain. These may relate to skills gaps, regulatory barriers, unreliable supply logistics, or limited access to finance. Although a more detailed SWOT-style assessment typically requires in-depth field research, early insights gathered from stakeholders can already reveal patterns that guide later phases of market analysis.

A further element of the mapping process involves identifying the different markets to which the product or service is supplied. This may include household, institutional, agricultural, or commercial markets, depending on the technology in question. Grouping these market segments into broader categories helps clarify their relative importance and, where relevant, their growth potential. This information can strongly influence decisions about where to focus subsequent research and intervention efforts.

With end markets defined, the analysis turns to mapping the routes by which products and services reach these markets. This requires allocating the previously identified market players to the specific market segments they serve. For example, some distributors may focus exclusively on household consumers, while others engage with institutional buyers, or agricultural users. Understanding these pathways is essential for identifying bottlenecks and opportunities within specific market channels.

b. Value Chain Research

Value chain research builds on the preliminary insights from the mapping stage and aims to uncover the underlying systemic causes behind the bottlenecks identified earlier. According to the ILO, this stage seeks not only to describe what is happening in the chain, but to understand why it is happening, by examining the incentives and capacities of market players, the relationships that shape their behaviour, and the structural conditions that influence market performance. Through this process, research helps identify the pathways for sustainable change, highlight market opportunities, and determine the leverage points where interventions are most likely to generate long-term improvements.

The first step involves deciding which constraints or deficits to prioritise and determining the corresponding market players whose perspectives are most relevant. This requires selecting a limited number of issues that align with the project's primary interests and

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target groups, recognising that not all problems can be addressed within the scope of a single intervention. For example, if the mapping stage has revealed widespread challenges in after-sales service provision, the research may focus on technicians, and training providers. On the other hand, if affordability is the primary constraint, financial institutions, retailers, and end-users become more central. Prioritisation ensures that subsequent research efforts are both feasible and strategically aligned.

Once priorities are defined, the content and focus of the research is determined. This involves identifying the indicators and questions that will guide investigation, such as those relating to causes of constraints, market incentives and disincentives, the technical and organisational capacities of key players, and the quality of relationships within the chain. The ILO emphasises that research should extend beyond the core market to explore supporting functions and rules, such as training systems, financing mechanisms, regulatory frameworks, and informal norms. This is because these supporting functions often shape the root causes of observed bottlenecks. Understanding how these factors interact helps reveal whether challenges stem from information gaps, capability limitations, coordination failures, misaligned incentives, or structural barriers.

With the research framework established, the final step is choosing appropriate data collection methods. The ILO recommends a mix of qualitative and observational approaches, including key informant interviews, focus group discussions, and direct observation. Secondary research, such as reviewing existing studies, policy documents, or market reports, helps contextualise primary findings. Using local facilitators is strongly encouraged, as they can support interview processes, ease access to community actors, and ensure cultural relevance and accuracy in data collection. The research phase is typically time-sensitive and participatory, fostering early engagement and ownership among market actors while building a nuanced understanding of how and why the value chain operates as it does.

c. Value Chain Analysis

Value chain analysis synthesises the findings from earlier stages to determine where meaningful improvements can be achieved within the market system. The process begins by examining the major constraints that emerged from the research phase, focusing on those that most significantly affect the performance, inclusiveness, or growth potential of the chain. These constraints are assessed to understand how they interact and which of them present the most strategic entry points for change.

A key part of the analysis involves linking each constraint to the supporting functions and rules that underpin the wider market. This step helps clarify whether the root causes lie, for example, in training and information systems, financial services, regulatory frameworks, coordination mechanisms, or informal norms. Situating constraints within this broader system makes it possible to distinguish between issues that stem from

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immediate operational challenges and those that arise from deeper structural gaps.

The analysis then considers which market players are best positioned to address the identified issues, paying particular attention to actors who already perform relevant functions or who have a clear incentive to assume them. This involves assessing their capabilities, interests, and potential motivations to take on enhanced roles within the chain. Understanding these dynamics is essential for identifying partners who can drive change without long-term external support.

Finally, the process leads to the formulation of sustainable solutions for value chain upgrading. These solutions aim to address underlying causes rather than symptoms and are designed to align with the incentives and capacities of local actors. The resulting proposals typically focus on strengthening or introducing functions that improve the overall efficiency, quality, and resilience of the value chain. Crucially, the emphasis is on solutions that can be maintained, adapted, and scaled by market players themselves, ensuring that improvements continue to take hold beyond the duration of the project.

d. Data Sources

The analysis in this report draws on data and insights generated across several tasks of the SUNNY project. In particular, it integrates findings from the context analysis in T1.1, the eco-design toolkit developed in T1.3, and the technology-specific information compiled for training module development in T2.4. Together, these sources provide a comprehensive foundation for assessing LVC opportunities, constraints, and localisation potential for each SUNNY solution.

From T1.1, the report uses the system-centred descriptions of both demonstration sites, the person-centred analyses of refugee and host communities, the environmental assessment of biowaste flows and valorisation options in the Bidibidi Settlement, and the regulatory and policy review for Rwanda and Uganda. These inputs support the identification of relevant market players, supporting organisations, and enabling or constraining factors that shape local value chain development.

The eco-design toolkit produced under T1.3 provides a structured set of key performance indicators (KPIs) relevant to LVC development, organised under four themes:

(I) nature-based design and environmental footprint,

(II) durability and repairability,

(III) recyclability and end-of-life management, and

(IV) service orientation.

From Theme I, KPIs related to local material sourcing, the use of natural or low-impact materials, water-risk sensitivity, and circularity of sourcing inform the potential for local

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procurement of virgin or recycled materials. Theme II KPIs, such as ease of disassembly, tools needed for maintenance, spare parts availability and cost, and the presence of repair documentation, shed light on the feasibility of using local skilled labour for maintenance and repair. From Theme III, KPIs on recyclability, reusability, ease of material separation, the availability of local disposal and recycling chains, and end-of-life documentation highlight the potential for managing products locally at the end of their lifecycle; this aspect is further developed in Task 2.3.2. Finally, the KPI on service models in Theme IV provides insight into the extent to which technology providers intend to work with local partners for ongoing operation and maintenance, rather than relying on one-off product sales. Collectively, these themes help assess the potential for localising core value chain activities for each SUNNY solution.

The data gathered under T2.4 further complements these insights. As part of preparing training modules, technology partners supplied detailed descriptions of their system components, operational and maintenance tools, and installation, operation, and servicing procedures. This information enriches the findings from T1.3 by offering a deeper understanding of the practical requirements, opportunities, and bottlenecks associated with localising manufacturing, installation, maintenance, and end-of-life processes within each value chain.

3. Results

a. Hydrogen for cooking in Mahama

The hydrogen cooking solution demonstrated in the SUNNY project combines on-site renewable hydrogen production with safe, low-pressure storage and dedicated hydrogen cookstoves to enable clean cooking without reliance on conventional fuels. Hydrogen is produced using SOLHYD solar hydrogen modules, which extract water from ambient air and convert it into low-pressure hydrogen using electricity from integrated photovoltaic panels. Each system consists of modular hydrogen-producing units together with an autonomy module equipped with battery storage and supervisory control, enabling fully autonomous operation with no external inputs beyond sunlight. The produced hydrogen is delivered at low pressure and can be safely channelled into local storage units.

Storage and distribution are managed through mobile gas bags, which are non-elastic multilayer bags with hydrogen-tight inner linings, or flexible tire-tube-based units. Both alternatives can be filled at the production site and transported manually to cooking points. In case stationary storage is required, rigid tanks equipped with pressure-release valves and flame arrestors can be used. The mobile storage options connect directly to hydrogen cookstoves, which use diffusion burners with flame-visualisation elements, integrated gas valves, and pressure regulators to ensure clean and efficient combustion. The cookstoves are intended for outdoor or semi-outdoor use and can be

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operated either in communal kitchens or at the household level.

Together, these components form a decentralised ecosystem in which hydrogen is produced locally, stored flexibly, and used directly for cooking. The system eliminates the need for biomass or fossil fuels, avoids local resource depletion, and offers a smoke-free cooking alternative that can reduce indoor air pollution and associated health risks. Its modularity and portability make it suitable for refugee-hosting contexts, where infrastructures may be limited and demand patterns can vary. This configuration provides multiple opportunities for local value chain development, including installation, maintenance, gas-bag handling, and stove upkeep.

The potential LVC for the hydrogen cooking solution, encompassing its three core components of hydrogen production modules, mobile storage units, and hydrogen cookstoves, has been developed using the ILO's methodological framework together with the inputs generated across relevant SUNNY project tasks. Figure 1 presents an overview of the resulting LVC map across the entire product lifecycle. The core value chain functions include the installation, operation, and maintenance of the hydrogen production facility; the storage, handling, and distribution of the generated hydrogen; its end use in cooking applications; and the management of components at their end-of-life. For each function, the analysis identifies potential local actors, key supporting services, and the principal risks and bottlenecks that may influence the viability of the chain. The map also highlights the overarching regulatory requirements applicable to hydrogen production, storage, and use, as well as the expected outcomes linked to the deployment of this clean cooking solution within the demonstration context.

Given the innovative nature of the hydrogen cooking solution, all core components—namely the hydrogen production modules, mobile storage units, and hydrogen cookstoves—are proprietary technologies developed by SOLHYD and SOLHYDAIR. These components will therefore be imported directly from the companies' headquarters in Belgium for deployment in the Mahama refugee–host community in Rwanda. As a result, the potential for substituting materials with locally sourced alternatives at this stage is limited. Nonetheless, SOLHYDAIR has proposed two possible avenues for localisation within the storage and end-use stages of the solution. The first involves the use of truck inner tire tubes as a substitute for SOLHYDAIR's dedicated hydrogen storage bags. However, their local availability and cost-effectiveness are still under assessment. The second option is the refitting of existing LPG stoves to operate using hydrogen. At the time of writing, SOLHYDAIR has not confirmed whether this pathway will be pursued in practice, and its feasibility will partly depend on the characteristics of the target user group. Survey results from Task 1.3 indicate that not all households in Mahama own LPG stoves, and that many rely on firewood, charcoal, or briquettes, either as primary fuels or as more affordable alternatives when LPG cylinders are depleted before scheduled refills. These patterns will influence both the practicality and potential uptake of locally

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adapted hydrogen cooking hardware. Thus, at the procurement stage, the principal risk lies in the solution's dependence on imported foreign components. These may be more costly than viable local alternatives, may incur import duties, and are associated with potentially long lead times before delivery to the demonstration site.

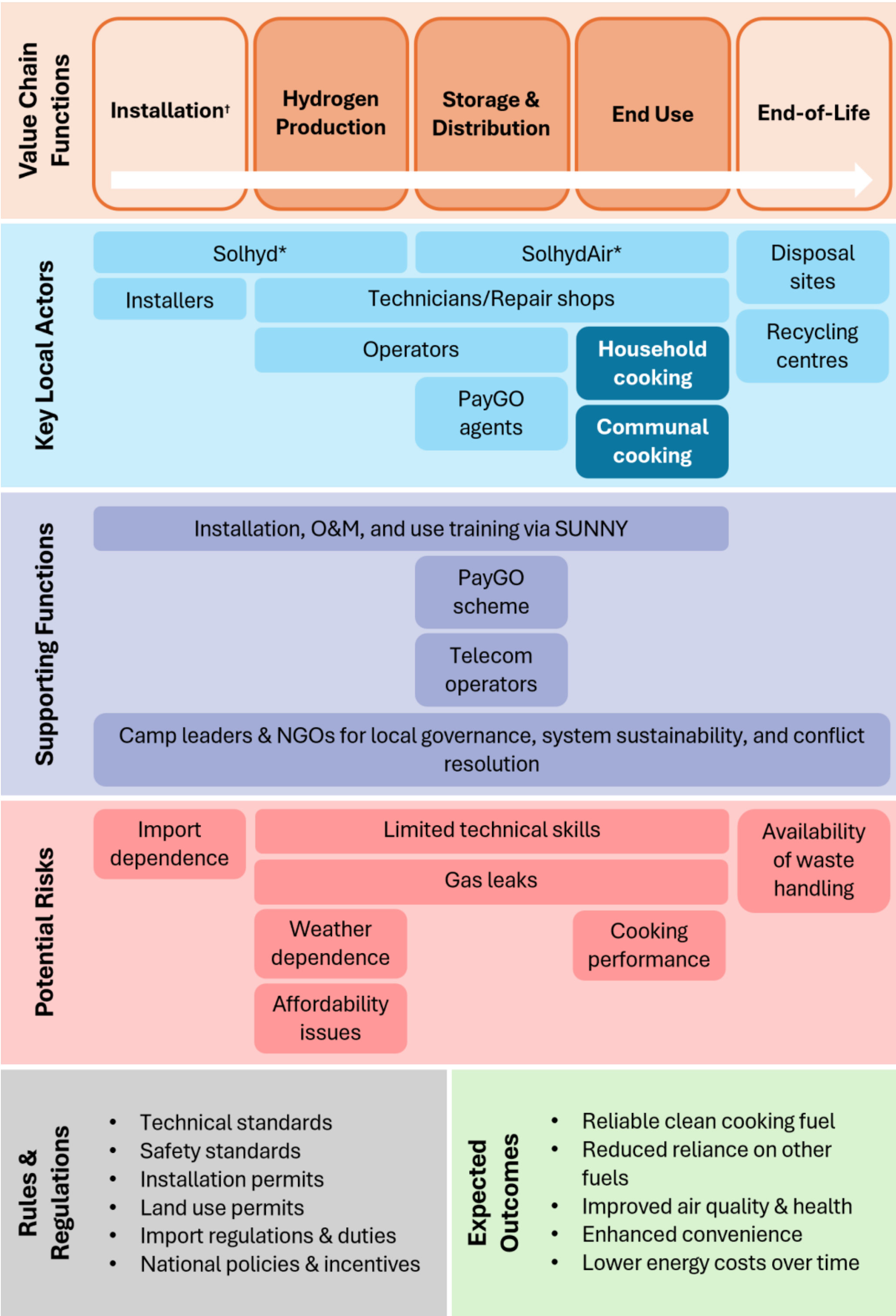

Figure 1. Local value chain map of the hydrogen cooking solution. Key actors marked with an asterisk are non-local ones.

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The installation phase of the hydrogen cooking solution introduces additional considerations for the local value chain. SOLHYD has indicated that the system setup and commissioning of the hydrogen production modules must be carried out exclusively by certified SOLHYD personnel, given the safety requirements associated with hydrogen generation. Nonetheless, the physical installation of the modules can be undertaken by trained local workers, provided they receive detailed instruction on installation procedures. This capacity-building process is planned within later work packages of the SUNNY project and presents an opportunity to develop technical skills within the local workforce.

Beyond the installation itself, the implementation site requires careful preparation to ensure optimal system performance. This includes conducting groundwork and constructing suitable foundations so that the modules can be placed on a stable, horizontal surface free of debris or sharp objects. The site must also be located outdoors with at least six hours of unobstructed sunlight, and should be positioned away from shading by nearby infrastructure or vegetation. These preparatory activities can be planned and executed jointly with local partners, creating opportunities for collaboration and local involvement.

In Mahama, site management structures are well established, as outlined in Task 1.1. The camp is overseen by a Camp Manager and Deputy Camp Manager appointed by the Ministry in Charge of Emergency Management (MINEMA), and governance within the settlement includes an executive committee elected from the refugee community, nine quarter leaders, and eighteen village leaders. Engagement with the appropriate local leaders will be necessary depending on the chosen installation location, both for logistical coordination and community acceptance. The United Nations High Commissioner for Refugees (UNHCR), working closely with MINEMA, is also a key actor given its role in service provision, safety, and site-level coordination within Mahama.

Finally, site preparation will require assessing the local availability of construction materials and skilled labour, such as cement, concrete, and experienced construction workers. Where feasible, these tasks can be delegated to local contractors or labour groups, thereby contributing to local economic activity and embedding the installation process more firmly within the local value chain.

The hydrogen storage bags supplied by SOLHYDAIR arrive ready for use, requiring no additional preparation before distribution to end users. However, if the bags need to be stored temporarily prior to collection, the storage area must meet specific conditions to ensure safety and prevent damage. As the bags are susceptible to puncturing, the storage surface should be stable, level, and completely free of debris or sharp objects that could compromise their integrity. For safety and security reasons, the storage area should also be fenced off, mirroring the precautionary measures recommended for the hydrogen production site, in order to minimise risks of unauthorised access, tampering,

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or theft. Ideally, the storage space should be located within the same secured perimeter as the production modules, which streamlines site supervision and simplifies operational logistics. As with the production site, site selection and preparation offer opportunities for collaboration with local partners and labour, including identifying suitable locations, preparing the ground, and installing fencing or other protective structures.

The hydrogen cookstoves provided by SOLHYDAIR are likewise delivered ready for use, requiring no additional preparation before deployment. Two potential use cases are envisioned: centralised cookstoves for communal cooking areas, and decentralised cookstoves used by individual households. In both cases, the stoves must be operated outdoors or in well-ventilated semi-outdoor spaces, and placed on a stable, level surface free of debris or sharp objects to avoid hazards and ensure proper functioning. For the communal cooking scenario, the selection and preparation of suitable cooking areas can be undertaken in collaboration with local partners and the local workforce, following the same approach as for the hydrogen production and storage sites. In the household-level use case, responsibility for meeting these conditions lies with individual households, who must ensure that their designated cooking space is safe, unobstructed, and compliant with the recommended operating environment.

At the operation stage, the hydrogen production modules function autonomously, initiating and suspending hydrogen generation based on solar irradiance and system pressure. Nevertheless, local operators will be required to oversee day-to-day functioning. Their responsibilities include routine visual inspections, maintaining the cleanliness of both the system and surrounding site, and activating the emergency stop mechanism in the event of hazards or technical malfunctions. As hydrogen technologies are entirely new to the local context, the SUNNY project will provide all necessary technical and safety training in later work packages to ensure operators are adequately prepared.

Operators will also be responsible for refilling the hydrogen storage bags, which requires adhering to the prescribed filling procedure, visually checking each bag for signs of wear or damage, and conducting leak detection using handheld sensors or appropriate sprays. Once filled, they must ensure that the bags are safely stored until they are collected by end users. Additional responsibilities may include managing payments and keeping distribution records, although these tasks could alternatively be assigned to local Pay-As-You-Go agents, depending on the final implementation model.

In the case of the communal cooking use scenario, an on-site supervisor will be needed to oversee the cooking area, ensure safe operation, and support users who may have questions or encounter issues when handling storage bags or cookstoves. This role is important both for maintaining safety standards and for fostering user confidence during the early stages of technology adoption.

Maintenance and repair activities that go beyond routine operational checks present

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opportunities for engaging local technicians and repair workshops, provided that they receive comprehensive training through the SUNNY project and have access to clear, practical repair documentation. According to SOLHYD, most of the tools required for maintaining the hydrogen production modules are standard, non-specialised tools, although local technicians may not currently own the full set needed for effective servicing. To enable local repair capacity, the required tools, as well as any proprietary items, should be supplied as part of the project. In addition, establishing a local stock of spare parts will be essential to avoid delays caused by shipping components from the European Union.

Some elements of the hydrogen production system, such as solar PV panels, piping, and pipe fittings, can be repaired or replaced using supplies that are readily available locally. However, the hydrogen-generating cores, which extract moisture from the air and produce hydrogen, remain a proprietary SOLHYD technology. Repairs on these components are currently undertaken by SOLHYD personnel, who have remote access to system data and can provide diagnostic support to trained local technicians. If a core requires replacement, it must be imported unless the project establishes a local buffer stock. SOLHYD has also indicated that the production facility should undergo annual inspections by SOLHYD service engineers to maintain and potentially extend the system warranty.

Similar considerations apply to the hydrogen storage bags and cookstove burners, which are proprietary products developed by SOLHYDAIR. Storage bags cannot be repaired, and any damage requires full replacement, while essential stove components, such as stove burners with visualisation elements, also need to be imported. To ensure continuity of service and avoid operational disruption, it will therefore be necessary to maintain a secure local warehouse for storing critical spare parts, overseen either by system operators or dedicated supply managers. This arrangement would help mitigate supply bottlenecks and support the long-term reliability of the hydrogen cooking solution.

The circularity aspects of the hydrogen cooking value chain are examined in depth in Task 2.3.2. However, preliminary inputs from SOLHYD and SOLHYDAIR indicate that most system components are currently manufactured from virgin rather than recycled materials. SOLHYD has noted that components of the hydrogen production modules can be returned at end-of-life for refurbishment and recycling, offering a degree of circularity within the production stage. In contrast, SOLHYDAIR has indicated that no take-back scheme is presently available for the hydrogen storage bags or cookstoves, meaning that end-of-life management for these components will need to rely on local disposal and recycling pathways, which are being further assessed in Task 2.3.2.

