SUNNY

DELIVERABLE 1.3

Use cases definition and technological requirements and specifications

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Nature of the Deliverable		
R	Document, report	X
DEM	Demonstrator, pilot, prototype	
DATA	Data sets, microdata, etc.	
OTHER	Software, technical diagram, etc.	

Dissemination Level		
PU	Public, fully open and automatically posted online	X
SEN	Sensitive, limited under the conditions of the Grand Agreement	
CI	Classified information: RESTREINT UE (Commission Decision 2015/444/EC)	
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Nature of the Deliverable			
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LIST OF ACRONYMS

Term	**Acronym**
ABPP	Africa Biogas Partnership Programme
AGRI-COOL	Advancing sustainable AGRIculture through off-grid energy and COOLing solutions in Africa
AKO	Project partner / company name used for the refrigerated food storage solution
AMPERE	Accessing Markets through Private Sector Enterprises for Refugees Energy
API	Application programming interface
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
AU	African Union
BRIDGE	BRIDGE use case repository / European energy initiative referenced in the deliverable
CAPEX	Capital expenditure
CO2	Carbon dioxide
COD	Chemical oxygen demand
COP	Coefficient of performance
DER	Distributed energy resource
EN	European Standard / European Norm
ENERGICA	ENERGy access and green transition collaboratively demonstrated in urban and rural areas in AfrICA
EOL	End of life
ESMAP	Energy Sector Management Assistance Program
EU	European Union
FAO	Food and Agriculture Organization of the United Nations
FNSSA	African Union – European Union Partnership on Food and Nutrition Security and Sustainable Agriculture
GFRP	Glass-fiber reinforced plastic
GHG	Greenhouse gas
GIZ	Deutsche Gesellschaft fur Internationale Zusammenarbeit
GRI	Global Reporting Initiative
GSM	Global System for Mobile Communications
HAZOP	Hazard and operability study
HEED	Humanitarian Engineering and Energy for Displacement
HH	Household
HOTOSM	Humanitarian OpenStreetMap Team

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HRT	Hydraulic retention time
IAMS	Individual Appliance Monitors
ICRW	International Center for Research on Women
ICS	Improved cookstove
ICT	Information and communication technology
IEC	International Electrotechnical Commission
IOM	International Organization for Migration
ISO	International Organization for Standardization
KPI	Key performance indicator
LCSA	Life Cycle Sustainability Assessment
LEAP-RE	Long-Term Joint EU-AU Research and Innovation Partnership on Renewable Energy
LED	Light-emitting diode
LHV	Lower heating value
LPG	Liquefied petroleum gas
LUT	LUT University
MAAIF	Ministry of Agriculture, Animal Industry and Fisheries
MAESHA	deMonstration of smArt and flExible solutions for a decarboniSed energy future in Mayotte and other European islAnds
MCI	Material Circularity Indicator
MECS	Modern Energy Cooking Services
META	Project partner / company name used for the biogas solution
MINEMA	Ministry in charge of Emergency Management
MININFRA	Ministry of Infrastructure
MJ	Megajoule
MTN	Mobile telecommunications provider referenced for mobile money payments
NEMA	National Environment Management Authority
NGO	Non-governmental organization
NREP	Organisation name used in the deliverable for a clean cooking partnership in Uganda
OGS	Off-grid solar products
OLS	Ordinary least squares
OPEX	Operating expenditure
OPM	Office of the Prime Minister
PAYG / PAYGO	Pay-as-you-go
PCB	Printed circuit board

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PURE	Productive use of renewable energy
PUE	Productive use of energy
PV	Photovoltaic
PVGIS	Photovoltaic Geographical Information System
PVC	Polyvinyl chloride
RBF4R	Result based Financing for Refugees
RE4R	Renewable Energy for Refugees
RE4RII	Renewable Energy for Refugees – Phase II
REFFECT AFRICA	Renewable energies for Africa: Effective valorization of agri-food wastes
REFUSE	ReFuse / project partner name used in the deliverable
RFS	Refrigerated food storage
RSB	Rwanda Standards Board
RURA	Rwanda Utilities Regulatory Authority
RWF	Rwandan franc
SESA	Smart Energy Solutions for Africa
SHS	Solar home system
SMS	Short Message Service
SNV	SNV Netherlands Development Organisation
SOLCO	Solar-Electric Cooking Partnership for Displacement Contexts
SOLDR	Project partner / company name used for frugal transport bags and adapted cookstoves
SOLEK	Abbreviation used in the deliverable for SOLEKTRA / system owner in use-case tables
SOLEKTRA	Project partner / company name used in the deliverable
SOLHYD	Project partner / company name used in the deliverable
SOP	Standard operating procedure
SSL	Solar streetlight(s)
SUM	Stove Use Monitors
SUNNY	Sustainable Energy Systems for Refugee and Host Communities in Africa
SWARM-E	Leave no one behind: Bottom-up energy transition of last-mile communities
UMAK	Makerere University (partner abbreviation used in the deliverable)
UNEP	United Nations Environment Programme
UNHCR	United Nations High Commissioner for Refugees
USD	United States dollar

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UV	Ultraviolet
WEF	Water-energy-food
WHO	World Health Organization
WP	Work Package
WUC	Water User Committee

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EXECUTIVE SUMMARY

The SUNNY project aims to sustainably improve access to energy services for refugee and host communities in Rwanda and Uganda through context-adapted renewable energy solutions. Within this broader framework, Deliverable D1.3 documents the work carried out under Task 1.3 and Task 1.4 and provides an analytical foundation for the further development, adaptation, and implementation of SUNNY technologies in the demonstration sites. The deliverable focuses on the five key technology areas addressed in the project: solar home systems, hydrogen cooking, biogas cooking, refrigerated food storage, and solar irrigation.

Deliverable D1.3 brings together several complementary components. It includes an overview of the SUNNY technologies and innovations, the specification of energy needs, the definition of environmental requirements, the development of project-specific use cases, and the comparison of these use cases with related projects and documented project learnings. Taken together, these components translate contextual understanding, user needs, sustainability considerations, and implementation experience into structured requirements and application-oriented insights for the project.

A central contribution of the deliverable is the structured link it establishes between local realities and technology development. The energy needs specification assesses current and future energy needs, aspirations, and adoption potential in order to derive user-oriented requirements for the different SUNNY solutions. The environmental requirements specification complements this by defining sustainability-oriented guidance and ecodesign-related indicators relevant for technology adaptation. The use-case specifies structured application scenarios for the SUNNY technologies, clarifying actors, processes, expected outcomes, and implementation conditions. In addition, the comparison with related projects situates SUNNY within a broader landscape of European research and innovation activities and documented energy interventions in relevant displacement contexts.