In addition to identifying local actors and supporting functions, the hydrogen cooking solution must comply with a range of rules and regulations. These include technical and

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safety standards governing hydrogen systems, installation and land-use permissions, and the import requirements and duties associated with bringing specialised components into Rwanda. SOLHYD and SOLHYDAIR have noted that all system components are manufactured from robust, durable materials that have been validated under outdoor conditions, although further testing in sub-Saharan African climates is required. This will be undertaken during the SUNNY project's piloting phase.

Beyond technical compliance, the project must also secure the relevant local permits and approvals. These are issued primarily by the camp authorities and national bodies, such as MINEMA. Findings from T1.1 further highlight the relevance of Rwanda's Energy Policy and the Energy Sector Strategic Plan, both issued by the Ministry of Infrastructure. However, these policy documents do not explicitly extend to refugee settlements, creating a degree of regulatory ambiguity for energy interventions in camps. Additional reference documents include the Plan of Action for Rwanda's Transition to Modern Energy Cooking, developed by the Modern Energy Cooking Services (MECS) programme and the Energy Sector Management Assistance Program (ESMAP). A full list of applicable regulations, policies, and standards is provided in Deliverable 1.1 of Task 1.1, which should guide ongoing implementation and compliance efforts.

Drawing on the preceding analysis of procurement, installation, operation, maintenance, end-of-life management, and regulatory considerations, the key strengths and weaknesses of the proposed local value chain, along with the main opportunities and threats that may influence its long-term viability, are summarised in Table 1.

Table 1. SWOT analysis of the hydrogen cooking local value chain.

Strengths	Weaknesses
The solution enables meaningful involvement of the local workforce in installation, site preparation, routine operation, storage handling, and some maintenance activities.	Heavy dependence on imported proprietary components from Belgium, leading to high costs, import duties, and long lead times.
Structured training planned within the SUNNY project builds local technical capacity and enhances safety and operational reliability.	Limited potential for local material sourcing due to the specialised and proprietary nature of major system components.
Strong governance and coordination structures exist in Mahama (MINEMA, UNHCR, refugee leadership), facilitating community engagement and oversight.	Critical components—especially hydrogen generating cores—cannot be repaired locally and require support from SOLHYD.
Certain non-proprietary components (e.g. PV panels, piping, fittings) can be repaired or replaced locally.	Hydrogen storage bags and cookstoves lack a take-back scheme, and damaged storage bags cannot be repaired.
Potential long-term localisation pathways exist (e.g. tire tube storage alternatives, hydrogen compatible stove retrofits).	Steep learning curve and significant training requirements due to lack of prior local experience with hydrogen systems.
The solution supports public health and	Ambiguity in national policy and regulatory

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environmental goals, reducing reliance on biomass fuels.	frameworks, as energy policies do not explicitly cover refugee settlements.
Opportunities	**Threats**
Creation of local jobs and skill building opportunities for operators, technicians, PAYGo agents, and maintenance personnel.	Hydrogen production relies on sufficient sunlight, and low irradiance could reduce daily hydrogen output during certain seasons.
Potential development of local micro-enterprises for storage bag handling, distribution, record-keeping, and site supervision.	If hydrogen cooking is more expensive than charcoal, firewood, or briquettes, households may be unwilling or unable to adopt it.
Scope for gradual expansion of local repair capability for non-proprietary components and possible future local adaptation or assembly.	Even with PAYGo mechanisms reducing upfront costs, irregular income patterns may still constrain household ability to pay for clean hydrogen fuel.
Local manufacturing or adaptation options may emerge if tire tube storage or stove conversions prove viable and scalable.	Improper handling of storage bags or stove connections may lead to hydrogen leaks if training and safety practices are not strictly followed.
Alignment with national clean cooking ambitions and international decarbonisation efforts may attract longterm partnerships and funding.	If the hydrogen flame is perceived as weaker, less visible, or less versatile than traditional fuels, user adoption may lag.
The pilot could serve as a proof-of-concept for hydrogen cooking in other camps or rural settings.	Environmental challenges such as dust, heat, and heavy rain may affect the durability of specific system components, while overall reliance on imported parts exposes the system to global supply chain disruptions.

b. Solar home systems in Mahama

The solar home system (SHS) solution deployed in the SUNNY project provides households with a stand-alone, off-grid electricity supply designed to meet basic energy needs such as lighting, phone charging, and the operation of small DC appliances. Each system consists of a solar photovoltaic module (typically 100–400 Wp), a charge controller equipped with overcharge and deep-discharge protection, a lithium iron phosphate ($LiFePO_4$) battery with an integrated battery management system, and a set of DC and USB output ports for powering end-use devices. LED lighting kits are included as part of the standard load configuration.

SHS units present a robust, clean, and user-friendly alternative to kerosene lamps, disposable torches, and other unsafe or polluting energy sources commonly relied upon in off-grid communities. In the context of refugee and host-community settings, they not only improve indoor air quality and safety but also support education, communication,

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and income-generating activities by providing reliable household-level electricity access.

The potential LVC for the SHS solution offered by SOLEKTRA, comprising its key components of the solar PV module, charge control unit, battery storage, and household DC output system, has been developed using the ILO's methodological framework alongside the inputs gathered from relevant SUNNY project tasks. Figure 2 presents an overview of the resulting LVC map across the SHS product lifecycle. The core value chain functions include the procurement and installation of the solar panels and balance-of-system components, the operation and routine maintenance of the system at household level, the provision of user support and troubleshooting services, and the management of components at end-of-life. For each of these functions, the analysis identifies potential local actors, supporting organisations, and the key risks and bottlenecks likely to influence the viability of the value chain. The map also highlights the overarching regulatory considerations relevant to the importation, installation, and safe operation of SHSs, as well as the expected outcomes associated with the deployment of this decentralised electricity solution in the demonstration site in Mahama, Rwanda.

Despite the technological maturity and widespread global use of SHSs, there is no local manufacturing capacity for any of the key SHS components. As a result, all system elements, including the PV module, charge controller, battery, and LED lighting kit, are imported and pre-assembled by SOLEKTRA before delivery to the demonstration site, where they are provided as ready-to-install kits. This creates a familiar risk for the procurement stage; a strong dependence on imported system components, which may expose the value chain to high procurement costs, import duties, and longer lead times. Nevertheless, findings from Task 1.4 on use-case definitions indicate that the Government of Rwanda offers significant tax exemptions and incentives for solar PV equipment, which can partly mitigate these risks.

Once the assembled SHS kits arrive at the demonstration site, the local community can take an active role in site selection, site preparation, and system installation. The PV module must be installed in a location with full solar exposure and no shading from structures, vegetation, or nearby obstacles, while the battery must be placed in a dry, well-ventilated, shaded space to prevent overheating and ensure long-term performance. SOLEKTRA has indicated that the SUNNY project will provide training for local installers and technicians, enabling their participation in system installation and reducing dependence on external specialists. The tools required for installation, such as screwdrivers, drills, multimeters, cable ties, and personal protective equipment, are standard and widely available, although some may need to be supplied to ensure that local installers are adequately equipped.

As with the hydrogen cooking solution, permits for land use and installation must be obtained from the camp authority, represented by MINEMA and supported by UNHCR.

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The use case proposed by SOLEKTRA involves multiple households sharing a single SHS to reduce costs and increase affordability, which implies that the solar panel will likely be ground-mounted in a shared community area rather than installed on individual rooftops. In such cases, groundwork may be required to stabilise the mounting structure and secure the installation site. These tasks can be undertaken by local installers and labourers, providing additional opportunities for community engagement and local employment.

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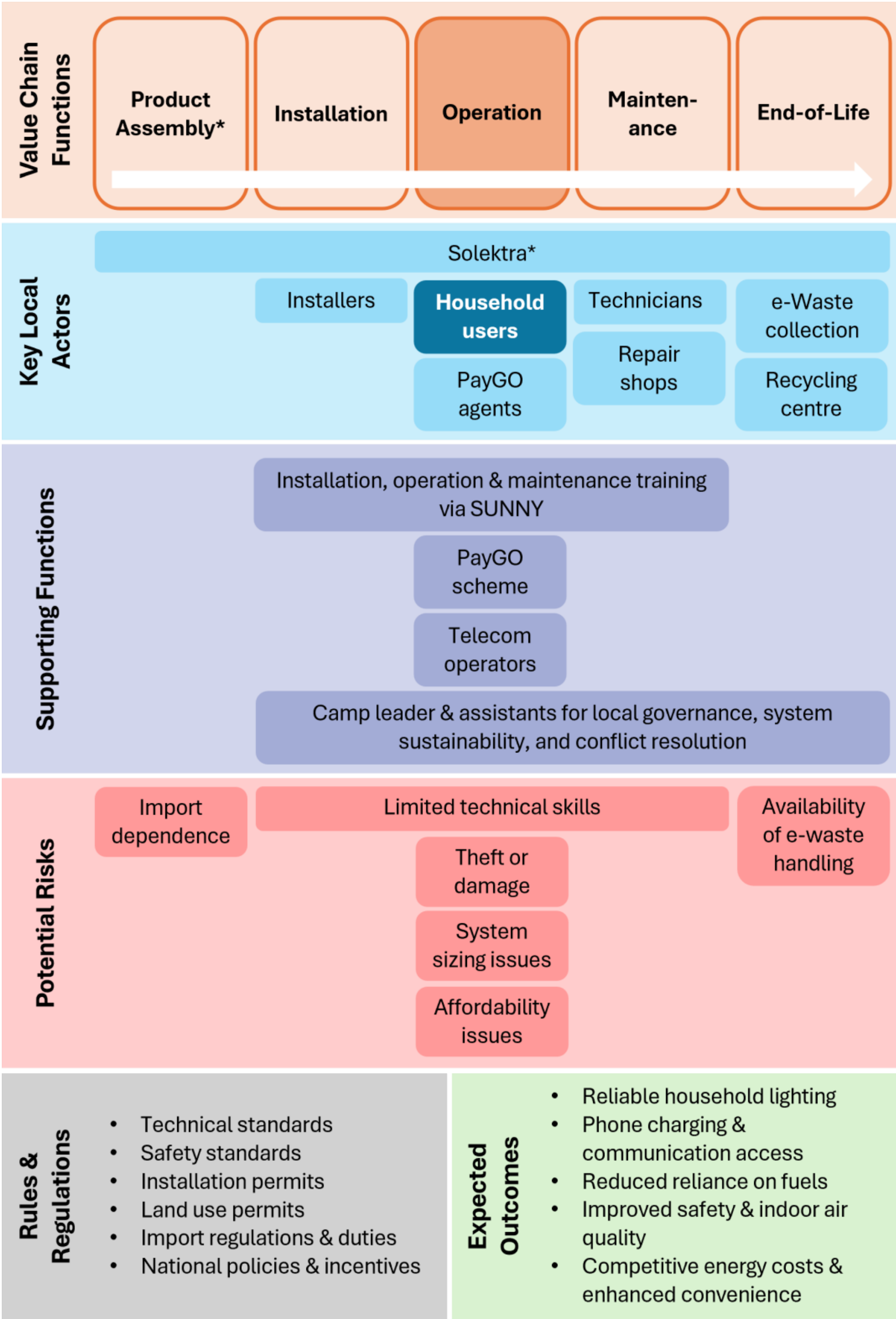

Figure 2. Local value chain map of the solar home system solution. Key actors and functions marked with an asterisk are not local to the demonstration site.

The operation stage of the solar home system is relatively simple, as the system functions autonomously once installed and activated. After installation, households can immediately begin using the SHS to power lights, charge phones, and operate small DC appliances. As part of the SUNNY project, SOLEKTRA will provide user training to ensure

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household members understand how to use the system safely and carry out basic maintenance tasks, such as regularly cleaning the solar panel to optimise energy generation and keeping the battery area dry and well ventilated to maintain battery health. Users are required to create a Pay-As-You-Go (PayGO) account, through which they can purchase electricity credits via mobile payments. This approach reduces upfront financial barriers and enables flexible, incremental payments. The operation stage represents the highest potential for local value creation, as electricity generation occurs directly at the household level, local PayGO agents can facilitate customer support and payment collection, and mobile network operators provide the digital infrastructure for payments and remote monitoring.

However, several risks may affect this stage. Users may encounter difficulties with system operation, incorrect use, or challenges in completing mobile payments. SHS components may also be vulnerable to damage or theft, particularly when the panel is ground-mounted. System size may prove insufficient to meet the combined needs of multiple households, especially during periods of low solar irradiation, leading to energy shortages. Finally, affordability remains a key concern, as some households may struggle to maintain regular PayGO payments, particularly during months with competing household expenses or reduced income.

Maintenance and repair activities also create meaningful opportunities for local value creation within the SHS value chain. According to findings from Task 1.1, technicians and repair shops with prior experience working on SHSs already exist in the local context, offering a foundation on which additional capacity can be built. However, complementary training will still be required to ensure that local technicians are fully familiar with the specific configuration, components, and safety protocols of the SHS solution provided by SOLEKTRA. Effective repair services will depend on the availability of spare parts, appropriate tools—including a small number of proprietary items—and clear, accessible repair documentation, all of which need to be readily available on-site or within the camp to minimise downtime. Establishing this local repair ecosystem is essential for avoiding long lead times, preventing unnecessary transport costs associated with servicing components elsewhere, and ensuring that households can maintain reliable access to electricity.

The circularity aspects of the solar home system value chain are explored in detail in Task 2.3.2. Preliminary inputs from SOLEKTRA to the eco-design toolkit developed in Task 1.3 indicate that most SHS components are currently manufactured from virgin materials rather than recycled inputs. Nonetheless, SOLEKTRA has noted that between 60% and 80% of the system's total weight can be recycled at end-of-life, suggesting a significant potential for material recovery if appropriate channels are established. Although no recycling facilities exist within the Mahama settlement itself, national-level recycling centres are available and could be utilised for the responsible handling of PV modules,

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batteries, and electronic components. SOLEKTRA has also indicated a willingness to take back system components at end-of-life for a fee, offering an additional pathway for responsible local disposal as a Rwandan company. However, further improvements to component labelling, traceability, and end-of-life documentation will be necessary to ensure that systems can be dismantled and processed correctly, whether at the local or national level.

In addition to identifying local actors and supporting functions, the solar home system solution must comply with a range of rules and regulations governing its deployment and operation. These include adherence to relevant technical and safety standards, obtaining installation and land-use permissions, and meeting the import requirements associated with bringing specialised solar equipment into Rwanda. According to inputs provided in Task 1.4, SOLEKTRA's SHS solution already complies with all required international and national technical and safety certifications, ensuring that the system meets established quality and protection benchmarks. Building on its prior experience deploying SHSs across Rwanda, SOLEKTRA has also strengthened the durability and safety features of the system to withstand local environmental conditions, including heavy rainfall and tropical thunderstorms typical of the region. As with the hydrogen cooking solution, any installation within Mahama requires securing the appropriate permits from camp authorities, coordinated through MINEMA and supported by UNHCR. At the national level, Rwanda's Energy Policy and Energy Sector Strategic Plan, both issued by the Ministry of Infrastructure, are also relevant frameworks guiding renewable-energy deployment. A comprehensive list of applicable national policies and regulations is available in Deliverable 1.1 of Task 1.1 and should be consulted to ensure full compliance across the SHS value chain.

Building on the preceding analysis of procurement, installation, operation, maintenance, circularity, and regulatory considerations, the main strengths, weaknesses, opportunities, and threats associated with the solar home system local value chain are summarised in Table 2.

Table 2. SWOT analysis of the solar home system local value chain.

Strengths	Weaknesses
SHS components are technologically mature, widely tested, and supplied as ready-to-install kits by SOLEKTRA, reducing system complexity for end users.	No local manufacturing capacity exists for SHS components, creating full dependence on imported PV modules, controllers, batteries, and accessories.
SOLEKTRA is a locally based Rwandan company with prior national experience deploying SHSs and enhancing durability for local weather conditions.	Spare parts, proprietary tools, and documentation must be stocked locally to avoid long lead times and high transport costs.
Local participation is possible in site selection, preparation, installation, and basic	Local technicians require complementary training to handle SOLEKTRA's specific

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maintenance, supported by SUNNY project training.	configuration, safety features, and maintenance protocols.
Routine maintenance tasks (panel cleaning, cable inspection, battery care) are simple and suitable for household-level involvement.	Shared-system configuration may strain system capacity during periods of low solar irradiation or high household demand.
The PayGO model lowers upfront costs and leverages Rwanda's strong mobile-money ecosystem, enabling local PayGO agents and digital system monitoring.	Ground-mounted PV modules in shared areas are vulnerable to accidental damage, tampering, or theft.
60–80% of system weight is recyclable, and SOLEKTRA can take back components at end-of-life for responsible disposal.	Components are mostly made from virgin materials, and improvements are needed in labelling and end-of-life documentation to support circularity.
Opportunities	**Threats**
Local job creation across installation, maintenance, troubleshooting, and PayGO operations.	Low irradiance during rainy seasons reduces generation and may affect user satisfaction.
Existing technicians and repair shops can expand capabilities to service SHSs, improving long-term sustainability.	Affordability risks persist, as households may struggle with regular PayGO payments despite lower upfront costs.
Potential for establishing local service hubs for diagnostics, spare-parts storage, and user support.	Payment interruptions could lead to disconnections, creating energy insecurity or loss of user trust.
Alignment with national solar policies and tax incentives supports future scaling.	System damage or theft is possible in shared or exposed locations, especially where panels are ground-mounted.
Potential for future system expansion or integration with productive-use appliances.	Community demand may exceed system capabilities, leading to perceptions of underperformance.
Circularity potential through national recycling centres and SOLEKTRA's take-back option.	Regulatory uncertainty persists in refugee settings, requiring close coordination with camp authorities for land use and installation.

c. Smart solar irrigation in Bidibidi

The solar irrigation solution developed by SOLEKTRA for the SUNNY project provides a solar-powered, off-grid pumping system designed to supply water for agricultural use in locations without reliable grid access. The system consists of several integrated components: solar PV modules mounted on a fixed structure; DC protection devices such as fuses and surge protection; a submersible or surface water pump controlled by a maximum power point tracker or variable-frequency drive controller; and a water storage and distribution system comprising an elevated tank, inlet and outlet piping, main and branch distribution pipelines, and optional metering or control devices. The

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system operates by converting sunlight into electricity to power the pump during daylight hours. Water is extracted from a borehole, well, or surface source and pumped into a raised storage tank, from which it flows by gravity through a distribution network to irrigation plots.

Solar irrigation systems offer a renewable, low-operating-cost alternative to diesel or manually powered pumps, reducing fuel expenditures, enabling more reliable water access, and supporting higher agricultural productivity. In the SUNNY project context, the solution has strong potential to enhance the resilience and economic opportunities of both refugee and host-community farmers by improving water availability for crops while avoiding the emissions and recurring costs associated with fossil-fuel pumping.

The potential LVC for the solar irrigation solution, comprising the solar PV array, pump, controller, water storage tank, and distribution network, has been developed using the ILO's methodological framework together with inputs from relevant SUNNY project tasks. Figure 3 illustrates the local value chain specifically during the productive-use phase, highlighting the activities carried out by farmers such as planting, irrigating, harvesting, and selling produce. By contrast, the full LVC analysis presented in this section covers both the system's technical lifecycle—procurement, installation, operation, and maintenance—and the productive-use phase that follows. The core value chain functions therefore include not only the installation and routine upkeep of the solar pumping system, but also the agricultural activities enabled by improved water access. For each function, the analysis identifies relevant local actors, required supporting services, and the major risks and bottlenecks that may influence the viability of the chain in Bidibidi, Uganda. The map also highlights the overarching regulatory considerations for water use, land allocation, and system installation, as well as the expected livelihood and food-security outcomes associated with deploying the solar irrigation solution in the refugee and host-community context.

Despite the technological maturity and widespread commercial use of the solar irrigation system components, there is no local manufacturing capacity within the Bidibidi settlement for any of the major hardware elements. As a result, key components such as the solar PV panels, pump, and electronic controller must be imported, creating a degree of procurement dependence that carries inherent risks. Such risks include cost fluctuations, long lead times, and vulnerability to supply-chain disruptions. However, several other components, particularly the water storage tank, HDPE/PVC distribution pipes, and associated valves, are likely to be available through national suppliers in Yumbe District, the nearby regional centre of Arua, or other parts of Uganda. Confirming the availability, pricing, and quality of these components will be an important next step, as sourcing them nationally could increase the local fraction of the procurement phase, support Ugandan suppliers, and reduce both transport costs and delivery times.

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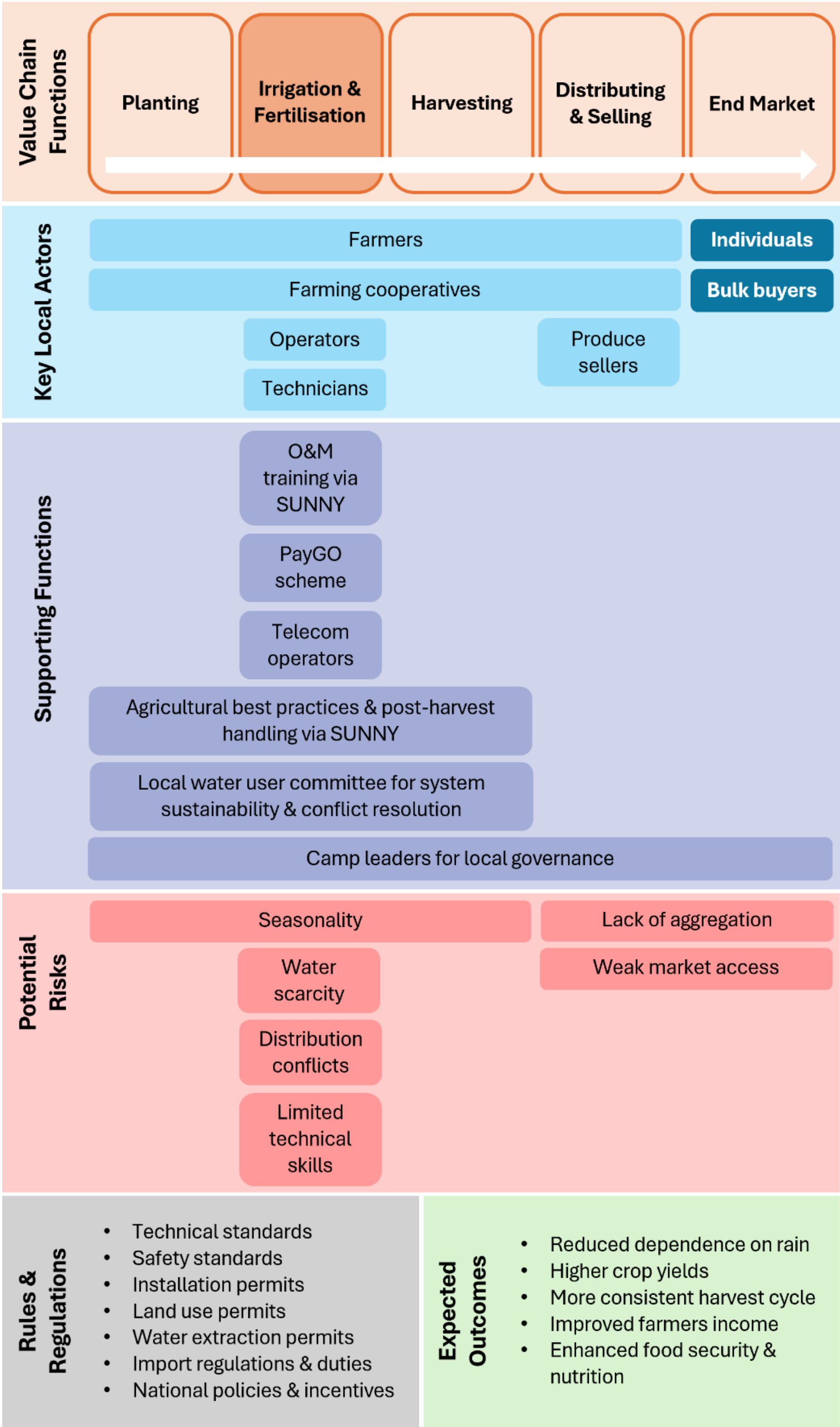

Figure 3. Local value chain map of the solar irrigation solution during its productive use phase.

SOLEKTRA is responsible for designing and delivering the solar irrigation system, but this design process can only be finalised once the implementation site has been selected. Site selection therefore represents a critical first step in the value chain, as the system specifications, such as pump type, controller settings, pipeline length, storage-tank size,

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and mounting structure, must be tailored to the specific characteristics of the chosen location. According to findings from Task 1.1, Bidibidi is organised into five zones of similar population size. UNHCR mapping indicates that zones 1–4 have access to natural water streams, while zone 5 depends primarily on wetlands. All zones include designated agricultural land, meaning that several potential sites may be technically suitable. Choosing the most appropriate location requires close coordination with camp leadership and the Office of the Prime Minister (OPM), who oversee land allocation and settlement governance. The selected site must provide reliable and sustainably extractable water resources, whether surface or groundwater, and extraction limits will need to be confirmed through hydrological and environmental assessments. Proximity to a cluster of agricultural plots is also essential to maximise the number of beneficiaries and minimise pipeline lengths and installation costs.

Once the site is confirmed and all required permits have been secured, SOLEKTRA can collaborate with local installers to carry out system installation. This includes mounting the solar PV array in a location with full sunlight exposure and no shading, installing the water pump at the selected water source, erecting the elevated water storage tank with adequate structural stability, and laying the distribution pipelines at the correct depths while maintaining appropriate gradients for gravity-fed irrigation. Depending on the nature of the water source, the local workforce may also be required to dig boreholes if groundwater extraction using a submersible pump is necessary. Risks at this stage include potential water scarcity, as well as limited local technical capacity or specialised equipment, which may affect installation quality or timelines.

The operational phase of the solar irrigation solution is considerably more complex than that of the hydrogen cooking or solar home system solutions, primarily because it enables productive use and involves a wider set of value-chain actors. In this context, the end users of the irrigation system, farmers and farming cooperatives, are distinct from the end market, which consists of buyers of agricultural produce. The core functions of the local value chain during the operational stage therefore extend beyond the technical use of the irrigation system to encompass the full agricultural production cycle: crop planting, application of irrigation using SOLEKTRA's solar-powered pumping system, harvesting, and ultimately the distribution and sale of crops to individual consumers, local markets, traders, or bulk buyers. Because the irrigation solution serves as an enabler of agricultural production rather than a final service in itself, the viability of the system depends not only on the technical performance of the irrigation equipment but also on the strength and coordination of the entire agricultural value chain. This includes the availability of farming inputs, access to land and water, functional producer groups, and well-developed market linkages. Ensuring that each of these elements is supported is essential for realising the economic benefits of the solar irrigation system and for achieving long-term sustainability in the Bidibidi context.

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The types and quantities of crops cultivated under the solar irrigation system will depend on several interrelated factors, including local climate conditions, soil quality, and the reliability of available water sources. Access to seedlings and the level of local demand for specific produce varieties will also influence farmers' planting decisions. Effective and timely irrigation is central to achieving good yields, and the availability, efficiency, and reliability of water delivery therefore play a major role in determining the productivity of the system. SOLEKTRA's solar irrigation solution is designed as a centralised system, whereby farmers request the amount of water they need and receive it according to an agreed irrigation schedule. The irrigation solution possesses a number of potential risks, including the affordability of water services for farmers, possible conflicts over water allocation when multiple users rely on the same system, limited technical skills for operating and maintaining the infrastructure, and potential shortages linked to water scarcity or weather dependence, as the pump operates on solar power.

To address these challenges, it will be essential to establish a local water-user committee responsible for operating and maintaining the system, coordinating irrigation schedules, resolving disputes, and supporting farmers in their use of the technology. This not only enhances system reliability but also creates an additional entry point for local value creation and community empowerment. Furthermore, SOLEKTRA has noted in Task 2.4 that the SUNNY project can provide supplementary training on agricultural best practices and post-harvest handling, delivered in collaboration with farmer cooperatives and local NGOs. Such training complements the technical operation and maintenance training by strengthening the broader agricultural value chain, improving farmers' skills, and enabling them to derive maximum benefit from reliable irrigation. Ultimately, this can support higher yields, improved incomes, and greater purchasing power.

Affordability risks can also be mitigated through the shared nature of the system, which distributes the overall cost across several farmers, rather than requiring a single user to bear the full financial burden. Farmers will pay only for the amount of water they request, rather than contributing to the upfront capital cost of the entire system. These payments may be structured on a monthly or seasonal basis, and while the optimal model is still under assessment within the SUNNY project, preliminary findings from Task 1.3 suggest that farmers may prefer seasonal payments aligned with the timing of harvests and market sales.

Additional risks arise during the harvesting and marketing stages of the agricultural value chain. Field visits to Bidibidi indicate that local markets are small, dispersed, and characterised by low purchasing power, which can limit farmers' ability to sell their produce at scale. As a result, even if irrigation enhances crop yields, farmers may face high post-harvest losses due to the fragmented and inconsistent demand from

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individual buyers. One way to mitigate this challenge is through aggregation, whereby farmers pool their harvests to meet the volume requirements of larger buyers. While bulk buyers may not be present within the settlement itself, they are more likely to operate in nearby urban centres in Yumbe District, meaning that access to these markets could significantly improve sales prospects. Another strategy to reduce the risk of market saturation is to spread sales over a longer period, rather than releasing the entire harvest to the local market at once. Whether farmers aim to reach larger markets or extend the selling period, cold storage becomes essential to prolong the shelf life of perishable produce and maintain its quality until it reaches the end market. This creates a natural synergy with one of the other SUNNY solutions planned for Bidibidi; solar-powered cold storage provided by AkoFresh. This can help stabilise supply, reduce losses, and strengthen the overall agricultural value chain enabled by the solar irrigation system.

SOLEKTRA has indicated, as part of the solution description in Deliverable 1.3, that the solar irrigation system includes the option to integrate a fertigation setup. Fertigation involves applying water-soluble fertilisers directly to plant root zones through the irrigation system, which can significantly enhance plant health and crop yields by improving nutrient delivery efficiency. This feature also creates a promising synergy with the biogas-to-cooking solution to be implemented in Bidibidi by Metanogenia. The biogas production process generates a nutrient-rich digested effluent as a by-product, which can be further treated and used as an agricultural amendment. Integrating this effluent into the fertigation system could reduce farmers' reliance on manufactured fertilisers and support more circular, resource-efficient agricultural practices. However, further assessment is required to determine the suitability of combining both systems, including evaluating the safety and effectiveness of treated effluent for fertigation and understanding farmers' preferences regarding organic versus commercially manufactured fertilisers. Both aforementioned project synergies can further enhance the local fraction and circularity of the proposed value chains across these three SUNNY solutions.

The next core function in the product-lifecycle value chain is maintenance and repair, which plays a critical role in ensuring the long-term performance and reliability of the solar irrigation system. A significant portion of routine maintenance can be undertaken by the local water user committee, which is responsible for day-to-day system oversight. Routine tasks include daily checks of pump operation and water-tank levels; weekly activities such as cleaning the solar PV panels, inspecting intake filters, and checking for leaks along the distribution network; as well as monthly inspections of electrical connections, pipes, and valves. In addition, a comprehensive performance assessment should be carried out every six months to ensure system safety and efficiency.

When system faults or malfunctions occur, repairs can be carried out by trained local

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technicians. As with the other SUNNY solutions, the feasibility of local repairs depends on providing adequate training to build technical capacity, ensuring technicians have access to the full set of required tools (including any non-standard or specialised items), and supplying clear, detailed repair documentation that supports accurate troubleshooting. SOLEKTRA has also indicated through the eco-design toolkit that they will provide full remote support, including diagnostic assistance and operational guidance, which can significantly improve response times and reduce the need for external intervention. Establishing a small local stock of critical spare parts will further minimise downtime by reducing reliance on external procurement and transport processes.

The circularity aspects of the solar irrigation solution are examined in greater detail in Task 2.3.2. Preliminary insights from the eco-design toolkit indicate that, although most system components are technically recyclable, there are no local disposal or recycling chains within the Bidibidi settlement capable of handling these materials. SOLEKTRA has noted that comprehensive end-of-life documentation is already available and that all components are clearly identified to facilitate proper dismantling and recycling. However, as there is no take-back or buy-back scheme offered by the company, end-of-life management will require either the establishment of suitable local disposal pathways or the transport of discarded components to recycling facilities outside the settlement. Addressing this gap will be essential to ensure responsible waste management and support the long-term sustainability of the system.

In terms of governing rules and regulations, the solar irrigation solution must comply with a range of requirements at both the settlement and national levels. In addition to the general permits needed for land allocation and system installation, the selected site will require a water extraction permit, which can be obtained through the camp authorities and the OPM. According to Deliverable 1.3, several national policy frameworks are relevant, including the Uganda Water Policy issued by the Ministry of Environment, the NEMA Guidelines for Water Resource Use from the National Environment Management Authority, and the Uganda National Irrigation Policy under the Ministry of Agriculture, Animal Industry and Fisheries. All imported components will also require the appropriate import clearance documentation, and the availability of tax exemptions for renewable energy or irrigation equipment will need to be confirmed with Ugandan authorities. Additional insurance or service-guarantee arrangements may be necessary to safeguard community assets and reduce financial risks associated with unforeseen maintenance needs. Finally, the system must comply with all applicable technical and safety standards to ensure safe operation and long-term reliability within the Bidibidi context. A comprehensive list of applicable national policies and regulations is available in Deliverable 1.1 of Task 1.1 and should be consulted to ensure full compliance across the solar irrigation value chain.

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Drawing on the above analysis of the entire LVC, the main strengths, weaknesses, opportunities, and threats associated with the solar irrigation solution in Bidibidi are summarised in Table 3.

Table 3. SWOT analysis of the solar irrigation local value chain.

Strengths	**Weaknesses**
Technologically mature system components with proven performance in off-grid irrigation contexts.	No local manufacturing capacity within Bidibidi; key components such as PV modules, pumps, and controllers must be imported, creating procurement dependence.
Local actors can participate in site selection, preparation, installation, routine maintenance, and system oversight, enabling skill development and local engagement.	Some installation activities require technical expertise or specialised equipment that may not be readily available locally.
Centralised irrigation system supports coordinated water distribution, improving efficiency and affordability.	Shared-use operation may generate conflicts over water allocation without strong governance mechanisms.
Local water user committee provides a clear governance structure, supporting daily system management, conflict resolution, and equitable access.	Routine maintenance and repair require additional training, repair documentation, and provision of non-standard tools.
Potential synergies with other SUNNY solutions (solar cold storage, biogas production by-products) enhance circularity and integration across value chains.	Lack of local recycling and disposal chains for system components; end-of-life handling requires off-site processing or new local solutions.
Opportunities	**Threats**
Reliable irrigation enables farmers to diversify crops, increase yields, and strengthen participation in local and regional markets.	Water scarcity risks due to seasonal variability or insufficient groundwater/surface water availability.
Harvest aggregation can improve access to bulk buyers (e.g. in Yumbe), reducing post-harvest losses and increasing income.	Solar-powered pumps may underperform during periods of low solar irradiance.
Additional training on agronomy, post-harvest handling, and use of organic fertiliser (e.g. biogas effluent) can strengthen the wider agricultural value chain.	Limited technical capacity could affect operation and repair responsiveness, prolonging downtime.
Shared-cost model and pay-per-volume or seasonal water payments make irrigation more financially accessible for multiple farmers.	Affordability risks remain for some farmers even with shared costs and flexible payment options.
Integration with solar-powered cold storage can extend shelf life and improve market opportunities for perishable produce.	Dispersed and small local markets may continue to contribute to post-harvest losses without improved aggregation or storage.

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Establishment of a water user committee strengthens local governance and long-term system sustainability.	Potential disputes over water allocation or land use if coordination with OPM and camp authorities is insufficient.

d. Solar-powered cold storage in Bidibidi

The solar-powered cold storage solution to be implemented in the SUNNY project by AkoFresh provides an off-grid refrigeration system designed to keep fresh produce cool, prolong shelf life, and reduce post-harvest losses. The system consists of a refrigeration unit, solar PV panels, a battery bank, and a structurally insulated cold room. For mobile applications, the solution can also be mounted on a trailer platform equipped with suspension, tires, and stabilising supports. Temperature regulation and system performance are monitored through an IoT-enabled digital control board, which transmits operational data via SIM-based connectivity. Together, these components form a closed, energy-autonomous system powered entirely by solar energy.

The solution is particularly well suited for remote, off-grid contexts like Bidibidi, where access to reliable electricity is limited and post-harvest losses remain high. By providing decentralised cooling capacity, the system contributes to food preservation, income stabilisation, reduced waste, and local job creation. Its standalone nature and pay-as-you-store potential also make it accessible to smallholder farmers who cannot afford conventional cold chain infrastructure.

The potential LVC for the solar-powered cold storage solution, comprising the insulated cold room, refrigeration unit, solar PV array, battery bank, and IoT-based monitoring system, has been developed using the ILO's methodological framework together with inputs from relevant SUNNY project tasks. Figure 4 illustrates the local value chain specifically during the productive-use phase, highlighting activities undertaken by farmers and produce traders such as harvesting crops, collecting and transporting produce to the cold room, storing it under controlled temperatures, and subsequently distributing and selling it to individual customers or bulk buyers. By contrast, the full LVC analysis presented in this section covers both the system's technical lifecycle—procurement, installation, operation, and maintenance of the cold storage facility—and the aforementioned productive-use phase. The core LVC functions therefore extend beyond the physical assembly and day-to-day upkeep of the solar cold room to include the post-harvest handling, aggregation, preservation, and marketing activities that the solution enables. For each function, the analysis identifies the relevant local actors, supporting services, and the major risks and bottlenecks likely to shape the viability of the value chain in Bidibidi, Uganda. The LVC mapping also highlights the overarching regulatory considerations relevant to land use, installation, food safety practices, and operations, as well as the expected improvements in livelihoods, income stability, and food security outcomes associated with deploying the solar-powered cold storage solution in the refugee and host-community context.

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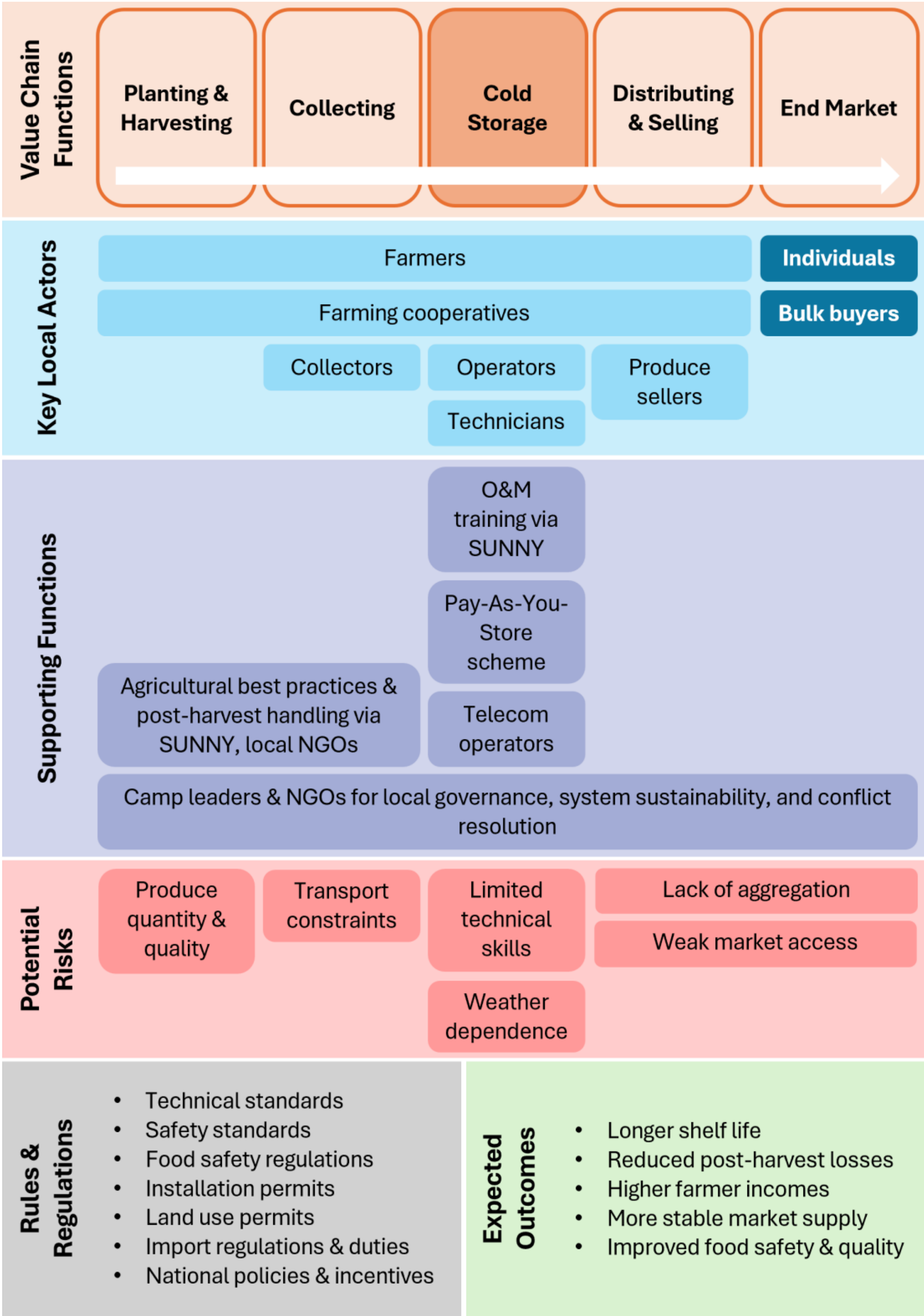

Figure 4. Local value chain map of the solar-powered cold storage solution during its productive use phase.