The deliverable is therefore not based on a single line of analysis, but on a broader package of interlinked activities. It reflects the multi-dimensional nature of Task 1.3 and Task 1.4 and shows how different methodological components jointly contribute to a common objective: providing a robust basis for technological requirements and specifications, use-case development, and implementation planning. In this way, the results support the continued work of the SUNNY project by informing technology adaptation and refinement in WP3, the preparation and implementation of demonstrations in WP4, and considerations related to transferability, replication, and impact in WP5.

Beyond its immediate project function, Deliverable D1.3 also contributes to a broader field of research and practice. The work documented in the deliverable expands the evidence base on energy access in displacement settings and supports the development of more holistic and context-sensitive approaches to technology design and implementation. In this sense, the deliverable not only advances SUNNY's internal objectives, but also provides a basis for wider scientific and practical contributions beyond the project itself.

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I. INTRODUCTION

This chapter introduces Deliverable D1.3 and situates it within the wider SUNNY project. It first provides the general background to the deliverable and then explains its objective, its contributions to the SUNNY project, and its relevance beyond the immediate project scope. In addition, the chapter outlines the overall structure of the deliverable.

1. General Background

The overall objective of the SUNNY project is to sustainably improve access to energy services for rural and displaced communities in Rwanda and Uganda by generating innovations in the respective energy environments. The project applies an integrated approach to address energy needs comprehensively and based on the circular economy concept, develop supporting systems that complement existing local value-chains. On a local level, interventions are tailored to the respective contexts by means of a co-design process. On an institutional level, the replication of the developed innovations is systemically advanced. The project is composed of a diverse project consortium to facilitate the wide scope of activities.

Gathering 17 partners from 3 African, 5 European countries and 2 associated countries, SUNNY is a 48-months project that aims to provide highly replicable solutions for green energy transition and energy access in Africa. To reach that goal, five Renewable Energy Technologies, reaching TRL 7-8 will be improved, adapted to the local context and demonstrated in two sites in Uganda and Rwanda, reaching around 1300 refugees and persons in the local host populations.

The technologies developed in SUNNY will be upgraded following circular economy and local value chain approaches in order to create economic activity locally as well as ensure relevance of the solutions and long-term sustainability. To ensure uptake, a strong focus will also be made on cost effectiveness and adapted business models. Solar home systems will ensure the access to basic energy needs at a household level (PR1). Clean hydrogen (PR2) and biogas (PR3) cooking solutions will allow cooking to be decarbonised while improving health conditions. Refrigerated food storage (PR4) and smart solar irrigation, combined with biogas, will allow to improve food security in rural African areas and address the WEF nexus. Holistic models (PR5) and assessment methods (PR8) will allow to identify and validate the benefits and sustainability of the technologies, while social innovation through among others capacity building will support the long-term socio-economic impact (PR6) and ensure local uptake as well as a strong replicability potential. Indeed, SUNNY ambitions to widely impact humanitarian energy practices through a replication plan comprising the involvement of 15 replication

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cases with new interoperability of technologies, training activities towards African and EU-wide energy-access and development agencies and camps managers, and policy recommendations (PR8).

2. Introduction to the deliverable and contributions to the SUNNY project

Deliverable D1.3 documents the activities conducted under Task 1.3 and Task 1.4 of the SUNNY project. Together, these two tasks address the definition of users' energy needs, technological requirements and specifications, use cases, and related requirements analysis. While the two tasks are closely linked, they each include different streams of work that contribute to a common objective, namely, to provide a robust basis for the further development and implementation of SUNNY technologies in the demonstration contexts.

Accordingly, Deliverable D1.3 brings together several complementary components. It includes the specification of end-users' energy needs, the definition of environmental requirements, the development of project-specific use cases, and the comparison of these use cases with related projects and documented project learnings. These components are analytically distinct but closely interrelated. Taken together, they provide a structured understanding of what the SUNNY technologies are expected to achieve, under which contextual conditions they are to operate, which requirements they need to fulfil, and how their development can be informed by both project-internal work and relevant external experience.

In this way, the deliverable documents not a single line of analysis, but a broader package of interlinked activities carried out in support of technology adaptation and demonstration planning. It therefore reflects the multi-dimensional character of the work in Task 1.3 and Task 1.4 and brings the different streams of work together in one consolidated deliverable.

a. Objective of the deliverable

The overall objective of Deliverable D1.3 is to provide the conceptual and analytical foundation for the further development, adaptation, and implementation of SUNNY technologies in the demonstration sites. More specifically, the deliverable aims to translate contextual understanding and stakeholder-related insights into a structured definition of energy needs, technological requirements and specifications, use cases, and implementation-relevant considerations.

This overall objective is met by combining different methodological approaches that address complementary dimensions of the same broader task. These include the

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assessment of current and future energy needs, the specification of environmental requirements, the development of context-adapted use cases, and the comparison of SUNNY use cases with related project experience. The following chapter explains in more detail how these different methodological components are combined within the overall methodology of the deliverable.

b. Contributions to the SUNNY project

Deliverable D1.3 makes an important contribution to the SUNNY project by providing essential inputs for the next phases of technology development and implementation. First, the assessment of energy needs supports the definition of user-oriented technological requirements and specifications. Second, the environmental requirements component contributes sustainability-oriented guidance for technology adaptation and design. Third, the use cases translate project objectives into concrete application scenarios that clarify actors, processes, and expected outcomes. Fourth, the comparison with related projects strengthens this work by situating SUNNY within a broader field of relevant project experience and by identifying practical learnings from comparable interventions.

Together, these contributions support the further work of the project in several ways. They provide an important basis for technology adaptation and refinement in WP3, inform the preparation and implementation of demonstrations in WP4, and contribute to considerations related to transferability, replication, and broader impact in WP5. More generally, the deliverable helps ensure that the continued development of SUNNY solutions is grounded in user needs, contextual realities, sustainability considerations, and implementation experience.

c. Contributions beyond the scope of the SUNNY project

In the early phase of the work in Task WP1 the partners involved identified a significant scientific and practical value in expanding the scope of the analysis to be conducted in WP1. The SUNNY project is pioneering novel conceptual approaches that focus on a holistic contextual understanding and systematically integrating the local communities throughout the innovation process. The project is positioned to make a substantial contribution to advancing research in this field. This is particularly significant given that displacement settings, and even more so the domain of energy access within these settings, are characterized by a fundamental lack of conceptual clarity and a limited evidence base. The initial submission date for Deliverable D1.3 was M12. Following consultation with the European Commission, the deliverable's submission date was shifted to M22 to facilitate the expansion of the scope of the work conducted.