At the procurement stage, the cold storage solution faces similar constraints to the other SUNNY technologies that rely on solar PV panels, batteries, and power electronics, as these components cannot be manufactured locally within Bidibidi or the surrounding

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region and therefore must be imported from abroad. However, inputs provided by AkoFresh to the eco-design toolkit indicate that at least 30% of the system's physical components can be sourced locally, depending on availability. These include the metal framework and mounting structures, the insulated wall and floor panels. If a mobile cold-room configuration is used, the trailer frame, tires, and suspension could also be sourced locally. Procuring these items from suppliers within Bidibidi or other regions in Uganda would increase the local share of the value chain and reduce transport and logistics costs. System installation also requires the construction of a reinforced concrete slab as the foundation for the cold room. The cement, aggregates, and labour required for this task can likewise be sourced locally where available, creating further opportunities for local value addition.

Similar opportunities for local value creation arise during the installation stage of the cold storage solution, echoing the patterns observed for the other SUNNY technologies. These opportunities centre on site selection, site preparation, and the physical installation of the cold storage system. Site selection must be carried out in close collaboration with camp authorities and the OPM to ensure that all required land use and installation permits are obtained. Additional stakeholders, such as farmer cooperatives and local NGOs, can play an important role in identifying an optimal location that is close to produce harvesting and handling areas while also meeting the system's technical requirements.

From a technical standpoint, the selected site must offer adequate solar exposure, with at least six peak sun hours per day and no shading from nearby buildings or vegetation, to maximise PV generation. It must also have proper drainage to prevent flooding around the foundation. Once the site has been confirmed, members of the local workforce can be recruited to construct the reinforced concrete foundation, assemble the insulated cold room, and assist in installing system components such as the solar PV array, battery bank, inverter, refrigeration unit, and IoT monitoring devices. These activities will require targeted training provided through the SUNNY project to ensure correct installation and commissioning, as well as the provision of any tools that are not readily available locally, including specialised or proprietary equipment required for solar PV and refrigeration installation.

Focusing on the productive-use phase of the cold storage solution, this stage encompasses the full sequence of post-harvest activities: crop harvesting, collecting and transporting produce to the cold room for storage, and finally retrieving stored produce for distribution and sale to end markets. In the case of a mobile unit, transporting the cold storage facility to harvesting or market locations is possible. The primary local actors at this stage are farmers and farmer cooperatives, who use the cold room to preserve their produce, manage storage timing, and coordinate delivery to buyers. These actors may also be responsible for transporting goods to and from the

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cold room, though in some cases local collectors, aggregators, or produce vendors may take on this role, depending on market organisation and capacity. The mobile cold storage configuration additionally enables produce to be chilled directly at harvesting or selling points, reducing handling time and losses.

Effective operation also requires local cold storage operators, who oversee day-to-day use of the facility, carry out routine checks, monitor temperature and system status, and ensure proper loading practices that maintain airflow and cooling efficiency. These operators are also responsible for collecting payments from farmers according to their storage needs, particularly in a pay-as-you-store model, and for maintaining a logbook that records temperature readings, storage patterns, and any issues requiring technical attention. Together, these roles strengthen the local value chain by creating employment opportunities, enabling better produce management, and supporting more reliable access to markets.

Potential risks during the productive-use phase relate to produce quantity and quality, transport constraints, weather dependence, and limited technical skills among local actors. Produce quantity is shaped by the seasonality of harvesting cycles as well as the availability and effectiveness of irrigation and agricultural amendments. While seasonal fluctuations are unavoidable, the availability of water and soil-enhancing inputs can be improved through synergies with other SUNNY solutions, namely solar irrigation and the use of digested effluent from biogas production. Produce quality can be safeguarded through pre-sorting, ensuring that spoiled or damaged items do not enter the cold room and compromise the cooling performance or condition of other stored goods.

Transport constraints can be mitigated in several ways. Optimising the location of the cold storage unit to keep it close to key harvesting and handling points reduces travel time for farmers. Alternatively, dedicated collectors or aggregators could shoulder the transportation burden for farmers with limited mobility or inadequate transport options. If produce is widely dispersed, a mobile cold storage configuration can increase flexibility by serving multiple locations across Bidibidi.

Weather dependence affects both the volume and quality of produce arriving at the cold room and the continuity of storage operation, since the system is fully powered by solar PV. The integrated battery storage system helps extend operation into the night and provides resilience for a limited number of cloudy or adverse weather days, but prolonged poor irradiance may still pose constraints. Finally, limited technical skills in operating and supervising the cold storage system can be addressed through the training and capacity-building activities planned in later SUNNY work packages, ensuring that local operators, farmers, and collectors are able to use the system effectively and safely.

Another key risk observed during field visits to Bidibidi concerns weak market access for farmers, which directly affects their profitability and, by extension, their ability to afford

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fee-based services such as solar-powered irrigation and cold storage. As noted in the analysis of the solar irrigation solution, limited access to reliable and high-value markets can constrain farmers' income potential, especially when local markets are small, dispersed, and characterised by low purchasing power. Cold storage can help mitigate some of these challenges. In cases where the primary constraint is market saturation, the cold room enables farmers to extend the selling period by preserving produce for longer, thereby avoiding distress sales immediately after harvest. Mobile cold storage can also prolong the shelf life of produce while it is transported to larger regional markets, which may be located outside the settlement and offer better prices and stronger demand.

However, technological solutions alone are not sufficient. Strengthening the broader agricultural value chain, through supplementary training in agricultural best practices, post-harvest handling, financial literacy, and entrepreneurial skills, is essential to ensure that farmers can fully leverage the benefits of cold storage. Training delivered in collaboration with farmer cooperatives and local NGOs can equip producers with the knowledge and skills needed to improve crop quality, reduce losses, negotiate with buyers, and plan production cycles more strategically. Such capacity-building efforts are crucial for ensuring the long-term viability, affordability, and sustainability of SUNNY solutions that target farmers in Bidibidi.

System maintenance and repair represent further opportunities for local value creation within the cold storage value chain. Inputs provided by AkoFresh to the eco-design toolkit indicate that the cold storage system is relatively easy to disassemble, and that most of the tools required for servicing and repairs are standard items that can be sourced locally. Several system components, such as solar panels, wiring, and general mounting hardware, can be sourced from local retailers, facilitating straightforward replacement when needed. Other components, particularly those related to the refrigeration unit, will need to be imported or transported from outside the settlement. Establishing a local stock of critical spare parts can therefore significantly improve on-site repairability and minimise system downtime.

Comprehensive maintenance and repair documentation is available for all hardware components, and the system's IoT-based monitoring platform enables remote diagnostics and operational guidance, reducing the need for external technical intervention. When combined with the training programmes provided through later SUNNY work packages, these features create strong potential for developing local technical capacity and embedding ongoing maintenance responsibilities within the community. As a result, the maintenance and repair stage offers a substantial opportunity to expand the local fraction of the value chain while ensuring the long-term sustainability and reliability of the cold storage system.

End-of-life handling and circularity aspects of the cold storage solution are examined in

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detail in Task 2.3.2. Preliminary insights from AkoFresh's responses to the eco-design toolkit indicate that most system components are technically recyclable, yet there is no local recycling capacity within the Bidibidi settlement. At the same time, a substantial portion of the system, such as the solar PV panels, battery, metal framework, and insulated structural materials, can be reused directly for other purposes, extending the useful life of these components beyond their initial application. AkoFresh also reported that detailed end-of-life documentation is available for all components; however, the company does not operate any take-back or buy-back scheme. This means that establishing a local disposal or recycling pathway will be necessary, or at minimum a collection and transport mechanism to move end-of-life components to the nearest recycling facilities outside Bidibidi. Addressing these gaps will be essential to ensure responsible waste management and support the circularity potential of the cold storage solution.

Similar to the other SUNNY solutions, the solar-powered cold storage system provided by AkoFresh must comply with all relevant technical and safety standards and obtain the necessary installation and land use permits from camp leadership and the OPM. Because the solution is used for handling fresh produce, additional food safety standards and guidelines may also apply to ensure that storage practices meet appropriate hygiene and quality requirements. Several system components, particularly the solar PV panels, batteries, and refrigeration equipment, are imported and therefore require the appropriate import clearance documentation and payment of any applicable duties. At the national level, one relevant policy framework is the Sustainable Energy Response Plan for Refugees and Host Communities, developed by the Ministry of Energy and Mineral Development in Uganda, which supports the adoption of renewable energy solutions in displacement settings. Deliverable 1.1 provides a comprehensive list of applicable global and national policies and regulations that should be consulted to ensure full alignment and compliance throughout the value chain.

Building on the preceding analysis of the solar-powered cold storage LVC, the main strengths, weaknesses, opportunities, and threats are summarised in the table below.

Table 4. SWOT analysis of the solar-powered cold storage local value chain.

Strengths	Weaknesses
Technologically mature system with detailed documentation supporting installation, operation, and end-of-life handling.	Key components must be imported, creating procurement dependence and exposure to customs delays and high transport costs.
Local value creation possible in site preparation, foundation construction, cold room assembly, and routine operation, especially where up to 30% of components can be sourced locally.	Lack of local recycling or disposal pathways for end-of-life components; no take-back scheme is offered by AkoFresh.
Improves produce shelf life, reduces	Limited local technical skills and gaps in

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post-harvest loss, and stabilises farmer income by enabling controlled selling.	specialised tool availability may affect installation quality and repair responsiveness.
IoT-enabled monitoring allows remote diagnostics, performance tracking, and rapid technical support, reducing reliance on external technicians.	Weather dependence can affect continuous cooling capacity during prolonged low-sunlight periods; battery autonomy is finite.
Cold storage can be either fixed or mobile, improving accessibility for farmers in dispersed locations and reducing transport bottlenecks.	Produce quality and quantity remain highly variable due to seasonality, farming practices, and water availability, limiting storage utilisation rates.
Opportunities	**Threats**
Reduces post-harvest losses and increases access to distant, higher-value markets by extending produce shelf life.	Weak market access and low local purchasing power in Bidibidi can still limit farmers' ability to monetise stored produce.
Potential integration with other SUNNY solutions such as solar irrigation (increasing yields) and biogas fertiliser (improving produce quality).	Transport constraints, especially for farmers with limited mobility, may still disrupt produce delivery unless aggregation and collection systems are well coordinated.
Creates jobs for cold-room operators, technicians, transporters, and cleaning staff.	High temperature, dust, or heavy rainfall events may affect system reliability if installation and maintenance are not consistent.
Cold storage supports the formation of farmer cooperatives and aggregation groups, strengthening bargaining power.	Theft or vandalism of solar panels, batteries, or refrigeration equipment may pose financial and operational risks.
Training in post-harvest handling, financial skills, and market linkages can strengthen the entire agricultural value chain.	Affordability risks for pay-as-you-store services may reduce utilisation during periods of low income or poor harvests.

e. Biogas for cooking in Bidibidi

The biogas for cooking solution developed under the SUNNY project by Metanogenia is a small-scale anaerobic digestion system designed to convert organic waste into clean cooking fuel. The system consists of several integrated components, including a screening and selection area, waste storage and mixing tanks, a manual milling system for particle-size reduction, a 6 m³ glass-fibre-reinforced plastic (GFRP) anaerobic digester, an 8 m³ floating-drum gasholder for biogas storage, and a series of PVC sedimentation and recirculation tanks for digestate handling. Together, these components enable the controlled biological breakdown of organic waste, such as kitchen scraps, crop residues, or animal manure, into biogas suitable for cooking, offering an alternative to firewood, charcoal, and other polluting fuels.

The potential LVC for the biogas cooking solution has been developed using the ILO's

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methodological framework together with inputs from relevant SUNNY project tasks. Figure 5 illustrates the LVC specifically during the operation phase, reflecting the high complexity of this stage and the need for regular, daily feeding of organic waste as well as continuous monitoring of digestion, gas storage, and stove performance. By contrast, the full LVC analysis presented in this section encompasses both the system's technical lifecycle; procurement, installation, commissioning, and maintenance, and the aforementioned labour-intensive operational stage.

The core LVC functions therefore extend beyond the physical assembly and routine upkeep of the system to include the ongoing biological and mechanical processes required to sustain biogas production, such as systematic waste collection, feedstock preparation, digestate handling, and safe use of the gas for cooking. For each function, the analysis identifies the relevant local actors, supporting services, and the major risks and bottlenecks likely to shape the viability of the value chain within the refugee-settlement context. The LVC mapping also highlights the overarching regulatory considerations relevant to waste handling, land use, safety procedures, and installation requirements, as well as the expected improvements in clean cooking access, waste-management practices, environmental health, and local skill development associated with deploying the biogas solution in the Bidibidi refugee-host community.

The envisioned biogas cooking solution developed by Metanogenia seeks to maximise the local fraction at each stage of the value chain, including the procurement of materials and components. According to Metanogenia's inputs to the eco-design toolkit, the target is to source approximately 70% of system materials locally, reflecting a deliberate effort to enhance local value creation in Bidibidi and the surrounding host community. Most materials required for the system are plastics or metals, many of which are commonly available in regional markets. These include PVC tanks of various sizes used for the reject tank, waste storage tank, mixer tank, and water tank, as well as connecting pipes and flexible gas lines that transport feedstock, digestate, and biogas between components. Other components, such as the GFRP anaerobic digester and floating-drum gasholder, along with the screw pump that transfers substrate or recirculates inoculum, are more specialised and may not be available within the settlement.

While the SUNNY project's existing data do not yet provide a full picture of local supply for these materials, related mapping efforts by the Humanitarian OpenStreetMap Team indicate that cookstove retailers are present in all Bidibidi zones, with many sourcing their inventory from suppliers in Yumbe District or the nearby town of Arua. This suggests that some system components, particularly standard PVC items, fittings, metal frames, and hoses, could potentially be sourced from these regional markets even if they are not available within the settlement itself. The main procurement risk at this stage is therefore that certain specialised components cannot be sourced locally, requiring import or

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transport from other regions. Nevertheless, there remains a promising opportunity to strengthen the LVC by leveraging host-community suppliers in Yumbe and Arua, especially given that many Bidibidi-based retailers already rely on these supply hubs for their stock.

Similar to the other SUNNY solutions, the installation phase of the biogas cooking system requires close collaboration with local actors to secure all necessary permits, identify a suitable site, prepare the ground, and assemble and install the anaerobic digestion system. According to the technical specifications provided by Metanogenia to Task 2.4, the selected site must be stable, not prone to flooding, and easily accessible for the routine activities required during operation. Coordination with camp leaders and the OPM is essential for identifying feasible locations and for validating potential sites already highlighted by ReFuse based on their key informant interviews (KII) in Bidibidi.

Site preparation involves constructing a level concrete slab to support the digester, gas holder, and associated tanks, ensuring stability and preventing uneven settlement over time. This presents an opportunity to source construction materials and labour locally, thereby increasing the local value fraction at this stage of the chain. Once the foundation is complete, system installation can be undertaken by trained local installers, drawing on the detailed installation and commissioning guidance included in the SUNNY project and using the set of standard tools specified by Metanogenia for assembling the mixer tank, digester, gasholder, piping, and safety fittings. Training provided in later SUNNY work packages will be key to ensuring that installation tasks are carried out correctly and safely, laying the groundwork for reliable long-term operation of the biogas cooking system.

Unlike several other SUNNY solutions, which operate largely autonomously and require only oversight during the operation stage, the biogas cooking system demands continuous, hands-on daily engagement to maintain stable gas production. For technologies such as SHS, solar irrigation, or cold storage, operators primarily ensure correct system use, monitor performance, coordinate schedules, and collect payments where applicable. In contrast, the biogas system relies on a series of labour-intensive daily tasks, all of which are essential for sustaining the biological digestion process. These tasks include sorting incoming organic waste to remove stones, plastics, and other impurities; milling the waste to reduce particle size; mixing the substrate with rainwater or recirculated liquid digestate to achieve the required dry-matter concentration; and feeding the prepared mixture into the anaerobic digester. Operators must also check the gasholder level, ensure airtightness of the gas drum, and discharge accumulated digestate from the sedimentation tank every three days to prevent overflow.

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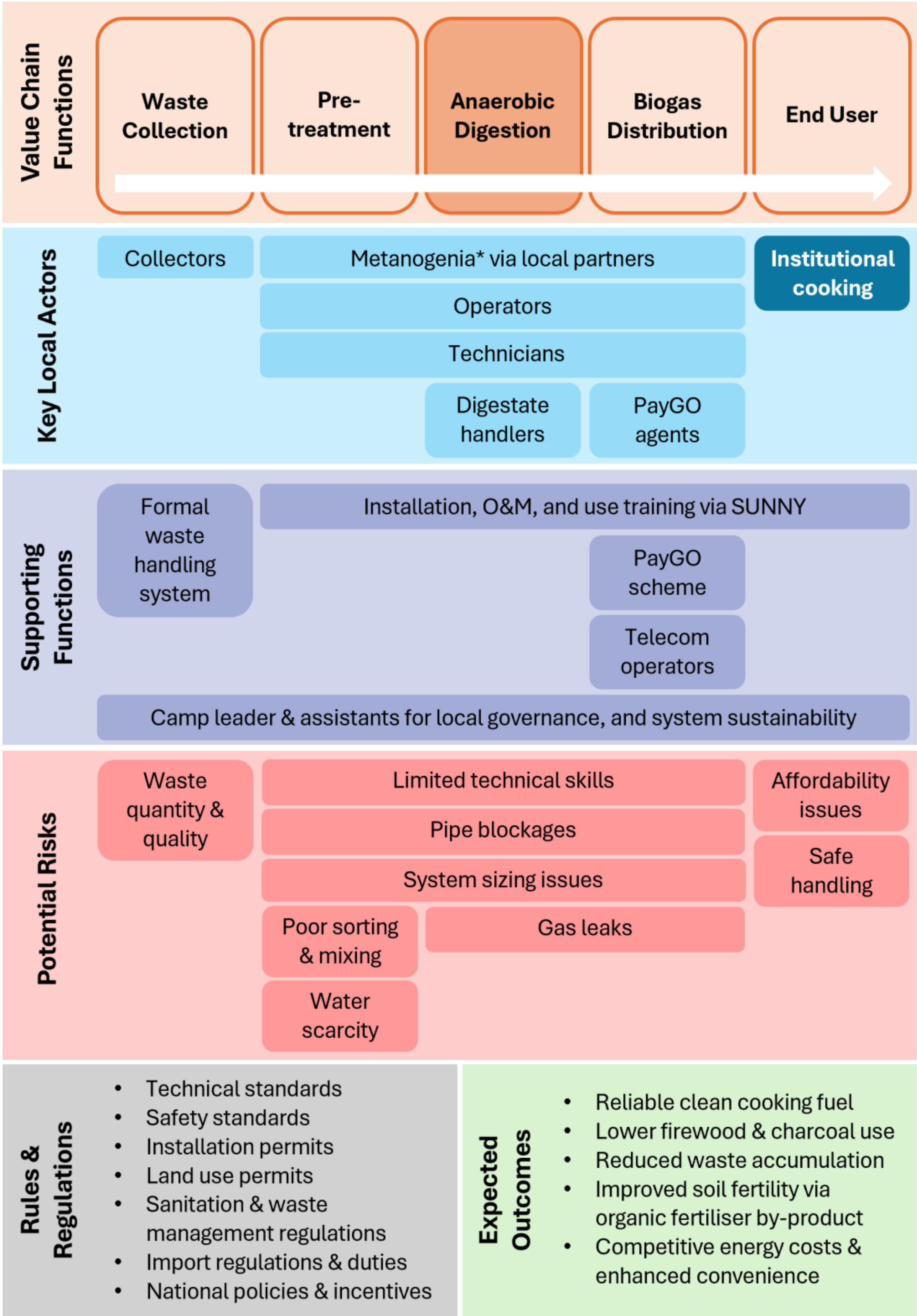

Figure 5. Local value chain map of the biogas cooking solution during its operation phase.

In addition to daily routines, several periodic maintenance activities are necessary to ensure reliable system performance. These include checking and lubricating the mill blades, inspecting and maintaining the pumping system, verifying the smooth movement and sealing of the gasholder guiding rails, and clearing the connecting pipes of any potential blockages. Operators are also required to maintain a feeding and

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operational log, which helps track performance issues, feeding consistency, and signs of system imbalance. With comprehensive training delivered through the SUNNY training modules, these responsibilities can be fully carried out by local operators and technicians, strengthening local capacity and embedding operational knowledge within the community.