The comprehensive work conducted in Task WP1 has the potential to make significant

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scientific contributions to the field, presenting a high impact potential beyond the SUNNY project. The scientific potential of the work conducted in WP1 is further reflected in the publications planned to emerge from this WP.

3. Structure of the Deliverable

Following this introductory chapter, the deliverable is structured into a set of chapters that document the work carried out under Task 1.3 and Task 1.4. Chapter II presents the overall methodology and explains how the different components of the analysis are linked within the deliverable. The subsequent chapters are organised according to the main analytical dimensions addressed in the two tasks. While each chapter focuses on a distinct component, they follow a common logic: first, the respective component is introduced; second, the methods applied are presented; and third, the results and their implications for the SUNNY project are discussed. This common structure is intended to support readability and to make the relationship between the different components of the deliverable clear.

Chapter III provides an overview of the SUNNY technologies and innovations. Chapter IV presents the energy needs specification. Chapter V addresses the environmental requirements specification. Chapter VI presents the SUNNY use cases. Chapter VII compares the SUNNY use cases with related projects and documented implementation experience.

Taken together, these chapters reflect the different but closely connected analytical dimensions of Task 1.3 and Task 1.4. Their combined presentation in this deliverable provides the basis for the further development of technological requirements and specifications, the refinement of use cases, and the preparation of later implementation activities in the SUNNY project.

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II. OVERALL METHODOLOGY

This chapter presents the overall methodology of Deliverable D1.3. It first introduces the overall methodological approach and subsequently provides a short description of the individual components that together structure the work reported under Task 1.3 and Task 1.4.

As such, the chapter serves as a guide to the analytical structure of the deliverable. It helps the reader understand how the different components relate to one another and prepares the ground for the following chapters, in which each component is presented in more detail in a dedicated chapter.

1. Description of the overall methodology

The overall methodology of Deliverable D1.3 integrates several complementary components that are part of Task 1.3 and Task 1.4 of the SUNNY project. Together, these components provide the analytical basis for translating contextual understanding, user needs, sustainability considerations, and implementation experience into requirements and application-oriented insights for the further development of SUNNY technologies.

The methodology does not follow a single analytical pathway. Rather, it brings together different but closely linked components that address distinct dimensions of the broader task. These include the description of the SUNNY technologies and innovations, the specification of energy needs, the definition of environmental requirements, the development of use cases, and the comparison of the SUNNY use cases with related projects. Each of these components addresses a specific analytical objective, while at the same time contributing to a shared overall purpose.

The following graph (Figure 1) provides an overview of these components. It illustrates how the different parts of the analysis jointly contribute to the conceptual and analytical foundation of Deliverable D1.3.

The following section provides a more detailed description of the individual components.

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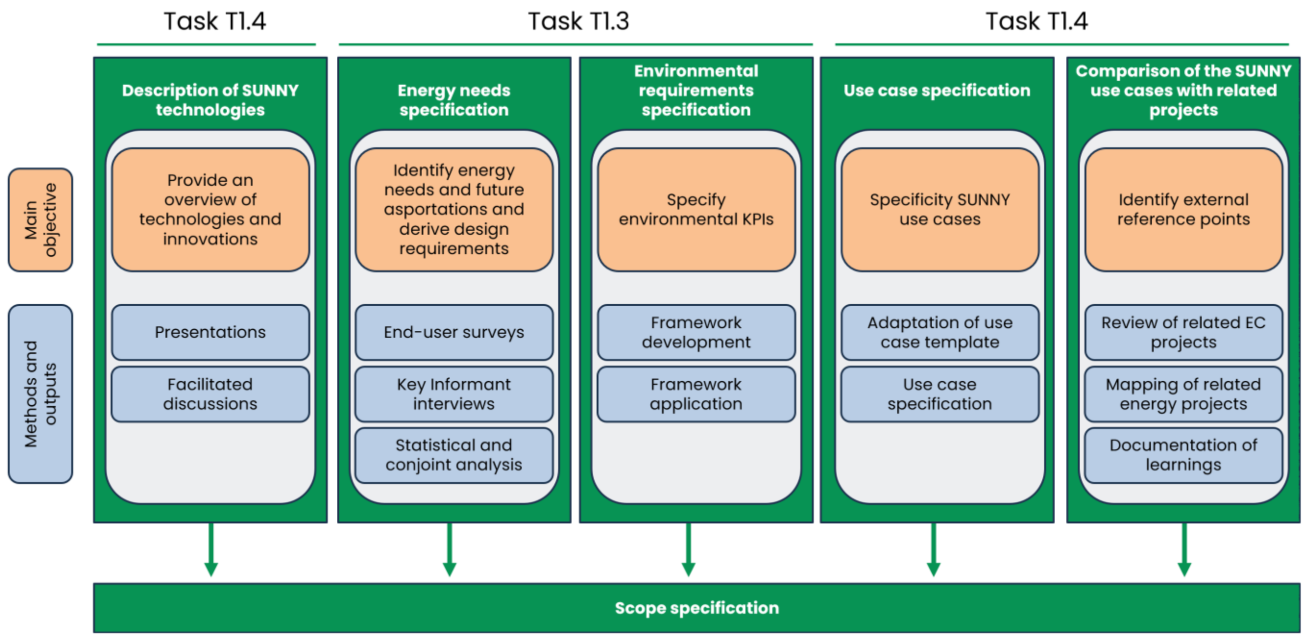

Figure 1: Overview of the overall methodology of Deliverable D1.3

2. Short description of the components of the deliverable

This section provides a more detailed introduction to the individual components that together make up the overall methodology of Deliverable D1.3. While the previous section outlined the overall methodological approach, the following subsections describe each component separately. For each component, a short description is provided of its purpose, methodological approach, main activities and results, and its link to other activities in the SUNNY project.

a. Description of the SUNNY technologies and innovations

Introduction:

This component provides an overview of the core technologies and innovations developed and adapted within the SUNNY project. It introduces the technological portfolio that forms the basis for the later analyses in this deliverable, including energy needs specification, environmental requirements, and use-case development. In addition, it documents the Technology Workshop as an important activity for building shared understanding of the technologies and identifying key considerations for their further development.

Objective:

The objective of this component is to provide a structured overview of the SUNNY technologies, their current state of development, the challenges they are intended to address, and the innovations pursued within the project.

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Methods:
The component combines two complementary elements. First, a descriptive overview of the SUNNY technologies was developed based on inputs from the technology partners. Second, a dedicated Technology Workshop was conducted during the consortium meeting, bringing together experts and thematic groups to discuss the technologies from environmental, social, economic, implementation, and regulatory perspectives. The workshop combined presentations, facilitated discussions, and thematic group work.