There are several operational risks associated with the biogas cooking solution, particularly regarding the availability and quality of organic waste required for sustained digestion. Preliminary findings from Task 1.1 indicate that Bidibidi currently lacks both formal and informal biowaste collection systems. Residents typically dispose of waste in open burning pits or dug rubbish pits, and the informal collectors operating within the settlement focus almost exclusively on dry recyclable waste, such as plastics, metals, and cardboard, which they can sell to larger waste-handling organisations outside the settlement. Organic waste streams suitable for biogas production are therefore highly dispersed, and meeting the system's daily feedstock requirement of around 72 kg/day (pre-sorting) necessitates aggregation from multiple locations. As part of their KIIs, ReFuse identified Locopio Technical School in Zone 2 as a potential centralised source of biowaste, given its generation of animal excreta, kitchen waste, and agricultural residues. However, the waste produced by the school alone is unstable and may not meet daily demand, meaning it would need to be supplemented with additional feedstock collected from households, markets, or other institutions across the settlement. Relying on decentralised waste sources introduces uncertainty regarding both quantity and consistency, and it underscores the need for dedicated collectors who can gather, sort, and transport suitable organic waste to the biogas site on a daily basis. Without reliable waste collection arrangements, the stability of biogas production, and consequently the cooking service it provides, may be compromised.

Additional operational risks relate to the limited technical skills currently available within the settlement, underscoring the importance of the dedicated training modules planned under the SUNNY project. Strengthening local capacity, together with the provision of a detailed operational and troubleshooting guide, will be essential for mitigating performance issues that can arise during anaerobic digestion. These include poor waste sorting, inadequate milling and mixing, improper feeding routines, gas leaks, and blockages in pipes or hoses, all of which can reduce gas production or compromise system safety.

The biogas system also requires mixing organic waste with water to achieve the correct dry matter concentration for digestion, which introduces an additional risk associated with water availability. To reduce reliance on external water sources, the system design incorporates the option of recirculating the liquid fraction of the digestate back into the mixer. However, both the initial setup phase and subsequent adjustments to substrate moisture content still require supplementary water inputs. To address this,

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Metanogenia's design includes a rainwater harvesting system, whereby rainwater can be collected from a rooftop constructed above the biogas plant. Alternatively, if the system is installed adjacent to Locopio Technical School, as suggested by ReFuse, PVC gutters can be installed on the school rooftop to channel rainwater into the water storage tank. Together, these measures help ensure a more reliable and self-sufficient water supply for daily feeding operations.

In the distribution and end-use phase, the biogas cooking solution initially envisioned by Metanogenia was designed for individual household cooking. However, this approach would require distributing biogas through pressurised cylinders or a buried pipe network, both of which entail significant costs and technical complexity. These distribution models would ultimately reduce the affordability of the solution for households. For this reason, the concept was revised toward institutional cooking, where biogas can be delivered to a single centralised cooking point rather than multiple dispersed users. This shift aligns naturally with the operational setup proposed in earlier assessments, which identified Locopio Technical School in Zone 2 as a promising location—both as a consistent source of organic waste and as a potential beneficiary of the produced biogas. According to findings from ReFuse, the school currently operates a structured kitchen but remains reliant on firewood and three-stone stoves, highlighting a strong opportunity for transitioning to modern gas stoves compatible with low-pressure biogas. Importantly, the short distance between the digestion system and the school kitchen enables biogas delivery through flexible low-pressure hoses, operating at 10–15 mbar, which is the natural outlet pressure generated by the weight of the floating PVC gasholder drum. This configuration eliminates the need for additional pressurisation equipment or costly distribution infrastructure. It also maintains a high level of safety, simplicity, and cost-effectiveness.

Other operational risks relate to system sizing, affordability, and safe handling during waste collection, digestion, and biogas use. Risks associated with sizing may arise if local waste sources do not generate enough feedstock to meet the digester's designed daily load, resulting in oversizing and underutilisation of the system. Conversely, if biogas production falls short of the school's cooking requirements, undersizing could undermine user confidence and affect perceptions of the solution's reliability. Affordability also poses a challenge. Metanogenia has proposed a pay-per-use model, based on gas usage time rather than upfront capital costs, to improve accessibility. However, the underlying business model still requires refinement to clarify payment responsibilities, particularly because the school would act both as the primary provider of organic waste and as the main consumer of the biogas produced. Safe handling risks can also occur throughout the operation and distribution phases, including improper waste sorting, unsafe stove operation, and hazards associated with low-pressure gas handling. These risks must be proactively addressed by providing comprehensive training to system operators and end-users on waste management, digestion procedures, gas-safety

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protocols, and the correct use of biogas stoves via the SUNNY training modules.

Beyond routine daily and periodic maintenance tasks, specialised technical support is required when system components are damaged, when mechanical or biological malfunctions occur, or when gas leaks are detected. According to Metanogenia's inputs, the system has been designed so that key components are easy to access, requiring only a small number of straightforward steps, and all necessary tools are standard, widely available items. The relative maturity of the technology also means that detailed repair documentation is available for every subsystem, from the mixer and pump to the digester, gasholder, and gas distribution lines, facilitating structured troubleshooting and repair by trained personnel.

With the training provided through the SUNNY project, local technicians can competently undertake most repair and maintenance tasks, strengthening local capacity and reducing reliance on external support. The main remaining limitation relates to the availability of spare parts. Components that are common in local markets, such as PVC pipes, fittings, flexible hoses, valves, and general hardware, can be replaced from suppliers in Bidibidi, or Yumbe and Arua, where many Bidibidi retailers procure their stock. However, if certain components are not available locally, such as specialised GFRP parts or specific pump components, a small local stock of critical spares should be established to enable timely repairs and minimise downtime. This would ensure operational continuity and support the long-term sustainability of the biogas cooking solution.

End-of-life handling and circularity considerations for the biogas system are discussed in greater detail in Task 2.3.2. Preliminary insights from the eco-design toolkit indicate that most system materials cannot be recycled, but more than half of the components can be directly reused for other purposes after appropriate cleaning and treatment. These reusable elements include several PVC and metal components used in storage tanks, piping, and structural supports. At present, Metanogenia does not provide dedicated end-of-life documentation, nor do they operate any take-back or buy-back schemes, meaning that responsibility for safe disposal, reuse, or repurposing lies with local stakeholders. This creates a need to establish local disposal or recycling pathways, or at minimum, a system for collecting and transporting end-of-life components to the nearest facilities capable of handling them. Addressing these gaps will require the development of clear guidance and training materials to support responsible end-of-life management within the community.

Beyond the general requirements for technical and safety standards, as well as the land use and installation permits needed for all SUNNY technologies, the biogas cooking solution must comply with an additional set of sanitation and waste management regulations. These stem from the nature of the system, which involves collecting, handling, and processing organic waste, as well as managing digestate by-products.

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Appropriate regulatory oversight is therefore essential to ensure safe waste handling, prevent environmental contamination, and protect public health within the settlement. Deliverable 1.1 provides a more comprehensive overview of the global and national policy frameworks relevant to SUNNY solutions, and should be consulted to ensure full compliance across all stages of the value chain.

The biogas cooking solution demonstrates strong synergies with other SUNNY technologies, reinforcing both its feasibility and its contribution to broader local value creation. In particular, the solar irrigation solution can enhance feedstock availability by increasing agricultural productivity and generating larger volumes of crop residues suitable for anaerobic digestion. On the other hand, the digested effluent produced by the biogas system can, in turn, be integrated as an organic fertiliser via fertigation in the solar irrigation solution offered by SOLEKTRA.

Another potential synergy under consideration in the SUNNY project is the integration of the biogas and hydrogen cooking solutions in Bidibidi. This combined approach was initially proposed as an innovative addition to the individual solutions, based on a decentralised household-level cooking model for both gases. Under this concept, biogas and hydrogen could either be pre-mixed and supplied to end users for use in a compatible mixed-gas stove, or provided separately for use in a cookstove equipped with multiple burners; each designed to operate safely and efficiently with its respective gas. At this stage, however, it remains unclear which of these alternatives, will be pursued, as the combined solution is still under active development by Metanogenia, SOLHYD, and SOLHYDAIR.

The feasibility of the combined solution has also been affected by findings from the biowaste flow assessment conducted by ReFuse. Their analysis confirmed that decentralised biowaste sources in Bidibidi are too dispersed and insufficient to meet the daily feeding requirements of the proposed anaerobic digester. This led to the identification of Locopio Technical School in Zone 2 as a viable centralised source of organic waste and therefore the most suitable installation site for the biogas system. While concentrating the solution at the school supports the biogas use case, it is not compatible in scale with the hydrogen system, as hydrogen production can supply only a small fraction of the cooking needs of a large institutional kitchen. As a result, the contribution of hydrogen to a combined cooking solution at the school would necessarily be limited by the overall system scale and by hydrogen's lower gas density and heating value relative to biogas. Despite these challenges, integrating hydrogen remains under discussion among the technology developers and project partners. Even at small scale, hydrogen could enhance supply security by supplementing biogas availability during periods of low gas production, feeding imbalance, or reduced waste input.

Building on the preceding analysis of the LVC, the main strengths, weaknesses,

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opportunities, and threats associated with the biogas cooking solution are summarised in the table below.

Table 5. SWOT analysis of the biogas cooking local value chain.

Strengths	**Weaknesses**
High potential for local value creation across procurement, installation, daily operation, and maintenance, with a design targeting up to 70% local material sourcing.	The system requires daily hands-on operation (sorting, milling, mixing, feeding, digestate removal), making it more labour-intensive than other SUNNY solutions.
Low-technology design with standard tools, clear repair documentation, and easy access to key components.	Biowaste sources in Bidibidi are highly dispersed, and waste quantities are uncertain—making daily feedstock availability a major operational risk.
Produces clean, smoke-free cooking fuel and supports improved waste management, reducing open dumping.	Some specialised components, such as the GFRP digester and floating-drum gasholder, may not be available locally and require importing or local stocking, increasing costs and procurement time.
Digestate by-products can be reused as organic fertiliser, contributing to soil improvement and circular resource flows within agricultural activities.	Lack of existing waste collection systems means that feedstock aggregation must be organised from scratch and may require dedicated collectors.
Centralised institutional cooking allows safe, low-pressure gas delivery via flexible hoses, eliminating the need for cylinders or complex distribution networks.	End-of-life recycling options are limited; most materials cannot be recycled locally, and no take-back scheme currently exists.
Opportunities	**Threats**
Strong synergies exist with solar irrigation, which can increase agricultural residues, and with digestate reuse through fertigation, strengthening local agricultural value chains.	If the quantity or quality of available organic waste declines due to seasonality or collection challenges, gas production may become unreliable and affect user confidence.
Pay-per-use model increases affordability by avoiding high upfront costs and spreading payments over time for institutional users.	Incorrect system sizing—either oversizing or undersizing—may reduce system efficiency or fail to meet cooking needs, undermining acceptance of the technology.
Training provided through SUNNY can build long-term local capacity in waste handling, digestion management, troubleshooting, and safe stove operation.	Safety risks related to gas leaks, improper stove handling, or poor waste sorting require training and strong operational oversight to avoid accidents.
Integrating small amounts of hydrogen could enhance energy-supply security by supplementing biogas production during low-production periods.	Reliable water availability is essential for substrate preparation, and dependence on rainfall or limited storage may constrain system operation during dry seasons.

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Locating the system at Locopio Technical School creates a stable end-use case, centralises operations, and encourages institutional ownership of the solution.	Limited market access and affordability within Bidibidi may reduce long-term financial sustainability unless business models are carefully designed.

4. Discussion

Across all SUNNY solutions—hydrogen cooking, solar home systems, solar irrigation, solar-powered cold storage, and biogas for cooking—there is substantial potential for local value creation, provided that implementation is accompanied by deliberate, coordinated efforts with local actors. Despite their technological differences, the solutions exhibit several common trends in how localisation can be meaningfully achieved.

A key similarity is that installation, operation, and maintenance offer the strongest opportunities for embedding local value, even when core components must be imported. In each solution, local actors can participate in activities such as site selection, site preparation, system assembly, daily operation, routine maintenance, troubleshooting, record-keeping, and user support. These functions rely heavily on labour, technical skills, and local knowledge; assets that already exist within the refugee and host communities, and which can be strengthened through the SUNNY project's structured training modules. Local value creation is therefore most feasible in service-based segments of the value chain rather than in the manufacturing of system components, which is currently limited or absent in all cases.

Similarly, all SUNNY solutions highlight the importance of forming clear institutional arrangements with camp authorities, governmental institutions, local leadership structures, farmer cooperatives, and community-based organisations. Installation and operation often require permissions, coordination across multiple stakeholders, and structured community governance mechanisms. Other examples include water user committees for irrigation, cold room operators and produce aggregators, PAYGo agents for SHS deployment, and dedicated waste collectors and digestate handlers for biogas. Establishing these governance structures early and collaboratively is essential for ensuring both system reliability and long-term community ownership.

Another overarching trend is the need for refined business models that clearly differentiate responsibilities across the core functions of each value chain. Sustained operation depends on transparent models that define who pays, who operates, who maintains, and who benefits. These roles vary across institutional cooking, household energy access, agricultural production, and cold storage. Whether through pay-per-use service models, cooperative cost-sharing, or delegated operator roles, each solution requires a context-appropriate financial structure that balances affordability with operational sustainability. Without this clarity, even technically sound systems risk under-utilisation, poor cost recovery, and reduced long-term viability.

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Despite the strong potential for local value creation, it is also important to recognise the limitations of the current analysis. This task did not include dedicated field-level data collection, value-chain interviews, or market-system diagnostics that would normally underpin a full LVC analysis as per the ILO's framework. Instead, it relies on secondary inputs from other SUNNY work packages, some of which were delayed or remain under development. As a result, certain assumptions, particularly regarding local supply chains, labour availability, material sourcing, and potential partner institutions, require validation through empirical field research and other SUNNY deliverables and milestones once they have been finalised. Future refinement of the LVC analysis should therefore integrate direct engagement with local suppliers, technicians, waste collectors, farmer groups, community leaders, and relevant authorities to confirm feasibility and refine roles, incentives, and governance structures.

Overall, while the SUNNY technologies differ in function and complexity, they share a common set of opportunities and constraints. Local value creation is strongest where human capacity, service delivery, and community governance are central to system performance. When paired with targeted training, inclusive community engagement, and well-defined business models, these solutions have the potential not only to deliver energy, cooking, irrigation, or cooling services, but also to support local employment, entrepreneurship, and circular economic linkages across the refugee and host-community context.

5. Summary and Outlook

This deliverable has assessed the potential for local value creation across the five SUNNY technological solutions—hydrogen cooking, solar home systems, solar irrigation, solar-powered cold storage, and biogas for cooking—using the ILO's Value Chain Development framework as a guiding structure. Despite the technological diversity of the solutions, the analysis reveals a set of consistent cross-cutting opportunities for embedding local value at various stages of each value chain. These opportunities are particularly concentrated within the service-based segments of the lifecycle, namely installation, daily operation, routine maintenance, troubleshooting, and community-level governance. While manufacturing capacity for specialised components remains largely absent within the refugee settlements and surrounding regions, installation, operation, and maintenance processes rely heavily on local labour, local knowledge, and context-specific problem-solving, making them key entry points for maximising local participation.

The analysis in this deliverable builds directly on the foundational insights generated through Deliverable 1.1 (Analysis of local contexts), which provides the broader socio-economic, environmental, institutional, and regulatory context for implementation. The identification of relevant governance actors is essential for mapping feasible local roles across each solution's value chain. These range from the Ministry in Charge of

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Emergency Management in Rwanda and the Office of the Prime Minister in Uganda to the UNHCR, settlement leadership structures, and other market actors. Deliverable 1.1 also revealed structural challenges such as limited waste management systems, fragmented market access, reliance on biomass fuels, and the absence of formal training pathways, all of which shape the constraints and opportunities presented in this local value chain analysis.

Similarly, Deliverable 1.2 (Community mapping) plays a critical role in informing the value chain assessment by identifying the socio-cultural and economic landscape within both refugee and host communities. Although Deliverable 1.2 was still under development at the time of writing, its final version should be consulted closely alongside the local value chain analysis to align the proposed local roles, responsibilities, and governance arrangements in each value chain with the actual actors and community structures identified in the settlement. This alignment is essential for grounding the local value analysis in an accurate understanding of the diverse stakeholders present on the ground, such as workforce groups, business owners, farmers, women, youth, minority ethnic groups, and local and refugee-led associations. This is crucial for ensuring that the SUNNY solutions are not only technically viable but also socially embedded and responsive to community needs.

The technical feasibility and operational requirements assessed in this deliverable also draw heavily on Deliverable 1.3 (Use cases definition and technological requirements and specifications). Deliverable 1.3 clarifies not only the operational conditions required by each technology but also the user profiles, expected service levels, and specific design constraints for each demonstration site. These inputs are essential for understanding the skills, tools, and governance mechanisms needed for local actors to participate effectively in installation, operation, and maintenance. In turn, the local value chain analysis feeds back into technical decision-making by highlighting where design choices have implications for local procurement, local skill development, or system operability.

Taken together, these linkages highlight that local value creation cannot be treated as an isolated exercise, but rather as an integrated process that depends on context-sensitive design, fit-for-purpose use cases, and robust community engagement. Across all SUNNY technologies, the creation of sustainable local value chains will require deliberate and coordinated efforts between technology developers, local authorities, community organisations, and implementing partners. Such coordination is particularly crucial for clarifying roles across the different functional stages of the value chain: who installs, who operates, who maintains, who pays, who benefits, and who governs. Establishing these differentiated responsibilities is essential for designing viable and resilient business models, whether based on pay-as-you-go models, cooperative structures, or institutional cost-sharing arrangements.

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At the same time, it is important to recognise the limitations of this deliverable. This analysis did not include dedicated field-level data collection or interviews, and instead relied on secondary inputs from other SUNNY work packages. Some of these work packages experienced delays or were still under development at the time of writing. As a result, several assumptions, particularly those concerning local supply chains, labour availability, or institutional arrangements, will require further verification. These gaps highlight the need for continued empirical research, community consultations, and iterative refinement as the project moves from design to implementation.

Looking ahead, the insights presented in this deliverable provide a strong foundation for the upcoming phases of the SUNNY project. They highlight both the potential for building locally anchored, socially embedded, and economically viable value chains, and the critical areas where targeted support, training, and governance strengthening are required. As the demonstration systems are deployed and monitored, real-world performance and community uptake will offer new evidence to refine the value chain models, validate assumptions, and strengthen the scalability and long-term sustainability of the SUNNY solutions across refugee and host-community contexts.

6. Literature

References are all obtained from other SUNNY deliverables and work tasks, which will be added after the draft has been reviewed and finalised.

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III. T2.3.2 DEFINITION OF TECHNOLOGICAL WASTE REPAIRING AND RECYCLING SOLUTIONS

1. INTRODUCTIONS AND OBJECTIVE

Solid waste management (SWM) remains a persistent global challenge, closely linked to poverty, inequality, and environmental degradation. Despite continuous international commitments to improve living conditions, waste generation continues to increase, particularly in low- and middle-income countries where institutional and financial capacities for adequate waste management remain limited. In the East African region, socioeconomic needs and consumption patterns are comparable, and municipal solid waste streams present similar characteristics, with high organic fractions and limited formal recycling structures. Waste management systems are further constrained by structural and financial limitations.

In humanitarian and displacement settings, these structural challenges are amplified. Rapid population growth limited operational planning, and emergency-driven service provision often result in uncoordinated waste systems. Traditional models frequently struggle to manage the increasing volumes and complexity of waste streams. Literature highlights the importance of collaboration between public and private actors to improve service efficiency and resource recovery outcomes. Market-based approaches (where private operators contribute to collection, transportation, recycling, and valorisation) can help bridge capacity gaps while fostering local entrepreneurship and economic participation.

Therefore, within this perspective, waste should not be framed as a burden requiring disposal, but as an untapped potential resource within local value chains. Value can be understood as the capacity of a material or service to meet user-defined needs at the right time and cost. What is considered “waste” by one actor may represent an input for another. Circular economy thinking, initially conceptualised by Stahel (1982), promotes the retention of material value through repair, reuse, remanufacturing, and recycling. Waste valorisation processes, transforming discarded materials into secondary raw materials, enable the creation of economic, environmental, and social benefits. Emerging models demonstrate how localised recycling systems can generate environmental and socio-economic benefits.

Applying these principles in humanitarian contexts requires a clear understanding of

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existing waste flows, stakeholder roles, technological infrastructures, and regulatory conditions. Market-based circular solutions must be adapted to local realities, including community practices, informal systems, and existing service providers.

T2.3.2 aims to maximise resource efficiency and minimise waste through a circular approach. Within this task, the objective is to establish at least three value chains across the two demonstration sites by engaging a minimum of twelve stakeholders.
In collaboration with local stakeholders, waste flows and existing recycling structures in the demonstration sites are assessed. The task clarifies what constitutes repairable waste, how it is collected, and where it is processed, ensuring alignment with applicable disposal, tracking, and reporting requirements. Specific safety protocols are defined for hazardous technological waste to ensure environmental and community protection (e.g., heavy metals or battery chemicals).