Main activities and results:
The first part of the component resulted in a structured overview of the five main SUNNY technologies: hydrogen for cooking, solar home systems, solar irrigation, food refrigeration, and biogas. The second part of the component consisted of the Technology Workshop. This activity supported a shared understanding of the technologies across the consortium and generated early insights for their further development, including cross-cutting requirements, risks, and contextual considerations.

Link to other activities in the project:
This component provides an important foundation for the subsequent parts of Deliverable D1.3. It supports the specification of energy needs, informs the environmental requirements analysis, and contributes to the development of use cases. It also provides input for technology refinement in WP3 and for demonstration planning and implementation in WP4.

b. Energy needs specification

Introduction: Understanding current energy needs—and aspirations for future use—is the foundation for designing technology that serves end-users. The analysis will guide technology upgrades and priorities. Equally important is assessing users' willingness to adopt new solutions, including motivations and barriers, so design, engagement, and implementation strategies can be tailored accordingly.

Objective: The main goal is to link energy needs, aspirations, and adoption potential to concrete design requirements and implementation steps. This will be achieved by addressing the following assessment objectives: i) Map current energy use, ii) Identify future energy requirements and aspirations, iii) Assess willingness to adopt new technologies and the link between affordability and level of services iv) identify barriers and motivations that can shape energy demand v) translate findings into actionable design requirements.

Methods: The study design integrates data collection from technology partners, local organizations, and end-users through surveys and Key Informant Interviews (KIIs),

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building on baseline context data from Rwanda and Uganda. KIIs, targeted at local organizations, are used contextualize adoption potential, while surveys are administered to potential end-users. Furthermore, data from relevant reports and studies are utilized to develop potential scenarios that inform and define the projected energy requirements. A conjoint analysis is embedded in the end-user survey to quantify the relative importance of technology attributes, thereby informing design and upgrade priorities. Resulting data are analyzed using statistical techniques, energy-system modeling, and thematic analysis.

Main activities and results:
Baseline technology analyses were completed across all technologies to characterize current settings and identify potential upgrade options. Preliminary context assessments were then conducted, after which end-user instruments were developed and field implementation began in Mahama.
For Bidibidi, multiple scenarios were developed for each technology based on data collected during the preliminary assessment conducted by UMAK and REFUSE in Bidibidi, complemented by desk-based research. The analysis provides an initial estimation of potential energy needs, derived from an overall assessment of camp conditions and infrastructure. This assessment should be regarded as a baseline analytical framework to inform planning and comparative evaluation of technology options. Final system sizing and technical specifications will require the identification and detailed characterization of specific demonstration sites, including site-level operational parameters.

Link to other activities in the project:
The outcome of this assessment will inform the definition of specific requirements for each SUNNY technological solution, including energy provision, sizing, storage, and payment mechanisms. It will also contribute to the development of use cases for Task 1.4 and implementation pathways. Additionally, the findings will provide the needed insights for Task 3.3, particularly regarding the need for an ICT-based supervision and monitoring system. Moreover, the assessment will inform WP7 with regard to purchasing capabilities, affordability constraints, and business models that align with user needs and support the broader adoption of the technologies.

c. Environmental requirements specification

Introduction: Building on the baseline findings of D1.1 and the stakeholder analysis of D1.2, this deliverable integrates environmental requirements into energy systems design and technology adaptation in WP3, favouring the design of solutions that are not only technically sound but also sustainable, circular, and adapted to fragile ecosystems.

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Objective and research question addressed: The objective is to define environmental specifications that guide the design, procurement, and piloting of SUNNY technologies, while addressing: (1) How can energy solutions avoid adding to existing waste and pollution problems in refugee and host communities? (2) What environmental KPIs ensure systems are durable, circular, and repairable under local conditions?

Methods: The approach taken is drawn from the GRI Standards to structure stakeholder-driven materiality analysis, the EU Ecodesign Directive and ISO 14062 to integrate environmental design principles and performance measurement, and Life Cycle Sustainability Assessment (LCSA) to combine performance scoring with materiality-based weightin, with the addition of REFUSE environmental expert expertise to contextualise findings for local conditions and SUNNY objectives.

Main activities and results:
A ecodesign toolkit was developed presenting KPIs and guidelines, structured into four main categories: (1) Nature- Based Design, Environmental Footprint; (2) Durability and Repairability; (3) Recyclability & End of life Management; (4) Service Orientation. Guidelines were integrated through project patners' feedback and field data on waste infrastructures, existing valorisation value chains, local repair practices and more. The toolkit was shared with technology providers (SOLEKTRA, SOLHYD, AKO, META) for baseline assessment of their systems.

Preliminary results include a preliminary recommendation for SUNNY technologies to ensure minimal waste generation, modularity, potential for reuse or recycling, and alignment with circular value chains.

Link to other activities in the project: The KPIs developed here connect to WP2's circularity and value chain analysis, ensuring procurement choices reflect sustainability priorities. The Ecodesign toolkit informs technology development in WP3 and provides a framework for performance assessment in WP6.

d. Use cases

Introduction: The standardised methodology for use cases is purely technical and primarily geared towards European contexts, not accounting for activities related to energy access. This deliverable integrates environmental, socio-economic, and business concerns into the existing use case template. The adapted template is then used to describe the use cases for each SUNNY technology.

Objective and research questions addressed: The objective is to define at least one use case for each SUNNY technology. We address the following research questions: (1) What

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are the use cases for each technology implemented in SUNNY? (2) How can these use cases move beyond purely technical aspects and account for the complexity of environmental, socio-economic, and business concerns relevant to the SUNNY contexts?

Methods: We adapt the IEC standard 62559-2 "Use Case Methodology - Part 2: Definition of the Templates for Use Cases, Actor List and Requirements List" to the characteristics and requirements of the SUNNY contexts, adding categories that address environmental, socio-economic, and business aspects. Data for this deliverable is collected through surveys and workshops with the technical partners in the SUNNY project.

Main activities and results:

- Adapt the use case template from the IEC standard 62559-2 for use within the SUNNY project.
- Conduct workshops with technology partners to specify the SUNNY use cases based on the developed template.

Link to other activities in the project: The use specification provides an input to the technology upgrades.

e. Comparison of the SUNNY use cases with related projects

Introduction: The specification of SUNNY use cases is complemented by a comparison with related projects. This component situates the SUNNY use cases within a broader landscape of relevant European research and innovation activities and of energy-related projects implemented in the demonstration contexts or comparable settings. In this way, it helps ensure that the SUNNY use cases are not only grounded in project-internal analysis but also informed by relevant external experience and documented implementation learnings.

Objective: The main goal is to compare the SUNNY use cases with related project experience in order to identify relevant points of reference for their further development. This is achieved by addressing the following objectives: i) identify relevant European projects with activities linked to the SUNNY use cases, ii) compare SUNNY use cases with related use cases and activities in these projects, iii) review relevant energy-related projects in the demonstration contexts and comparable settings, and iv) document practical learnings from these projects.