Waste flow assessments include geotagging and co-mapping activities, alongside the analysis of collected 2024 dry waste data to identify circular value chain opportunities. Circularity workshops are organised with project stakeholders and community members (MALLs) to demonstrate how reusable, recyclable, and biodegradable materials can be integrated into productive systems and livelihood activities. In addition, Local entrepreneurship initiatives in recycling and upcycling technological waste are supported to reinforce emerging circular value chains.

Deliverable D2.2 focuses on improving resource efficiency through locally feasible circular actions that could also be adapted to refugee settlement conditions. SUNNY technologies are evaluated in terms of durability, ease of repair with locally available skills, and potential for component reuse. Multistakeholder workshops support interoperability between community members, local authorities, and providers/suppliers to identify viable waste valorisation activities.

Overall, the objective is to operationalise small-scale value chains within existing constraints.

Timeline of activities
M6: Waste flow Assessment exploring drywaste in the host and refugee communities in Rwanda and Uganda.
M11/12: Implementation of the first circularity workshop in Uganda, Bidibidi Refugee settlement
M13: Implementation of the second and third circularity workshop in Mahama camp and Kirehe district - Rwanda
M22: Implementation of the fourth circularity workshop in Yumbe town, Uganda
M22: Submission of the Report Paper, all assessments done entitled “Assessing Dry waste

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flows, reuse practices and valorisation opportunities in Refugee camps and Host Communities in Mahama-Kirehe, Rwanda & Bidibidi-Yumbe, Uganda."

2. METHODS

A working group with local stakeholders was established to study innovative means to encourage the community's efforts in waste valorisation/recycling structures in demonstration sites.
The research methodology applied aligns with the overall assessment framework of the SUNNY project and combines person-centred and system-centred approaches. Data collection relied on three main tools: a structured questionnaire, key informant interviews, and geotagging of waste production, management, and disposal sites. While the broader research covered multiple waste streams, this report focuses specifically on findings related to dry waste.

A total of nine research assistants (RAs) supported field activities across Rwanda and Uganda. The team included members with knowledge of local languages (Rwandan, Ugandan, Congolese, and South Sudanese contexts). Six RAs were engaged through the refugee-led organisation Community Technology Empowerment Network (CTEN), one RA was engaged through Practical Action Rwanda as a field coordinator, and one RA from Makerere University (Department of Mechanical Engineering) participated under the supervision of Professor Michael Lubwama. All RAs received training from ReFuse's environmental expert on solid waste management to ensure methodological consistency and technical accuracy.

The research was conducted with formal approval from the relevant authorities in Rwanda and Uganda. Coordination meetings were held with the World Vision Camp Manager in Rwanda and local authorities in both countries. In Uganda, the Bidibidi Settlement Commander and local zone and village leaders were informed before data collection to ensure proper access and community engagement.

a. Person Centred Approach

A Person-centred research method was adopted to gain an understanding of refugees' and host communities' perceptions and behaviours around the topic of waste. A semi-structured qualitative questionnaire was developed to identify common waste habits, challenges, waste-related hazards and services within the settlement. It included 12

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questions, aligned with the research objectives, primarily featuring free-listing responses and 1 checklist question. Data were gathered on bio waste, dry waste issues, repairability and re-commerce practices. For example, types of waste generated, daily waste disposal, waste dumping sites, the possibility of transforming waste, household access to repair services and secondhand items, and problems related to inadequate management of waste.

Five refugee RAs from the CTEN team (two in Rwanda and three in Uganda) assisted other RAs (ReFuse & UMAK) in bridging communication gaps. The questions were read aloud, and then translated by CTEN into the native language, ensuring clear communication between the questioner and responder. Participation in the study was voluntary and based on informed oral and in-app signed consent. Each participant received a detailed explanation of the project's purpose, and how their data would be used. Anonymity and privacy were strictly upheld to ensure ethical standards were met.

All research data were securely stored and treated with confidentiality. Data entry was performed on a digital tool developed on the platform Appsheet, using identification numbers for each participant to preserve anonymity. Data is made available for use by SUNNY consortium partners with no other organization than ReFuse holding ownership of the data.

b. System Centred Approach

The study adopted a system-centered approach to assess waste management value chains, focusing on understanding waste as part of an interconnected network that includes the legal framework, and local environmental, social, economic, and technological systems. The aim was to identify troubleshoots which could be pivoted into opportunities to optimize the waste management cycle. The system-centred analysis focused on three methods of data gathering including: 1. Literature review; 2. Key Informant interviews; 3. Geotagging and co-mapping.

Before the field data collection, the ReFuse team performed a review of published literature on matters relevant to the research scope, gathering information available to match it with locally collected data. The information compiled was resourced from factsheets and reports published by humanitarian entities and United Nations' Agencies, from scientific journals and national waste management policies.

Key informant interviews (KII) were conducted with officials from the local governmental authorities, representatives from international organisations, workers, business owners and informal waste handlers in both camps/countries. Discussions focused on the

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amount of waste produced, needs, and gaps in waste collection, disposal, management, and recycling options. Interviews were led by the environmental expert (ReFuse) and two RAs from CTEN. Non-structured interviews were conducted, expecting a significant diversity of participants' backgrounds and experiences, and a variety of information to investigate with diverse informants. Notes were taken in writing in a diary and then transcribed for analysis. For the KIIs of waste producers and service providers, locations were recorded.

As a final method, geotagging and co-mapping were performed to build a spatial representation of waste-related significant elements through referrals. Mapping can be used to grasp and analyze spatial practices, spatial perceptions, and spatial knowledge (Genz & Lucas-Grodan, 2018). It is a powerful tool for understanding the complex interactions between social and spatial dimensions - particularly when aiming to build viable interventions adapted to the perceptions and needs of community members. The mapping exercise was used to amplify field observations, (UNEP, 2024) engaging with community members to identify relevant locations to visit, record. The aim was building a spatial representation through people's perspectives, acknowledging that maps are not objective representations of reality, but "operative images" (Kramer, 2008). The exercise conducted does not fully fall under broader definitions of participatory mapping (Cochrane & Corbett, 2020), as community engagement currently stopped at people's consultation, defined in participatory methodologies (IAP2, 2023). Nevertheless, it serves as a first step towards participation in future initiatives. The no-code platform Appsheet was used to allow data collection and location mapping. The platform enables users to create customized mobile applications.

The ReFuse team designed surveys and data collection tools on a proprietary application, allowing seamless entry of text, images, and other data types directly from a smartphone. The platform integrates GPS functionality, qualifying precise location mapping and geotagging of entries, which is especially useful for fieldwork and surveys. This feature was prominent in recording all sorts of dumping sites, waste producers and service providers in the settlement. The interface is easily integrated with data sheets, permitting direct exporting of data and easy login. In this study, members of the Refugee and Host Communities have therefore supported RAs in co-mapping different locations for 'Waste Producers' such as school canteens, hospital canteens, and farms. Several 'Service Providers' such as markets, repair shops, and charging stations. And, 'Disposal Sites' from unsanitary and/or informal landfills to dumping litter corners between households' clusters.

c. MALLs

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In line with the methodology defined in the SUNNY project, Multi-Actor Learning Labs (MALLs) were conceived as structured platforms to support social innovation and collaborative co-creation processes. This approach is based on the premise that understanding community preferences, perceptions, and decision-making factors is essential for designing solutions that are appropriate to the local context and can be sustained over time. Initial community mapping activities aimed to identify local needs, capacities, available resources, and the roles of key stakeholders around the demonstration sites, forming the basis for the design and composition of the MALLs.

Within this framework, REFUSE implemented an adapted MALL approach, taking into account the available budget, project timeframe, and feasible number of participants. Participants were selected based on the relevance of the topics discussed and their potential contribution to the circularity activities addressed during the workshops.

REFUSE, in collaboration with CTEN, Practical Action (PA) and HUDARA, organised four circularity-focused workshops following the MALL approach across the demonstration sites. The formatting of each workshop reflected SUNNY's technological needs, the local context and included refugee and host community members, camp administration representatives, local authorities, project partners, researchers, and relevant organisations (see table below). Considerations related to gender balance, social background, and stakeholder diversity were integrated into the participant selection process.

These workshops served as participatory platforms to support the discussion and co-development of circular solutions, ensuring that proposed technical interventions were informed by local knowledge and operational realities. They also contributed to strengthening stakeholder coordination, encouraging community participation, and identifying opportunities for exploring existing and new value chains (link to WP7).

Table 6. Workshops conducted, with dates, locations and participants.

Aspect	UGANDA – W1	UGANDA - W2	RWANDA – W1	RWANDA – W2
Workshop title	Circularity Workshop – Circular Economy for Electrical and Electronic Equipment:	Circularity Workshop – Supporting Waste Diversion Value Chains	Circularity Workshop – Building Recyclability and Repair Value Chains	Circularity Workshop – Building Recyclability and Repair Value Chains

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	Repair and Reuse			
Date & Location	Bidibidi - Zone 1, Apr 26–May 3 2025	Yumbe town, 24-25-26 February 2026	Mahama Camp, June 11 2025	Kirehe district, June 12 2025
Participants	18 technicians from Bidibidi refugee camp and the surrounding host community in Yumbe	6 Waste Workers from Bidibidi refugee camp and host community Yumbe. And 7 NGOs representatives (UNHCR, OXFAM, IRC, Warchild…)	19 NGO & partner representatives (Save the Children, UNHCR, World Vision, community…)	14 health & sanitation officers (Kirehe sector)

3. Results

a. Data Collection Results

(1) Person-centred analysis

Through random sampling, a total of 208 individuals were interviewed using a semi-structured questionnaire (SSQ) across refugee camps/settlements in Rwanda and Uganda, as well as within the surrounding host communities. Gender balance, age representation, inclusion of both refugee and host populations, and spatial distribution were considered to ensure a representative sample. Only respondents aged 18 years or older were eligible to participate, and one individual per household was interviewed. To avoid exclusion due to literacy barriers, all questionnaires were administered orally by trained research assistants.

Among the respondents, 98 were women and 110 were men. A total of 126 participants belonged to the refugee community and 82 to the host community. The age distribution reflected the demographic profile of the settlements, where a significant proportion of the population is under 35 years old (UNHCR, 2022).

The sample size per country was calculated to achieve an error margin of ±10% at a 90% confidence level, which is considered acceptable for exploratory and preliminary

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research (Fink, 2017). In Uganda, ensuring spatial representation was particularly important due to the dispersed structure of Bidibidi settlement, where household clusters can be located more than 20 km apart and present varying environmental and livelihood conditions (JEU, 2019). Bidibidi hosts a refugee population of approximately 246,294 individuals (UNHCR, 2022) and is distributed across a large territory where host communities also reside.

In Rwanda, Mahama refugee camp, located in Kirehe District, was opened in 2015 and hosts approximately 58,968 refugees (MINEMA, 2019). Compared to Bidibidi, Mahama presents a more concentrated settlement structure, although the surrounding district has a relatively limited population in the immediate vicinity of the camp. To account for interactions with host populations, a proportional target of approximately 40 respondents from host communities was established, resulting in 42 host community participants being interviewed.

The data collected through the semi-structured questionnaires (SSQs) were analysed by categorising and aggregating similar responses from the free-listing questions. The survey first explored purchasing behaviours to understand consumption patterns across refugee and host communities, as these may influence waste generation and disposal practices.

Results indicate that expenditures are primarily directed towards basic subsistence goods. Food products such as vegetables, greens, beans, and maize were the most frequently mentioned items purchased by respondents in both countries. In Uganda, soap was also commonly reported, while in Rwanda respondents indicated slightly higher spending on clothing and shoes. Overall, purchasing patterns appeared largely similar between refugee and host communities.

Gender-disaggregated analysis showed no major differences in purchasing behaviours, although male respondents in both countries reported slightly lower spending on household-related items. Some differences were observed between community groups: host community respondents appeared to purchase clothing less frequently, while refugees reported fewer purchases of higher-cost comfort food items, consistent with the classification used by the World Food Programme (WFP, 2024).

When asked about the items they dispose of most frequently, respondents reported waste streams largely composed of biodegradable materials. Plastic bags were frequently mentioned in Uganda, while paper bags were more commonly reported in Rwanda, reflecting national regulations restricting single-use polyethylene bags under Law Nº 57/2008 (REMA, 2008). Plastic waste, including containers and bottles, was commonly reported in both countries, suggesting similar waste generation patterns across communities.

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Comparing purchased items with commonly discarded materials indicates a significant presence of non-biodegradable waste, particularly plastic containers, jerrycans, and bottles. These materials represent an important component of the local waste streams.

Respondents were also asked how they define waste. In Uganda, waste was commonly described as something damaged, harmful, or potentially causing health problems, with women slightly more likely to associate waste with health risks. In Rwanda, waste was most frequently defined as something that has no value or is no longer needed.

Waste disposal practices vary across locations. In Uganda, most host community respondents reported disposing of waste in mixed rubbish pits or through open burning, while separate waste pits were only occasionally mentioned. In Rwanda, disposal practices were primarily divided between rubbish pits and designated disposal sites, both typically involving mixed waste streams. Refugee respondents in Rwanda reported bringing waste to assigned disposal sites within the camp, reflecting the presence of organised collection systems.

Respondents' knowledge of waste valorisation was explored by asking how discarded materials could potentially be reused. Many participants indicated that these materials had no alternative use. However, some respondents in Uganda mentioned selling materials such as plastics or metals, suggesting the presence of informal recycling markets. In Rwanda, several respondents reported using plastic materials to assist in lighting cooking fires. Other responses included biological reuse practices such as mulching, planting seeds, or using materials for fencing. Refugee respondents appeared somewhat more aware of reuse and repair practices.

Respondents were also asked to identify problems associated with waste at both individual and community levels. Health-related concerns were the most frequently mentioned, including the spread of diseases and the attraction of insects. Environmental impacts such as pollution, unpleasant odours, and reduced soil fertility were also noted. Male respondents were slightly more likely to refer to environmental impacts affecting agricultural productivity.

Participants generally recognised that unmanaged waste can increase exposure to diseases such as cholera and malaria and can contribute to insect breeding and other health issues. Environmental concerns such as soil degradation and general pollution were also identified.

The survey further explored existing waste collection systems. Responses indicated that formal waste collection services are largely absent in host communities, with most respondents reporting that no organised waste collection exists in their areas. Within Mahama camp in Rwanda, however, respondents widely recognised the role of World

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Vision in collecting waste from designated disposal sites. In Uganda, responses suggested the presence of informal collection systems, with some respondents reporting selling recyclable materials to informal collectors.

When asked whether there are places where waste materials can be sold or delivered, respondents in Uganda generally indicated that such opportunities exist through informal buyers operating both within and outside refugee settlements. In Rwanda, however, most respondents reported that such options were not available, although a small number mentioned informal exchanges in markets.

Ownership of electrical and electronic appliances was also explored. Mobile phones were the most commonly owned devices across both countries and communities, indicating widespread access to basic communication technologies. In Uganda, some respondents also reported owning solar home systems and solar lamps. In Rwanda, similar patterns were observed, although ownership of devices such as radios, laptops, and wearable electronics varied slightly between genders.

Finally, the survey investigated the presence of repair services and second-hand markets for electrical and electronic appliances. In Rwanda, many refugee respondents indicated that repair or second-hand services were limited or unavailable, although some recognised providers operating within the camp. Host community respondents were more likely to report that such services did not exist in their areas.

In Uganda, respondents identified a greater availability of repair and second-hand services. Service providers were reported both within settlements and in nearby towns such as Mvepi, Yumbe, and Arua. Some respondents also referred to mobile or informal providers who periodically offer repair services or trade second-hand appliances near distribution centres.

Overall, the findings highlight similarities and contextual differences in consumption patterns, waste management practices, and access to repair and reuse services across the surveyed communities.

(2) Key Informant Interviews

Research assistants (RAs), together with the environmental expert, conducted key informant interviews (KIIs) to better understand waste management systems, stakeholder roles, and existing practices in the study areas. In total, 64 KIIs were carried out across Rwanda and Uganda, involving a wide range of actors engaged in waste generation, management, governance, and service provision.

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Local authorities and administrative representatives were interviewed to assess governance structures and regulatory frameworks. These included officials such as the Yumbe District Environment Officer and the Office of the Prime Minister Commander responsible for the settlement in Uganda, as well as the Mayor of Kirehe District and other local government representatives in Rwanda. In total, eight interviews were conducted with local authorities and community representatives (three in Rwanda and five in Uganda).

Sectoral stakeholders contributing to waste generation were also consulted. These included school representatives (seven interviews in total, with one in Rwanda and six in Uganda) and health centre representatives (three interviews, one in Rwanda and two in Uganda) to better understand institutional waste production and disposal practices. Two farmers were interviewed in Uganda, reflecting the relevance of agricultural activities as a source of organic waste.

Humanitarian organisations were another important stakeholder group given their operational role in refugee settlements. Nine interviews were conducted with representatives from humanitarian organisations, including international non-governmental organisations and United Nations agencies (three in Rwanda and six in Uganda). These discussions aimed to identify previous or ongoing interventions related to waste management, including both successful approaches and operational challenges.

Private and informal sector actors involved in waste management were also extensively represented in the interviews. A total of 21 private service providers were interviewed, including nine in Rwanda and twelve in Uganda. These actors typically operate small-scale enterprises engaged in waste collection, sorting, recycling, repair services, or material trading. In addition, 14 informal waste workers were interviewed (six in Rwanda and eight in Uganda), including collectors and traders involved in the recovery and resale of recyclable materials. Two industrial actors were also interviewed, one in each country.

Given the diversity of stakeholders involved, KIIs were conducted using a flexible and non-structured format, allowing discussions to adapt to the expertise and roles of respondents.

(3) Geotagging and Co-mapping

A complementary geotagging exercise was conducted to map waste sources, resource flows, and service providers identified through interviews and community consultations.

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The objective was to spatially identify waste producers, waste management actors, and disposal sites in order to better understand local waste dynamics.

The mapping of waste producers highlighted several categories of actors generating significant waste streams. In Uganda, a larger number of waste-producing sites were recorded compared to Rwanda. These included two farms engaged in animal breeding, one food processing unit (mill), two market areas, one business centre, three humanitarian warehouses, six schools or training centres, and two health centres. In Rwanda, a smaller number of sites were recorded, including one farm, two trader or business centres, one school or training centre, and one health centre.

These results indicate that educational institutions represent one of the most frequently identified institutional waste producers, particularly in Uganda, where six schools or training centres were mapped. Market areas, food processing activities, and farms were also identified as key sources of organic waste, particularly biodegradable residues originating from food preparation, agricultural production, and market activities.

The geotagging exercise also mapped actors involved in waste service provision. Overall, 38 waste service providers were identified across both countries, with a higher concentration in Uganda. These included activities related to material recovery, repair services, and waste treatment. The majority of identified actors were engaged in the informal collection and trading of recyclable materials, with 13 operators identified (five in Rwanda and eight in Uganda).

Repair services for electrical and electronic equipment represented the most common type of waste-related service identified. A total of 22 repair service providers were mapped, including nine in Rwanda and thirteen in Uganda. These actors typically operate small workshops repairing mobile phones, electronics, and basic hardware items, highlighting the potential role of repair activities in extending product lifecycles and reducing waste generation.

Other waste-related activities were less common. Three briquette production initiatives were identified in Uganda, demonstrating emerging efforts to valorise organic waste into alternative fuel sources. Additionally, two sanitary wastewater treatment operators were recorded in Uganda, while none were identified in Rwanda within the mapped areas.

Overall, the mapping exercise suggests that most waste-related economic activities in the study areas are linked to the recovery and reuse of dry recyclable materials, particularly plastics, metals, and electronic components. In contrast, fewer actors were found to directly manage biodegradable waste streams.

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Waste disposal sites were also recorded during the field mapping in order to assess waste accumulation practices and compare field observations with existing literature. The mapping revealed multiple informal waste pits where mixed waste is accumulated and, in some cases, periodically burned.

Field observations indicated that these disposal sites typically contain a heterogeneous mixture of waste materials, including recyclable materials such as paper, cardboard, and plastics (including LDPE, HDPE, and PET), as well as organic residues such as fruit and vegetable peels and banana stems. Other commonly observed waste types included textile materials and disposable hygiene products such as diapers. It also highlight the presence of potentially recoverable materials within disposal sites.

(4) MALLs

Workshop 1, Uganda

- **Objective:** To assess the existing technical expertise and roles related to electrical and electronic equipment within the refugee settlement and host community, while providing technical knowledge and mapping local repair capacities (including technicians, skills, tools, locations, and contacts), in order to establish a network of technicians and support the development of local circular value chains.
- **Description of Action:**
    - Days 1 and 2 included sessions on understanding e-waste and the circular economy, safe handling of electronics and identifying common causes of electronic device failure.
    - Day 3 sessions covered diagnostics, maintenance, and repair of computers, chargers, and understanding the mechanics of engines.
    - Day 4 involved a deep dive into Community Association, its governance and different financial models.
    - Day 5 entailed solar energy technology and devices, from PVP repairing to battery testing and refilling.

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Workshop 2, Uganda

- **Objective:** Facilitating the collection and transportation of valuable recyclables to existing market infrastructures, avoiding open dumping/ burning.
    - Identification of opportunities and bottlenecks to expand the types of materials that informal waste collectors trade in Yumbe.
    - Viability assessment of value chain configurations for the market expansion (collection, trading, transfer, disposal)
    - Identification of potential partners, stakeholders, and support projects.
- **Description of Action:**
    - Day 1 included a session with HUD on the waste management reality and challenges within Bidibidi/Yumbe, and the recycling value chain in Kampala, followed by a meeting with the deputy mayor of Yumbe and the chief leader of the GABBAGE waste workers group (Worker at the municipality in charge of waste collection)
    - Day 2 sessions covered a presentation on findings from the dry waste report, a session on waste management systems in yumbe, and a discussion on informal sector role and possible collaborations.
    - Day 3 involved an introduction to the MSWM systems, recycling value chains, threats and solutions, importance of private sector and a discussion on possible organisational support.

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Workshop 1 & 2 , Rwanda

- **Objective:** To share knowledge on the current waste management situation, harmonize the understanding of circular economy practices among stakeholders, and identify of potential circular value chains.

The same workshop was conducted with minor modifications to incorporate information relevant to the local contexts of Mahama Camp, and Kirehe District.

- **Description of Action:**

Days 1 and 2 included sessions on understanding SWM systems, presentations of findings in Mahama and Kirehe (dry waste report), exploring waste as a resource, and showcase of low-cost/low-tech circularity models solutions.


b. SWM system of Kirehe and Yumbe

The contrast between Rwanda and Uganda, refugee and host communities highlights a fundamental divergence in how geography and funding structures dictate environmental health. A compartive analysis is presented in table 7. In Rwanda, the Mahama Camp demonstrates the paradoxical advantage of high-density displacement. Because the camp is organized into 18 dense, close villages, it allows for a concentrated logistical footprint that is far more sophisticated than the surrounding Kirehe District.

While Kirehe's waste management is starved for resources - relying solely on meager local tax revenue and a struggling fleet - Mahama operates under the well-funded umbrella of UNHCR and

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World Vision. This humanitarian capital has financed permanent masonry collection points and a system for faecal sludge dehydration that converts waste into fertilizer. Consequently, the refugee settlement enjoys a higher level of managed sanitation and specialized infrastructure than the host community outside its borders, where the district authority often has to borrow trucks from the camp just to maintain basic roadside collection.

Uganda's Bidibidi Settlement, by contrast, proves that even significant humanitarian presence cannot easily overcome the challenges of extreme geographic dispersion. Unlike the compact "urban" layout of Mahama, Bidibidi's 270,000 residents are spread across five massive zones, making a centralized truck-and-hub system logistically and financially unviable. While Yumbe District has recently leapfrogged the settlement in terms of technology - benefiting from a World Bank-funded Fecal Sludge Treatment Plant - the settlement itself remains trapped in a state of "emergency" waste management. In Bidibidi, the burden falls on individual households to manage overflowing, unlined pits through open-air burning. While Yumbe Town slowly modernizes with international development funding, the settlement residents must rely on the informal "Kilokilo" pickers to bridge the gap between their survivalist waste disposal and the scrap markets of the outside world.

Ultimately, the significant difference lies in how humanitarian money can be leveraged against spatial reality. In Rwanda, the compact nature of Mahama allows humanitarian aid to function like a high-performance municipal utility, creating an island of better-managed services in a resource-poor district. In Uganda, the sprawl of Bidibidi dilutes the impact of humanitarian aid, leaving it unable to match the slow infrastructure gains of the Yumbe host community. This highlights a critical lesson in regional waste management: density enables the transition from "emergency dumping" to "resource recovery," whereas dispersion, as seen in Bidibidi, often results in the systemic failure of formal waste services despite the presence of international actors.

Table 7. A comparative analysis of workshop outcomes in Kirehe District, Mahama Camp, Yumbe District and Bidibidi Settlement describes the differences in waste management organisation, collection and treatment.

	Rwanda		**Uganda**	
	Kirehe District	**Mahama Camp**	**Yumbe District**	**Bidibidi Settlement**
SWM Authority	The central government advocates for proper SWM and sustainable measures, yet it does not finance it. The district solely relies solely on tax revenue to fund waste management efforts.	The SWM authority is UNHCR, who owns equipment, directs operations through implementing partner World Vision International. Coordination and advocacy initiatives target MINEMA to address waste management	The National Environment Management Authority regulates the sector. The 2025 National Waste Management Policy, focuses on circular economy, value extraction. Under the devolved system, individual cities are	UNHCR and the Office of the Prime Minister (OPM) oversee operations, with implementation led by humanitarian partners. Local coordination is integrated within the Yumbe District local government framework to ensure

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		challenges in the camp.	legally responsible for collection and disposal in their area.	host-community inclusion.
Waste Production	With a population of +460,000 people, MSW is primarily influenced by its rural nature and agricultural activities. With no large industries present, most waste is organic stemming from agricultural, food transformation processes. The district's central market is the most dense source of MSW.	Household MSW adds to residues from market areas. Higher concentration of waste generates in large facilities such as schools and business centres. The camp is expanding, with 500 new houses being built, +64,000 people, distributed across 18 dense, close villages.	Estimated at 0.3–0.4 kg/capita/day, heavily dominated by organic matter (70%) and agricultural residues. Significant presence in non-biodegradable waste (plastics and textiles) is observed in Yumbe town and surrounding trading centres.	With over 270,000 residents across 5 zones, waste is primarily organic from household cooking and markets. A distinct rise in "dry waste" (solar batteries, lanterns, and packaging) has triggered specialized e-waste pilot projects.
MSW Collection	MSW collection is limited along main roads, with no system in place for secondary roads, or villages outside the district center. INEMA, the contracted provider, operates four trucks with a tipping system, collecting waste twice a week. When trucks break (due to excessive weights, when mixed with soil from sweeping) they are occasionally replaced by trucks borrowed from refugee camps.	105 permanent waste collection points are planned to gather MSW. 53 were constructed: brick structures divided into 4 sections, covered by a metal roof. 2 trucks of 14 m^3 are manually loaded by daily workers, and conduct 2 to 3 trips to unload once full. The waste system is sized on 2 m^3 of waste per person per year. 784 m^3 were disposed of in 2024.	Collection is primarily centralized in Yumbe Town Council using one tractor-trailer operated by 1 driver, 2 workers. Collection only reaches the main roads, market areas of the Yumbe District. No appropriate bins are present, used to collect MSW. Coverage in side rodes, rural sub-counties is minimal, where households rely on backyard pits or communal burning.	No hub-and-spoke model is managed to handle waste. Most blocks still rely on household-level pits typically dug during humanitarian emergency onset, yet pits are often overflowing, hardly outlined. open burning and littering are vastly observed. Minor scattered collection interventions with no volume significance are operated by community groups, humanitarian organizations.
MSW Sorting	Source sorting is absent. Some recyclables are saved through informal drop-off locations operated by waste dealers. A	Waste collection points allocate 2 sections for organic, biodegradable, green waste and 2 for residual waste. Yet, collection is	Sorting is largely informal. Waste pickers ("Kilokilo" and "Chumachuma") recover metals (steel, brass, aluminium, scrap,	There is no formal system for source sorting in place. Sorting is almost exclusively informal, where independent refugee pickers

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	previous initiative to collect electronic waste was launched with a designated collection unit in Rusumo, later abandoned. Informal collectors gather metal scraps, hard plastics, and rubber without conflict with municipal authorities. Some collect plastic, glass bottles, primarily for reuse.	mixed and no source sorting happens. Waste used to be sorted at the early stages of system set-up.	electronic boards, batteries) and plastics (PP, HDPE, some LDPE and PET) from transit sites. There is no formal government-led source segregation system in place. The waste truck operators informally sort recyclables before disposing loads at the dumpsite, where more informal collectors sort valuable materials.	gather valuable materials and trade them to larger waste dealers in Yumbe Town. Only a few scattered, specialized projects exist (such as the IOM solar e-waste initiative or the battery recovery unit BatLab) that offer localized repair, recovery, or recycling services.
MSW Disposal	MSW is disposed of at a dumpsite with controlled boundaries, though waste often overflows and is regularly burned. To manage capacity, Kayonza District receives excess waste when emptying the local dumpsite. Human excreta is taken to the Kayonza dumpsite, while dry waste is sent to the Kirehe landfill. Plans were made to treat sorted organics mixed with manure to produce compost. Implementation is a challenge due to limited infrastructure and resources.	MSW is disposed of in excavated, non protected pits in a rented private land 2-3 km away from the settlement. Waste trucks daily unload waste in the non-fenced area. Waste is stored for an expected 6 months period in pits before being manually dug by operators, who segregate major residual waste and dry, presumably treated organic matter. Residual solid waste remains on site. Minor sorting of valuable recyclables is done by workers.	Waste is currently managed at the Yumbe Town Council dumpsite, which lacks modern lining or leachate treatment. Open-air burning is frequently used to manage volume during the dry season. The dumpsite is located in an agricultural area 6 km away from the main market.	Waste disposal is primarily managed through open-air pits and uncontrolled burning. While communal disposal pits are excavated in each zone, waste often accumulates on the surface due to slow degradation. Open burning is the standard practice at both household and communal levels, leading to significant air quality concerns.
Healthcare Waste Handling	Healthcare waste is incinerated at both hospital and health centre levels. Each	NGOs operating health centre levels disposed of medical waste,	Handled through De Montfort-type incinerators located at the Yumbe	Health facilities (run by humanitarian partners) use brick incinerators for

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	health facility operates its incinerator, ensuring on-site burning. Ashes are disposed of in pits.	mixed waste in simple incinerating brick structures. Ashes and sharps are buried in concrete pits. One facility runs a shredding, sanitation process to dispose of waste at the dumpsite.	Regional Referral Hospital and lower-level Health Centre IVs. Sharps are managed in dedicated concrete-lined pits.	clinical waste. Sharps are secured in safety boxes and buried in concrete pits to prevent scavenger access. Crushing units - where functional - allow disposal of glass vials for volume reduction and burying in pits.
Waste-Water Treatment	No centralized wastewater treatment system exists. Non-biodegradable waste (e.g. diapers) accumulates in latrines and clog desludging pipes.	Wastewater is handled in dehydration pits, where infiltration allows sludge thickening. Pumping trucks daily dispose of sludge from septic tanks. After 180 days, dry matter is used as fertilizer. Chemicals are added to reduce odors, pests.	New Centralized Facility: A World Bank-funded Fecal Sludge Treatment Plant has been established to serve Yumbe Town. It includes stabilizing ponds, drying beds to treat sludge from septic tanks. Desludging is still partial due to operating costs.	Largely decentralized via household latrines. High-density areas use communal latrine blocks. Sludge is occasionally treated in stabilization ponds before being buried or reused as soil conditioner. A centralized treatment facility is built, not operated.

Comparative analysis of SWM systems in target areas in Rwanda and Uganda.

c. Recylcing Markets

The transition of waste from a discarded liability to a tradable commodity depends on a chain of specialized stakeholders who bridge the gap between the isolated refugee settlements and the regional industrial hubs of Kirehe and Yumbe Districts.

While the settlements - Mahama and Bidibidi - operate under humanitarian mandates, their waste economies are deeply integrated into the host community markets. In Rwanda, the compact density of Mahama allows for a more hierarchical flow toward high volume traders and recycling industries. Whereas in Uganda, the sprawling geography of Bidibidi necessitates a decentralized network of informal collectors and localized "Kilo Kilo" shops to aggregate materials for the long-distance trade toward Yumbe Town, Arua or Kampala. The value chain is supported by four primary categories of actors, each fulfilling a distinct economic function:

- Frontline Collectors (Moving Waste Pickers): These are the most active agents of

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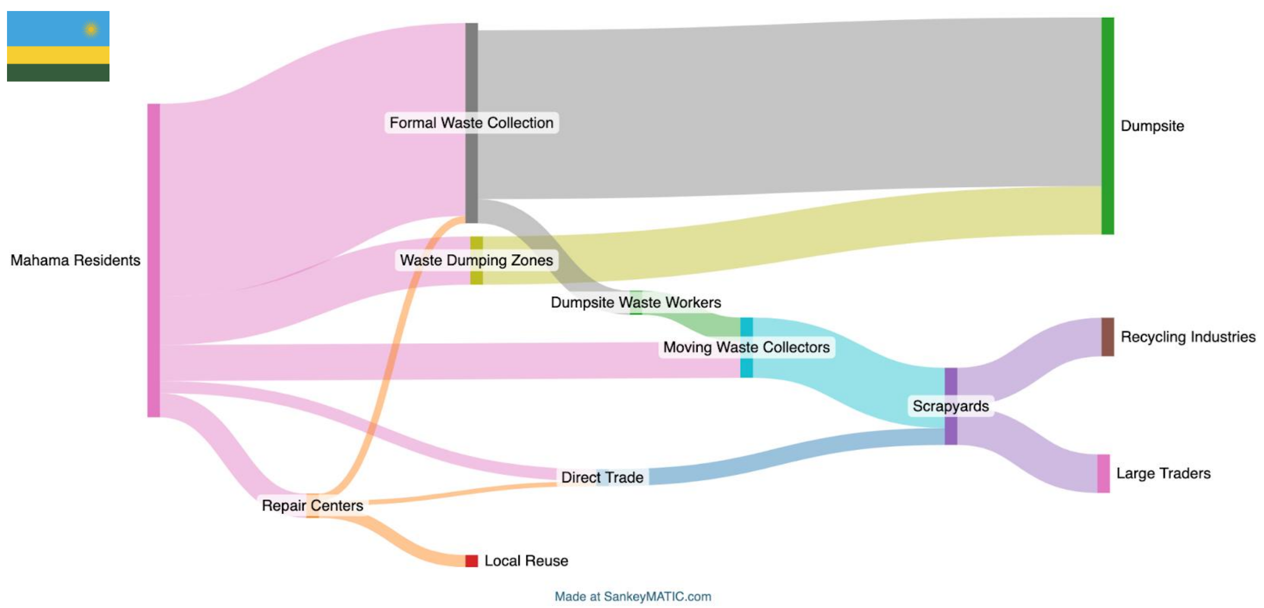
material recovery. They perform the labor-intensive task of "mining" waste from collection points, household pits, and even open burning areas to "rescue" metals and plastics before they are permanently lost to the environment.

- Commercial Aggregators (Scrapyards & Mobile Traders): Known locally as Kilo Kilo or Chuma Chuma in Bidibidi and Mobile Bike-Traders in Mahama. They provide the first point of "formalization," where loose scrap is weighed and converted into cash, providing liquidity to refugees.
- Value Retainers (Repair & Innovation Centers): Stakeholders like Solectra (Mahama) and the Bat Lab (Bidibidi) focus on technical restoration. Their role is to divert high-value e-waste from the scrap heap and return it to the community as functioning assets.
- Industrial Off-takers (Large Traders & Recycling Industries): These are the final destinations located in major urban centers (Kigali or Kampala). They require the bulk volumes provided by the settlement aggregators to feed industrial furnaces and processing plants.

The waste valorization architectures of Mahama and Bidibidi represent two distinct responses to humanitarian settlement logic, presented in the figure below.



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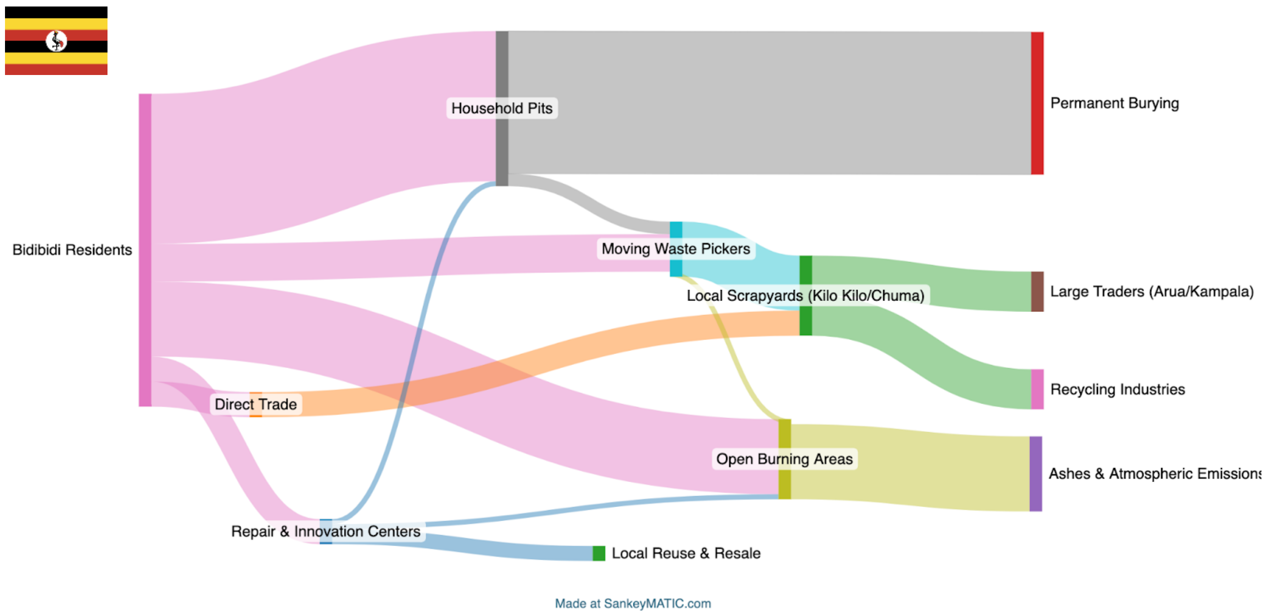

Sankey Diagram representing waste valorization architetures in Mahama Camp and Bidibidi settlement [KII, SSQ] Bar size does not represent an exact proportion of materials yet reflects KII's explanations, statistics, field observations.

In Mahama, the flow is characterized by a "funnel" effect enabled by high-density villages and centralized collection points. The formal waste collection system acts as the primary conveyor, but the dumpsite itself serves as a minor secondary marketplace where waste workers act as internal filters for valuable recyclables. These workers, along with moving waste pickers collecting from households, feed the mobile traders who bridge the gap to the district's scrapyards - in and out of Mahama. People, often kids, directly sell "*Injyamani*", scrap, to scrapyards, where available. Technical retention projects further enhance this system by creating a high-value inner loop that prevents waste from electric and electronic items and components from exiting the camp as low-value scrap.

In contrast, the flow in Bidibidi is defined by decentralization and significant environmental leakage across a vast geographic area. Without a centralized dumpsite, the largest terminal flows end in household pits for permanent burying or open burning areas for atmospheric emission, representing a massive loss of potential raw materials. The moving waste pickers in this context are particularly vital, as they rescue part of the volume already destined for uncontrolled disposal (in pits or burning sites).

A distinct flow of direct trade also exists, where residents bypass pickers to sell high-value scrap directly to local scrapyards, called "*Kilo Kilo*" or "*Chuma Chuma*" in local dialects. Local trading partially reflects market awareness, as discussed in chapter 6.1. The system faces a "technical leakage" challenge where repair and innovation centers, despite their successes in local reuse, must eventually discard unrepairable, often hazardous residues back into household pits, burning sites due to the lack of a professional outlet in the district.

The economic logic governing waste recovery in Kirehe and Yumbe Districts is defined by a balance between the "scrap value" of raw materials and the "functional value" of repaired assets. While the materials traded are largely identical, the logistics of the two regions create distinct

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pricing behaviors and stakeholder priorities. Across both districts, metals represent the most stable and sophisticated segment of the circular economy, though they are treated with varying levels of granularity. In Kirehe, the market for steel and iron (Injyamani) is highly formalized through approximately 100 traders who operate on thin margins, buying at 250–300 RWF/kg and selling to Kigali-bound aggregators for 400 RWF/kg. In Yumbe, the "Kilo Kilo" system operates at a higher price point (1,000–1,200 UGX/kg), reflecting the longer logistical chains to Kampala.

The "precious" metals—aluminum, copper, and brass—drive more aggressive scavenging behaviors. Aluminum fetches a significant premium—up to 3,000 UGX/kg in Yumbe and 800 RWF/kg in Kirehe—due to its utility in regional artisanal foundries for casting cooking pots. Copper remains the highest-value commodity in the settlement ecosystem, reaching up to 12,000 UGX/kg. This high valuation creates a "destructive incentive" in both Mahama and Bidibidi; as noted in interviews, children and pickers often strip wires from repairable electronics to secure immediate cash, effectively "killing" the potential for technical reuse to capture the material's weight-value.