Methods: The component combines two complementary streams of work. First, relevant Horizon 2020 and Horizon Europe calls were identified based on defined selection criteria, and the funded projects under these calls were reviewed to identify those most relevant to SUNNY. Their activities were then compared with the SUNNY use cases. Second, a

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review of relevant energy-related projects in the demonstration contexts and comparable displacement settings was conducted based on grey and scientific literature. Identified projects were mapped in structured overview tables, and documented learnings were extracted from project descriptions, reports, learning briefs, publications, and related sources.

Main activities and results: The first stream of work resulted in an overview of relevant Horizon 2020 and Horizon Europe calls, an overview of projects identified as relevant to SUNNY, a comparative matrix linking these projects to the individual SUNNY use cases, and a qualitative assessment of their relevance for SUNNY. The second stream of work resulted in structured overviews of energy-related projects in Uganda and Rwanda, as well as a synthesis of documented learnings from projects in the demonstration contexts and beyond. Together, these results provide both a broader European comparison and a context-specific overview of practical lessons relevant for the further development of SUNNY use cases.

Link to other activities in the project: The comparison provides an important input for the further refinement of SUNNY use cases and their requirements. The documented project learnings can inform technology adaptation in WP3, demonstration planning and implementation in WP4, and wider considerations on transferability, replication, and impact in WP5.

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III. DESCRIPTION OF SUNNY TECHNOLOGIES AND INNOVATIONS

This chapter provides an overview of the SUNNY technologies and innovations and thereby introduces the technological foundation of Deliverable D1.3. The chapter first presents the different SUNNY technologies and their main areas of application. It then reports on the Technology Workshop, which supported a shared understanding of the technologies across the consortium and helped identify important considerations for their further development.

1. Description of SUNNY technologies

The SUNNY project integrates a set of complementary technologies designed to improve access to sustainable, reliable, and context-appropriate energy services in remote and displacement settings. These technologies address different points along household and community energy chains—from clean cooking and electricity access to agricultural productivity and cold-chain management. Together, they form a coherent portfolio that supports both basic energy needs and productive uses, while enabling new business models and community-led operation. The following section provides a brief overview of the technologies.

Off-Grid Technologies

- Hydrogen solution
  - SOLHYD: design their H2 panel to include IoT monitoring
  - SOLDR: design frugal transport bags and adapted cookstoves.
- SHS
  - SOLEK: extend the scope of individual SHS to serve more than one household through the development of a PCB control unit enabling the use of IoT functionality

WEF nexus technologies

- Biogas
  - META: design biogas production plant to optimise construction costs while selecting suitable and local materials
  - SOLDR and META: design multi-fuel cookstoves through the retrofit of LPG stoves
- Solar irrigation
  - SOLEK: improve the control of water flow of their solar irrigation solution, also studying interoperability potential with other SUNNY solutions to enhance flexibility
- Refrigeration

- AKO: energy use by further developing IoT systems for enhanced monitoring of the refrigerated food storage solution.

a. Hydrogen for cooking

Technology: How does the technology work and if relevant, what is the associated delivery model?

Hydrogen production

- Air is blown through the cores at night, to absorb & store moisture.
- Sunlight is converted into electricity by the solar PV module on top.
- Electricity is fed to the cores, which contain electrodes for oxygen & hydrogen production, and a membrane to keep the gases separated. Oxygen is vented into the air.
- Hydrogen is produced in a separate compartment at low pressure (< 500 mbar) and collected from the panel with a plastic tube.

Hydrogen storage

- Air is blown through the cores at night, to absorb & store moisture.
- Sunlight is converted into electricity by the solar PV module on top.
- Electricity is fed to the cores, which contain electrodes for oxygen & hydrogen production, and a membrane to keep the gases separated. Oxygen is vented into the air.
- Hydrogen is produced in a separate compartment at low pressure (< 500 mbar) and collected from the panel with a plastic tube.

Hydrogen cooking

- Unique hydrogen burner technology: Safe and efficient combustion
- Customize stove to local context and user needs: Power; Size and burner distribution; Look and feel
- Certify to EU standards

State of the art: What version of the technology/ prototype already exists?/ What was previously implemented?

- Prototypes of panels, storage unit and cooker exist

Challenges: What are the challenges in the demonstration location that the technology addresses?

- Avoid air pollution (from firewood and other solid fuels)

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- Access to cooking fuel (vs gathering wood, buying charcoal/LPG)
  - On-site fuel production: no fuel distribution problems/costs, no electrical grid required.
  - Energy autonomy & security. Local community owns & maintains the fuel production equipment
- No CO_2 emissions
  - No climate impact
  - No reliance on fossil fuels
  - No harm to biodiversity & environment, no water consumption, no deforestation

Innovations: What are the innovations developed in SUNNY regarding this technology?

- Cost reduction
  - Through a redesign tailored for SUNNY's context
- Connectivity
  - Providing low-cost sensors and connectivity for remote monitoring
- Repairability
  - Optimizing the design & materials choices to enable self-repair procedures and minimize downtime
- Low-tech storage and transport solutions
  - Hydrogen gas bags
  - Tire tubes
- Biogas integration
  - Combination via admixing and/or multifuel stove
- Integrated hydrogen cooking solution
  - Deployment & operation of the integral system

Critical Questions: What are the most critical questions regarding the upgrading of technology?

- Safety & anti-tampering measures
  - Safe operation of hydrogen panels
  - Integrity of gas storage bags
  - Proper and safe usage of the hydrogen cookstove and multi-fuel stove
- Connectivity & sensors for remote monitoring
  - Data collection vs cost vs low maintenance
  - Internet access & interruptions
- Cost reduction
  - Avoid unnecessary costs while ensuring safety & longevity
  - Tire tubes as a low-tech storage alternative
- Repairability & circularity

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- Self-repairs vs safety
- Spare parts vs shipping parts

b. Solar Home Systems

Technology: How does the technology work and if relevant, what is the associated delivery model?

Solar Home System (SHS)

- Developed in phases since 2018, starting with a keypad-based PAYGO model.
- Improved version includes a 76Wh battery, audio feedback for keypad input, and a robust motherboard adapted to African conditions.
- The latest version supports multiple households, each with its own keypad for independent energy access

Delivery Model

- Pay-As-You-Go (PAYGO) Model
    - Users acquire the SHS through a keypad-based PAYGO system, allowing them to pay in small installments.
    - Each household has a personal keypad to input codes after making payments.
- Multi-Household Access
    - A single SHS unit can now serve multiple households, expanding reach and reducing unit costs.
- Community-Based Distribution
    - SHS units are deployed via local agents or community networks, trained in installation and support.
- Technical Support and Training
    - Users and local technicians receive training for installation, usage, and troubleshooting, ensuring long-term sustainability.