The recovery of polymers is heavily dictated by density and transport costs. HDPE plastics (jerrycans and basins) are prioritized by collectors in both regions because their density provides a viable return on effort, with prices reaching 150 RWF/kg in Kirehe and 600 UGX/kg in Yumbe. In Bidibidi, truck operators even perform "pre-unloading" sorting of these hard plastics before reaching the dumpsite to maximize profit. Conversely, PET plastics (bottles) suffer from a low weight-to-value ratio. While they are recovered from transit sites in Yumbe for the Kampala market, they largely accumulate in the waste streams of Mahama due to the low return on investment. Rubber follows a similar localized logic; while it is a low-value scrap commodity, it finds a second life in "frugal innovation" cycles, such as the production of ropes and cobbler repairs, which keep the material within the settlement rather than exporting it for industrial processing.

Electronic waste represents the most complex flow, where the "Service Value" of repair often competes with the "Material Value" of scrap. In both Mahama and Bidibidi, e-waste trading as pure scrap is surprisingly rare; instead, a robust network of private technicians and humanitarian-backed projects (such as Solektra or specialized repair centers) prioritizes the "spare parts" economy. Techs in Rusumo and Kirehe buy broken items to salvage components, while in Bidibidi, the focus remains on restoring function over extracting circuit boards. Lead-acid batteries occupy a unique position as both high-value scrap and critical infrastructure. While they are traded by weight in Mahama (250 RWF/kg) or as units in Yumbe (10,000–20,000 UGX/unit), they are rarely processed in controlled facilities, presenting a significant environmental risk. However, the emergence of regeneration projects in Bidibidi and battery-swapping services in Mahama points toward a shift in the value chain. By regenerating or refilling batteries, these actors move the material from a "dead-end" scrap flow into a circular energy loop, significantly extending the life of essential solar systems in the settlements.

Table 8. A comparative analysis of workshop outcomes in Kirehe District, Mahama Camp, Yumbe District and Bidibidi Settlement describes the differences in recycling markets.

Rwanda		Uganda	
Kirehe District	**Mahama Camp**	**Yumbe District**	**Bidibidi Settlement**

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Steel & Iron	Scrap Shops, informal traders buy metals at 250–300 RWF/kg to resell at 400 RWF/kg.	Mobile Traders, scrap shops buy iron, steel 250–300 RWF/kg.	"Kilokilo" pickers, people sell mixed iron to town dealers for 1,000–1,200 UGX/kg.	Waste pickers trade scrap to larger dealers; primary source is damaged iron sheets.
Aluminum	Traders buy at 600–800 RWF/kg for regional resale.	Cans are not commonly collected. Broken cooking pots, pickers prioritize engine parts: higher weight-value.	Aluminum's value reaches 2,500–3,000 UGX/kg. Collected for regional artisanal foundry work and casting.	Aluminum, rarely present, is "mined" from pits and burning areas as it fetches a premium over iron.
Copper & Brass	Value: 2,500–3,500 RWF/kg. Mostly stripped from electrical cables and motor windings.	High price drives children to strip wires from electronics, often ruining repairable items, reusables.	Value: 8,000–12,000 UGX/kg. Highly prized by specialized "Kilo Kilo" dealers.	Households often hide copper to sell directly to shops rather than through pickers. Market awareness is very high.
Rubber	Bought by weight along with metals at lower rates.	Flip-flops/boots are commonly sold to waste traders, scrapyards for small cash amounts.	Occasionally collected for local "cobbler" repair rather than industrial scrap. Rubber from wheels commonly reused for ropes production.	Rubber often lacks a buyer; mostly stays in pits or is burned for lack of weight-value, unless reused for ropes production.
PET Plastics	Partially reused: Sold as second-hand containers in markets for liquid storage.	Minimal Market: Low weight-to-value ratio; traders rarely buy them; they accumulate in waste.	Recovered from transit sites, markets for regional plastic recycling hub in Kampala. Low ROI limits collection.	Few pickers gather PET bottles to trade to Yumbe dealers, though local prices are extremely low.
HDPE Plastics	Larger jerrycans/basins are sold by weight when damaged beyond repair. Sales prices ranges between 100-150 RWF/Kg.	Often unsegregated due to the high cost of transport relative to weight. Large items, scraps sold to scrapyards.	Prioritized over PET because the density provides a better weight-price. Sales reach 400-600 UGX/Kg.	Aggregators: Truck operators sort "hard plastics" before unloading at the dumpsite to sell to town traders.
E-Waste	Repair Shops: Techs in Rusumo/Kirehe buy broken items for "spare parts" rather	Private actors repair rather than trade (e.g. torches/radios for	E-waste is rarely sold for the circuit boards/ copper content to informal	Projects run by humanitarian actors add to private repair businesses and

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	than scrap. Electronics trading as scrap was not reported.	a 1,000 RWF fee). Electronics trading as scrap is not common.	dealers. E-waste repair, recovery is common despite limited financial capacity, access to technology.	focus on function over scrap weight. E-waste does not have recycling outlets - rarely e-boards do.
Batteries	Small shops buy old lead-acid batteries to salvage lead or rarely for "refilling." Batteries can be sold at 250 RWF/kg	Large, small lead acid batteries are traded as scrap. In the market, batteries are swapped, refilled by few suppliers (e.g. Solektra).	High value is recovered for large lead batteries (10,000-20,000 UGX/Unit), sold but not safely processed in controlled facilities.	Batteries are traded to Yumbe. A limited volume is regenerated by humanitarian-backed private businesses, projects.

Table 8. FIeld Assessement of the retail of various recyclable streams flowing in Rwanda and Uganda [KII, SSQ]

d. Circularity Approach

Drawing from the SUNNY project's strategic framework, the proposed **circular value chains** in Uganda and Rwanda represent a shift from linear "take-make-dispose" models to a systemic waste valorization approach tailored for displacement settings. In these contexts, valorization is not merely an environmental objective but a socio-economic catalyst designed to transform ecological liabilities into productive local assets. The SUNNY project aims to close resource loops, thereby reducing the reliance on dwindling natural resources while mitigating the public health risks associated with informal dumping and open burning.

The primary target of these value chains is the c**reation of a self-sustaining circular economy ecosystem** that functions within the unique logistical constraints of refugee settlements and host municipalities. Strategically, the project emphasizes "local-loop" circularity, where waste generated in institutional or household settings is processed and reintegrated into the local economy. This approach is designed to enhance community resilience, provide diversified income streams for marginalized groups, and significantly lower the carbon footprint of essential services.

Central to the success of these interventions is the **engagement of a diverse multi-tier stakeholder network**. The project strategically builds (see KPI 12) a chain of stakeholders active in the repair, reuse, and recycling value chains. The project aims to involve at least 12 distinct entities—including local MSMEs, waste collector cooperatives, technology providers, and institutional partners—across these chains. In the specific cases of the

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Biowaste, Recycling/Repair, and Micro-MRF chains, the involvement ranges from individual "Kilo Kilo" traders and the *"Yumbe GABBAGE Collectors' Group"* to international agencies like UNHCR and municipal authorities. This collaborative density ensures that the value chains are not isolated technical pilots but are instead embedded within the existing social fabric, ensuring long-term operational viability and local ownership.

The SUNNY project proposes three strategic value chains to transform waste into local assets. These are formally consolidated through **Work Package 2 (WP2)**, which defines the circular economy framework and identifies the specific local stakeholders required for long-term viability. Yet, in parallel, **Work Package 3 (WP3)** handles the technical engineering, ensuring that the "SUNNY technologies" are tailored to use local materials and are easy to maintain within these specific value chains. Value chains could accordingly adapt. This coordination ensures that the technical solutions are matched to the socio-economic reality of the communities they serve.

Value Chain 1: Biowaste Valorisation through Anaerobic Digestion - Uganda

The first value chain focuses on biowaste valorisation in Zone 2 of the Bidibidi Refugee Settlement, Yumbe District. The value chain works for the deployment of METANOGENIA anaerobic digestion technology. The proposed site for the implementeation of the technology is the **Locopio Technical School** in Zone 2, identified during field assessments as a promising institutional setting. The comprehensive assessment conducted in Bidibidi identified that biowaste can constitute up to **88.5%** of the total waste produced, with peak generation during the wet season. The choice focuses on "concentrated" waste streams - locations where the volume and energy density support a viable system. Opportunities include:

- **Institutional organic load.** The primary feedstock source is the school's kitchen. This provides a consistent flow of high-nitrogen food scraps and vegetable peelings, ensuring a stable organic Loading Rate for the microbial community inside the digester.
- **High-Yield Agricultural Residues.** Seasonal residues from nearby subsistence farms, such as maize husks, cassava peelings, and groundnut shells, serve as carbon-rich co-substrates. The School itself owns its own agricultural fields with a variety of crops ensuring multi-season waste provisioning.
- **Livestock Manure.** Waste from small-scale poultry and cattle producers within the school itself and in the surrounding host community can contribute to the digestion process, and possibly prevent system acidification.

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- **Sanitation Valorization (Future Potential).** The field assessments also highlighted the presence of clustered latrine pits and wastewater treatment units as potential long-term sources for organic matter recovery.

The value chain transforms an environmental liability into two distinct products that reinforce local food security.

- **Biogas: Cooking Energy.** The produced biogas woukd replace carbon, firewood in the school's kitchen. This reduces the local demand for tree biomass and minimizes the health risks associated with indoor air pollution.

- **Digestate.** The liquid effluent from the digester is a concentrated organic fertilizer. This creates a **resource loop** where local farmers supply agricultural waste to the school in exchange for nutrient-rich fertilizer, improving crop yields in the surrounding Zone 2 farms.

To strengthen the circularity of the system, local farmers or farmers' groups could supply additional organic residues in exchange for the produced liquid fertilizer, creating a small local resource loop between waste generation, treatment, and agricultural reuse.

Stakeholders involved:

- Locopio Technical School.

- Local Farmers; Local Farming Groups.

Value Chain 2: Strengthening the Recycling and Repair Network - Uganda

The second value chain aims to **professionalize the collection and trading of recyclables** in the Bidibidi Refugee Settlement and Yumbe District. Field research showed that the recyclables economy in Bidibidi operates through a decentralised network of informal actors. Frontline collectors recover valuable materials from household pits, informal dumps, and open burning areas, preventing them from being permanently lost to the environment. These materials are typically sold to local scrapyards ("Kilo Kilo" or "Chuma Chuma") and mobile traders. By supporting the recently formalized "Yumbe GABBAGE Waste Collectors Group" and helping to establish similar collectives, the aim is to shift informal waste picking into a structured business system. Based on the Dry Waste Assessment, the main problem in Yumbe is the "**volume-to-value**" barrier. Because the district is isolated, transport costs for bulky waste are often higher than the value of the waste itself. The value chain suport fixes this through:

- **Focus on High-Value Fractions:** Instead of just collecting heavy scrap metal, the

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group is trained to capture "technical value" from materials like PET bottles, HDPE plastics (like jerrycans), and repairable e-waste.

- **Mechanical Compaction:** The project provides **manual compressors**—simple, "frugal" machines engineered under **WP3**. These allow the collectors to squash bulky plastics into dense bales. This reduces the space needed for storage and cuts transport costs significantly, allowing the group to sell directly to big factories in Kampala rather than to local middlemen who pay very little.
- **Repair Before Scrap:** To keep value inside the community, the chain connects collectors with repair labs like **BatLab**. Before a radio or solar lamp is smashed for scrap metal, it is checked for repairability. This keeps useful items in the community and generates more money than selling raw scrap.

Forms of technical support would need to be matched with direct assistance in reinforcing and uniting the group through:

- **The VSLA Scheme.** The aim is to support teh establishment, reinforcement of the traditional Village Savings and Loan Association (VSLA). This is a community-managed "mini-bank" where members save money together. It provides the group with a fund to pay for machine repairs, buy safety gear (PPE), or support members when waste prices are low.
- **Defining Technical Roles:** To run like a business, members are assigned specific roles. Some can act as **Quality Control Officers** (ensuring plastic is clean and sorted by type – which is a significant constraint reported by several waste collectors), while others are **Market Linkage Coordinators** (checking market prices and talking to truck drivers and factory buyers).
- **Expanding the Market.** By baling waste and sorting it technically, the group stops being "scavengers" and becomes "suppliers." This allows them to sign formal contracts with regional recycling industries, leading to higher profitability and more stable income for the members.

Estimated stakeholders involved include:

- **Yumbe GABBAGE Waste Collectors Group** (20+ waste collectors members).
- **BatLab & Local Repair Shops** (Technical partners who fix electronics, upcycle electrical components requesting them at a higher market price).
- **Regional Recycling Industries.** Large buyers, recycling industries (closer to Kampala) who provide the final cash injection into the local economy.

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- **Local Authorities & UNHCR:** Partners who provide the space and rules for the sorting sites to operate safely.

Value Chain 3: Micro Material Recovery Facility (Micro-MRF) in Kirehe District – Rwanda

The third value chain focuses on establishing a micro-MRF in Kirehe District, designed to receive and sort recyclable materials generated both within Mahama Refugee Camp and the surrounding host community. Due to the administrative structure governing Mahama, where most services inside the camp are managed by humanitarian agencies such as UNHCR and World Vision, direct infrastructure investments inside the camp areless urgent to implement compared to the surrounding host community. For this reason, the preferred approach is to collaborate with Kirehe District authorities. The facility will be owned by Kirehe Municipality, while its operation and management will be contracted to a local operator through a tendering process.

A Material Recovery Facility (MRF), often called a "**waste collection point**" in community settings, is a specialized hub where recyclables are brought to be sorted, cleaned, and processed for sale. Instead of waste being burned or buried, the MRF acts as a filter that captures value from trash. **ReFuse** brings extensive experience in setting up these types of centers, having successfully established similar community-driven collection points that bridge the gap between informal waste picking and industrial recycling. The process is straightforward: residents or collectors bring mixed dry waste to the facility. There, the materials are manually **sorted** by type and grade to meet industry standards. Once separated, bulky items like plastic bottles are **compacted** using manual balers to make them easier and cheaper to transport. These dense bales are then sold to large-scale factories that turn them into new products. Materials accepted include:

- **Plastics:** PET bottles (water/soda), HDPE (jerrycans, detergent bottles), and LDPE (nylon bags).
- **Metals:** Aluminum cans, copper wiring, brass, and scrap steel.
- **Paper/Cardboard:** Clean cartons and brown paper packaging.
- **E-waste:** Old electronics or solar components that can be harvested for parts or repair
-

The proposed micro-MRF will strengthen the link between local waste collectors and regional recycling markets. The facility will receive mixed recyclable materials from service providers operating in the discrtirc, including Mahama. The main streams recovered are mixed metals, plastics (particularly HDPE and PET) and are sold to recycling industries located in Kigali. To improve logistics and storage efficiency, the

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facility will be equipped with one or two manually manufactured compactors (depending on price and availability) to compress recyclables and reduce transport volumes. Additional infrastructure will include collection containers, basic sorting areas, signage, and operational guidelines to support safe and organised material handling.

The intervention will therefore strengthen the regional waste valorisation chain, transforming discarded materials into resources while supporting both refugee and host community livelihoods. To ensure the facility doesn't fall into disrepair, the project uses a professional management model:

- **District-Led Support:** The facility is owned by the Kirehe Municipality, ensuring it has the legal permits and land to operate long-term.
- **Private Operator:** Management is handled by a **local contractor** selected through a tender. This operator is motivated to keep the machinery running because their profit depends on the volume of bales they sell to Kigali's industries (like EnviroServe).
- **Standardized Sorting:** The facility provides a clean, organized space where waste is sorted by technical grade. This ensures the operator gets the highest possible market price by delivering "clean" streams to the factories.

Estimated stakeholders involved (KPI 12: >12 total across chains):

- **Kirehe District / Municipality** (Owner and regulator).
- **UNHCR & World Vision** (Partners ensuring waste flows from the camp to the MRF).
- **Micro-MRF Private Operator** (Technical lead and business manager).
- **Kigali Recycling Industries** (Industrial buyers and final destination for materials).

4. Discussion and implications for the SUNNY project

The data collection activities and stakeholder workshops largely met the objectives of the task, particularly in identifying circular economy opportunities, assessing the viability of potential waste valorisation pathways, and mapping relevant partners for implementation. Waste flow analysis, interviews, and participatory workshops enabled to create an understanding of waste management practices and recycling structures in

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the demonstration sites and analyse strengths and weaknesses in the current waste management systems, listed in table 9.

Table 9 Analysis of strengths and weaknesses of waste management practices, waste flows and waste markets recognised in waste flow analysis, interviews and workshops.

Strengths	Weaknesses
Purchasing patterns appear similar	Waste defined as something damaged, harmful or having no value
Waste streams are mostly biodegradable materials	Waste disposal practices vary from disposal in mixed rubbish pits and open burning to designed disposal sites
Gender-disaggrated results no difference in purchasing patterns	Perceptions of waste valorisation mainly on selling metals, lighting fires with plastics and reusing biological materials in mulching or planting seeds.
Existing informal waste markets in Uganda	Formal waste collection systems absent
Repair or second-hand services for e-waste in Uganda (22 service providers)	Non-existing informal waste markets in Rwanda
Waste streams from educational institutions	Limited repair or second-hand services for e-waste in Rwanda (9 service providers)
Mahama density, concentrated logistics	Bidibidi extremely dispersed, unfeasible logistics
Donor-funded waste management infrastructure in Mahama for masonry and sludge treatment	Low-level waste management infrastructure in Bidibidi
established waste collection in Mahama	Waste sorting is largely informal

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Healthcare waste incinerated	Waste management based on formal or informal dumping or open-air burning of waste
Established waste water treatment system in Mahama	Wastewater treatment decentralized in Bidibidi
Existing network of informal waste collectors, commercial scrapyards, waste repair centers	

The analysis identifies several structural challenges that may limit the potential of the circular approach. Waste was perceived primarily as harmful or without value, and current waste valorisation practices remain limited to basic recovery activities such as selling scrap metals or reusing organic materials. Waste management practices consist of informal dumping or open-air burning, and waste sorting remains largely informal. Furthermore, Bidibidi's dispersed spatial structure and limited waste management infrastructure complicate waste collection and logistics, while Rwanda currently lacks the informal recycling and repair markets.

A key contribution of the analysis is the identification of circular value chains that can transform waste into local assets within the SUNNY project framework. Through Work Package 2 (WP2), the project establishes a circular economy framework and identifies local stakeholders required to support long-term value chain viability. In parallel, Work Package 3 (WP3) focuses on technical engineering solutions, ensuring that the SUNNY technologies are adapted to local conditions and capable of operating with locally available materials and maintenance capacities. The insights generated in this deliverable can inform eco-design practices and technological upgrades in WP3.

The proposed value chains depict this integration. In Bidibidi settlement in Uganda, the high proportion of biowaste presents a significant opportunity for valorisation through anaerobic digestion, enabling the production of biogas and fertilizer from organic waste collected from sources such as educational institutions and wastewater treatment facilities. At the same time, the presence of an informal waste sector offers a foundation for strengthening recycling and repair networks, where repair labs and targeted recovery of high-value waste fractions can improve material retention within the community while addressing logistical barriers in waste transport and collection. In Rwanda, the waste management context in Mahama camp and the surrounding Kirehe

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District presents an opportunity to establish a Micro Material Recovery Facility (Micro-MRF) that can improve sorting and recycling of plastics, metals, paper, and electronic waste. Such a facility could help divert waste streams away from disposal or open burning and channel them into recycling and reuse pathways, strengthening the local circular economy.

Across the three value chains, the findings demonstrate how circular approaches to waste management can contribute not only to environmental improvements but also to local economic development and livelihood creation. However, the successful implementation of these value chains will depend on addressing challenges in waste collection infrastructure, coordination between actors, and the need for stronger local recycling markets.

5. Summary and Outlook

This deliverable contributes to Task T2.3.2: Definition of technological waste repairing and recycling solutions, which aims to maximise resource efficiency and minimise waste through a circular approach within the SUNNY project. The analysis focused on identifying waste flows, existing recycling structures, and opportunities for repairing, re-valorisation, and recycling of technological waste in the demonstration sites of Bidibidi settlement and Yumbe District in Uganda and Mahama camp and Kirehe district in Rwanda. Through surveys, waste flow analysis, stakeholder engagement, and multistakeholder circularity workshops, the study assessed how discarded materials can be reintegrated into productive systems while creating livelihood opportunities for local communities.

The analysis builds on the preceding deliverable on local value chain development, that located that potential for local participation lies in service-based stages of the value chain, particularly installation, operation, routine maintenance, troubleshooting, and community-level governance parts of the life cycle.

The findings show that waste streams in both demonstration sites are largely composed of biodegradable materials, indicating strong potential for circular waste valorisation pathways such as anaerobic digestion or composting. In Uganda, an established network of informal waste collectors, scrap dealers, and repair services, particularly in e-waste management, already supports repair and reuse activities. In Mahama, donor-

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supported waste management infrastructure, established waste collection systems, and the spatial density of the camp present an opportunity for coordinated waste management and recycling intervention.

6. LITERATURE

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