State of the art: What version of the technology/ prototype already exists?/ What was previously implemented?

- Version 1 (2018 – H2G Model):
    - Introduced with a keypad-based PAYGO system.
    - Limitations: no audio feedback during code entry, prone to user input errors; motherboard had performance issues with lighting in African conditions.
- Version 2 (Improved SHS):

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- Integrated a 76Wh battery.
- Added audio feedback to improve usability.
- Featured a redesigned motherboard tailored for harsh environmental conditions (heat, dust, etc.).
- Current Development (Version 3 – Multi-Household SHS):
  - Each household has its own individual keypad.
  - Designed to serve multiple households from a single SHS unit, improving scalability and accessibility

Challenges: What are the challenges in the demonstration location that the technology addresses?

- Context: Energy Access Challenges
  - Many rural and off-grid communities in the demonstration areas (e.g., near Mahama Refugee Camp in Kayonza District) face limited or no access to reliable electricity.
  - Traditional energy sources (like kerosene or diesel) are costly, unsafe, and environmentally harmful.
- Technology Response: Solar Home System (SHS) with a Pay-As-You-Go (PAYGO) model offers affordable, scalable, and clean electricity.
  - Audio-feedback keypads improve usability for users with low literacy levels or limited technical skills.
  - Multi-household functionality expands access with fewer physical systems.

Innovations: What are the innovations developed in SUNNY regarding this technology?

- Enhanced PAYGO with audio feedback
- Multi-household access with individual keypads
- Improved motherboard and a durable 76Wh battery

Critical Questions: What are the most critical questions regarding the upgrading of technology?

- Usability:
  - Can the system be easily used by low-literacy or non-technical users?
- Technical Resilience:
  - Will upgraded components withstand harsh environmental conditions?
- Scalability:
  - Can the system reliably support multiple households or larger farms?
- Data & Connectivity:
  - How is usage and system data collected and managed, especially in remote areas?
- Affordability:

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    - Can the upgraded system remain affordable, especially through PAYGO models?
- Maintenance:
    - Is local technical support available and are spare parts accessible?
- Intellectual Property:
    - How will ownership and use of improvements be managed within and beyond the project?
    - Are energy and water use optimized under varying local conditions?

c. Solar Irrigation System

Technology: How does the technology work and if relevant, what is the associated delivery model?

Smart Solar Irrigation System:

- A fertigation-based system that adjusts irrigation using real-time weather and soil data.
- First deployed in Kayonza District, benefiting 17 households over 20 hectares.
- Supports the full agricultural value chain, including post-harvest handling, market access, and financial services.
- Delivery Model:

Community or Cooperative Ownership

- The irrigation system is typically implemented at a community or group-farm level, such as cooperatives or farming groups.

Full-Service Package

- SOLEKTRA delivers a turnkey solution: solar power system, fertigation setup, sensors, and control software.

Smart Management

- Uses automated controls based on sensor data (weather, soil moisture) to optimize irrigation schedules.

Capacity Building and Support

- Farmers are trained in system use, maintenance, and agricultural best practices, including post-harvest and market integration

State of the art: What version of the technology/ prototype already exists?/ What was previously implemented?

- First full prototype deployed in Kayonza District, Eastern Province, near Mahama

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Refugee Camp.
- Covered 20 hectares and served 17 households.
- Used real-time data (weather and soil) to optimize irrigation schedules.
- Integrated fertigation technology—applying nutrients via the irrigation system.

Challenges: What are the challenges in the demonstration location that the technology addresses?

Agricultural Water Scarcity and Unpredictability

- Context: Kayonza and similar regions suffer from water scarcity, erratic rainfall, and climate change-related stress on agriculture.
- Traditional irrigation methods are inefficient and labor-intensive, often leading to crop failure.
- Technology Response: The smart solar irrigation system:
  - Uses real-time weather and soil data to optimize water use.
  - Reduces water waste and improves crop yields.
- Incorporates fertigation, delivering both water and nutrients, saving labor and improving plant health

Low Agricultural Productivity and Post-Harvest Losses

- Context: Farmers often lack access to post-harvest handling technologies, markets, and financing.
- This limits their ability to generate income and scale production.
- Technology Response:
- The SUNNY Project includes support for:
  - Post-harvest technologies
  - Improved market linkages
  - Access to financial services

Innovations: What are the innovations developed in SUNNY regarding this technology?

Smart Solar Irrigation System

- Sensor-Based Smart Controls:
  Adjusts irrigation schedules based on real-time weather and soil data, conserving water and improving yields.
- Pilot Implementation in Kayonza:
  A 20-hectare pilot site demonstrating scalable, sustainable agriculture powered by solar energy.
- Fertigation Integration:
  Combines irrigation with nutrient delivery for more efficient and productive

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farming.

. Value Chain Enhancement

- Beyond Technology Deployment:
  Integration of post-harvest handling, market access tools, and financial services to support the entire agricultural value chain.

Critical Questions: What are the most critical questions regarding the upgrading of technology?

- Usability:
  - Can the system be easily used by low-literacy or non-technical users?
- Technical Resilience:
  - Will upgraded components withstand harsh environmental conditions?
- Scalability:
  - Can the system reliably support multiple households or larger farms?
- Data & Connectivity:
  - How is usage and system data collected and managed, especially in remote areas?
- Affordability:
  - Can the upgraded system remain affordable, especially through PAYGO models?
- Maintenance:
  - Is local technical support available and are spare parts accessible?
- Intellectual Property:
  - How will ownership and use of improvements be managed within and beyond the project?
  - Are energy and water use optimized under varying local conditions?

d. Food Refrigeration

Technology: How does the technology work and if relevant, what is the associated delivery model?

- 5-ton capacity solar powered cold room at farm gate
- IoT enabled for remote monitoring of temperature
- Fresh produce stored in stackable 20kg crates in a temp. range of 4 - 10°
- Extends shelf life from 5 to 21 days
- Pay - as - you - go & co-op revenue model for users

State of the art: What version of the technology/ prototype already exists?/
What was previously implemented?

- 5 -ton stationery and mobile cold rooms at farm and market, 1 ton cooling tricycle

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for last mile delivery
- Built using PU insulated panels for thermal efficiency.
- Refrigeration unit enables cooling temperature of 4 to 10 degrees
- IoT enabled for remote monitoring and regulation of temperature and requires internet connectivity
- Post harvest storage for perishables like tomatoes, peppers, garden eggs

Challenges: What are the challenges in the demonstration location that the technology addresses?
- 1.3 billion tonnes Food lost every year around the globe. (source: UN FAO)
- 10% CO2 Food waste emissions. (source: UNEP)

Innovations: What are the innovations developed in SUNNY regarding this technology?
- Optimizing energy efficiency with a decrease from 8kW to 5kW capacity solar system
- Mobile unit to move from one point of need to another in the demonstration site
- An energy/charging station for community use to charge energy efficient devices like mobile phones, lamps and radio only
- IoT monitoring to include more parameters: Temperature, Humidity, Airflow and/or Ethylene concentration
- Lithium (LiFePO) batteries for 28-hour power backup system for uninterrupted cooling during days of cloud cover and nighttime

Critical Questions: What are the most critical questions regarding the upgrading of technology?
- IoT:
  - Are there interruptions in internet connectivity?
  - Can the IoT dashboard generate real-time alerts and automated responses (e.g., power surge, ethylene buildup)?
  - How is data stored and accessed (locally vs. cloud)? Who owns it?
- Mobility:
  - Is the structural design (chassis, axle, frame) roadworthy and durable for repeated movement over rural terrain?
  - Can it be moved without damaging the panels, insulation, or refrigeration components?
- Maintenance:
  - Who will be trained to manage and service $LiFePO_4$ batteries, clean ethylene sensors, and calibrate IoT systems?
  - What is the MTTR (mean time to repair) and response protocol in case of breakdown?

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- What spare parts are needed on-site?

e. Biogas

Technology: How does the technology work and if relevant, what is the associated delivery model?

- Main functions of the system: Waste collection & sorted / Milling & mixing / Anaerobic digestion / Biogas production & digestate recirculation

State of the art: What version of the technology/ prototype already exists?/ What was previously implemented?

- Low-tech biogas plant: Pumps, crusher & screw / No temperature control / Low-cost materials

Challenges: What are the challenges in the demonstration location that the technology addresses?

- Biowaste: availability, % organic matter, seasonality, lack of transport, absence of large farms, open grazing.
- Water supply: dry seasons.
- Biogas production: winter season, biowastes seasonality, monitoring.
- Electricity: Its access is limited.
- Local stakeholders: local manufacturers of technological equipment.
- Capacity building: monitoring, biowastes sorting.

Innovations: What are the innovations developed in SUNNY regarding this technology?

- This project innovates by adapting to the reality of Bidibidi Settlement, providing an easy-to-operate, low-tech biogas plant made the most from local materials.
  - Rooftop to collect rainwater: Solar pannels.
  - Liquid fraction is recirculated to humidify dry biowastes.
  - Single pump for sludge agitation and digestate recirculation.

Critical Questions: What are the most critical questions regarding the upgrading of technology?

- Location
- Biogas production
  - Temperature
  - Gathering an adequate amount of quality biowastes
  - Standardize the input mixture
- Lacking electricity
  - Manual mixing

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- Rooftop affordability
  - Are there alternatives?
- Local stakeholders
  - Sourcing of parts such as pumps, crusher & screws

2. Technology Workshop

a. Introduction and Objectives

As part of the SUNNY project's preparatory phase for technology development and upgrading, a dedicated technology workshop was organized during the second Consortium meeting to strengthen shared understanding of the project's core technological innovations. The workshop covered all SUNNY technologies: hydrogen, biogas, solar irrigation, solar home systems (SHS), and refrigeration technologies. Given the interdisciplinary nature of SUNNY, the workshop created a space for technology experts and thematic groups (environmental, social, economic, implementation, and regulatory considerations) to exchange perspectives, highlight key challenges, and identify cross-cutting requirements relevant for subsequent tasks—most importantly Task T1.4 on use-case specification, the technology upgrade in WP3 and the technology implementation in WP4. The workshop was structured around short expert presentations, facilitated discussions, and multiple rounds of thematic group work.

The workshop pursued three overarching objectives:

1. Strengthening the shared understanding of SUNNY technologies
   Participants received concise, structured introductions to each technology, focusing on the challenges addressed, the main innovations introduced by SUNNY, and the technology-specific development pathways.
2. Uncovering key considerations for technology development
   Through facilitated discussions, thematic groups identified critical aspects, potential risks, and opportunities associated with each technology area. These discussions supported a holistic understanding across environmental, social, financial, implementation, and regulatory dimensions.
3. Providing inputs for use-case development (Task T1.4), WP3 and WP4
   A core aim of the workshop was to generate early insights relevant to defining detailed technology use cases, requirements, and initiate the technology update process in WP3. The outputs of the group discussions directly feed into the use-case specification, the technology upgrade in WP3, and the technology implementation in WP4.

Overall, the workshop supported the alignment of the continued technology

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development process with contextual, socio-technical, and regulatory local conditions.

b. Methods

The workshop followed a structured, multi-stage format (visualized in Figure 2):

1. Plenary introduction and formation of thematic groups
   Participants were assigned to one of five thematic groups (environmental, social/capacity-building, financial/business, implementation, and regulatory), with a parallel online group for online participants of the consortium meeting.
2. Technology Speed Dating rounds
   For each SUNNY technology, the following 30-minute sequence was conducted:
   - Expert presentation:
     - Introduction to the technology, challenges addressed, SUNNY innovations, and expected impacts.
   - Q&A:
     - Clarification of technical aspects and context-specific questions.
   - Thematic group discussion:
     - Participants joined a thematic group based on their individual expertise (visualized in Figure 3)
     - The thematic groups included are:
       - Group 1: Environmental considerations
       - Group 2: Social considerations
       - Group 3: Economic and business considerations
       - Group 4: Implementation
       - Group 5: Regulations
     - Each group reflected on the technology from its respective thematic perspective, guided by questions regarding:
       - critical considerations
       - potential challenges
       - potential opportunities
       - important open questions
       - links to technology-specific KPIs
3. Documentation process
   All groups were provided with posters, flipcharts, worksheets, and note-taking templates. Online groups documented their contributions in a shared writing pad. A dedicated timekeeper ensured strict adherence to time allocations, reflecting the need to cover all technologies within the workshop period.
4. Cross-group synthesis
   In the final stage, groups summarised their findings in a structured plenary

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session (approx. 5 minutes per group), allowing comparison across thematic lenses and technologies.

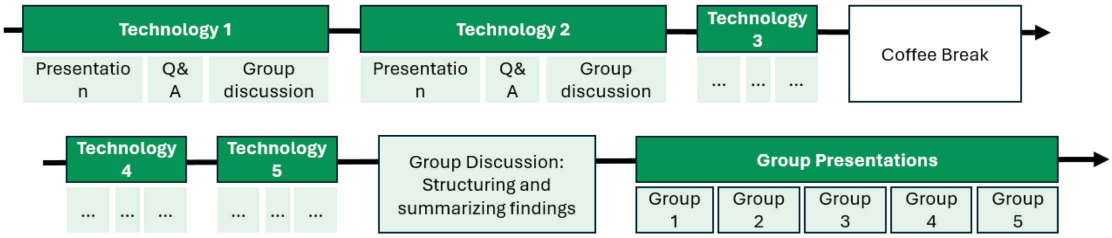

Figure 2: Different stages of the Technology Workshop

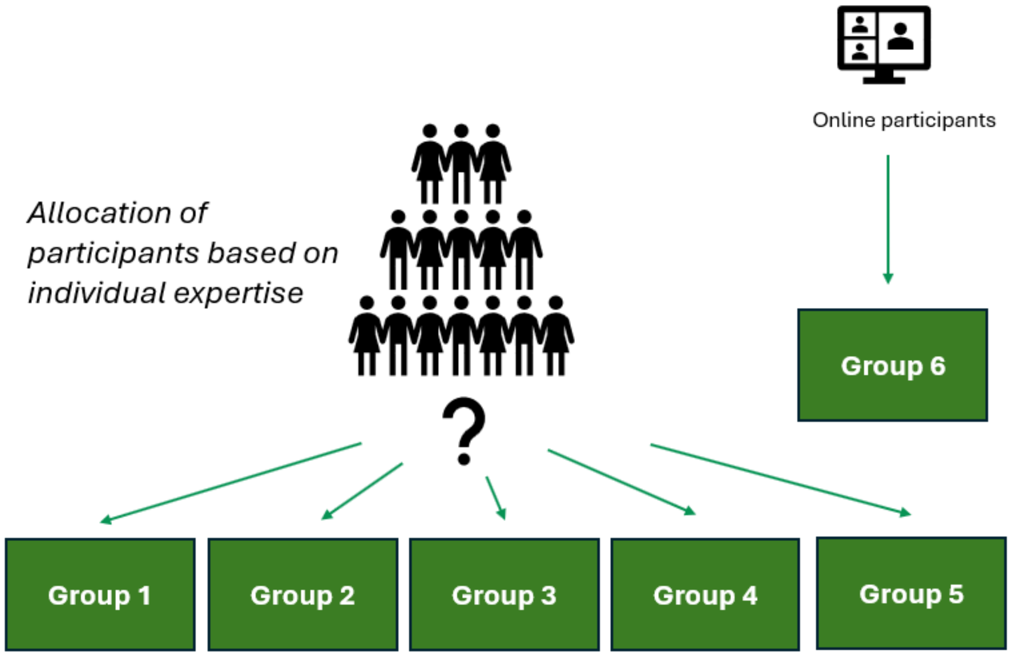

Figure 3: Allocation of participants to the thematic groups based on their individual expertise

c. Results

To complement the structured discussions conducted during the workshop, each thematic group documented its reflections on dedicated posters. These posters served as a visual summary of the key insights generated during the "Technology Workshop" sessions, capturing critical considerations, perceived challenges, opportunities, and open questions for each SUNNY technology. The posters reflect the collective reasoning of the groups and provide an accessible overview of the main points raised during the facilitated discussions. In the following we resent the photographed posters as they were produced during the workshop.

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In the final part of the workshop, each thematic group prepared and presented a poster summarising its main reflections. These poster presentations enabled participants to share their insights across groups, compare perspectives, and collectively refine the understanding of critical issues related to the SUNNY technologies. During the presentations, groups highlighted the key themes captured on their posters, explained the reasoning behind their assessments, and discussed cross-cutting implications for technology development and use-case specification. This session ensured that the diverse viewpoints generated in the group work were brought together in a coherent and transparent manner, supporting a shared foundation for the next steps in the project.

Environmental Dimension

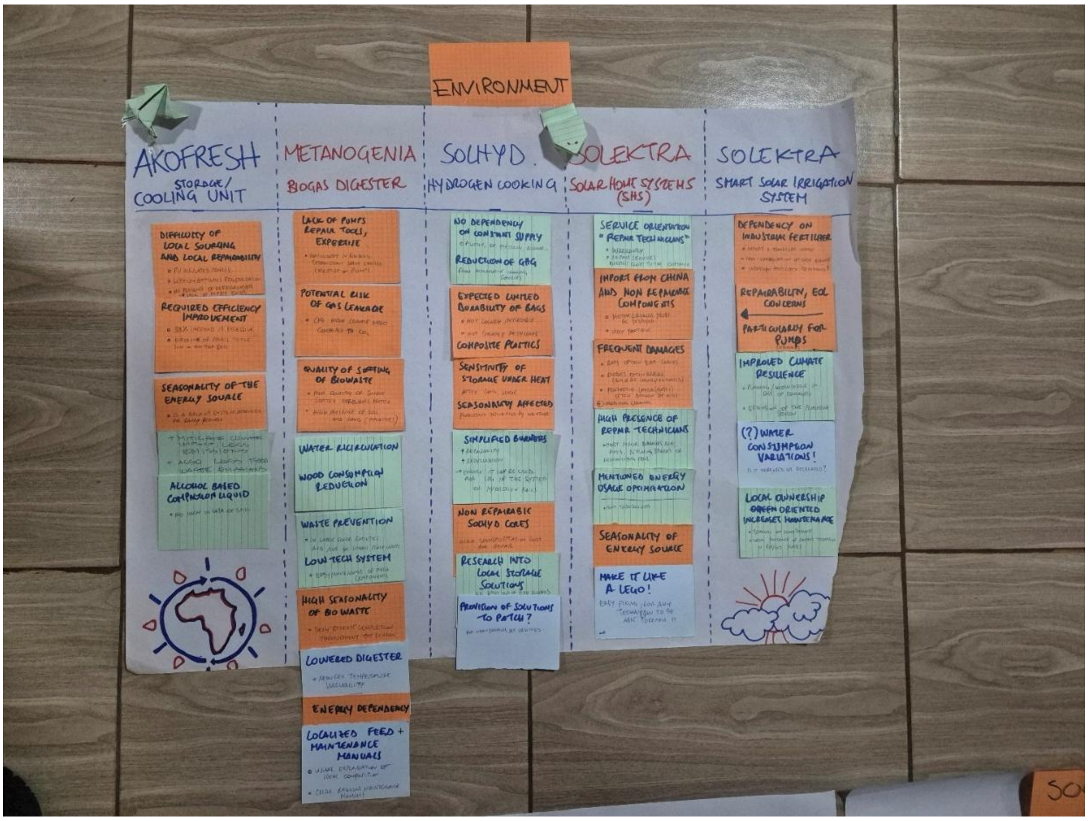

Figure 4: Poster of the environmental considerations highlighted during the Technology Workshop

Social Dimension

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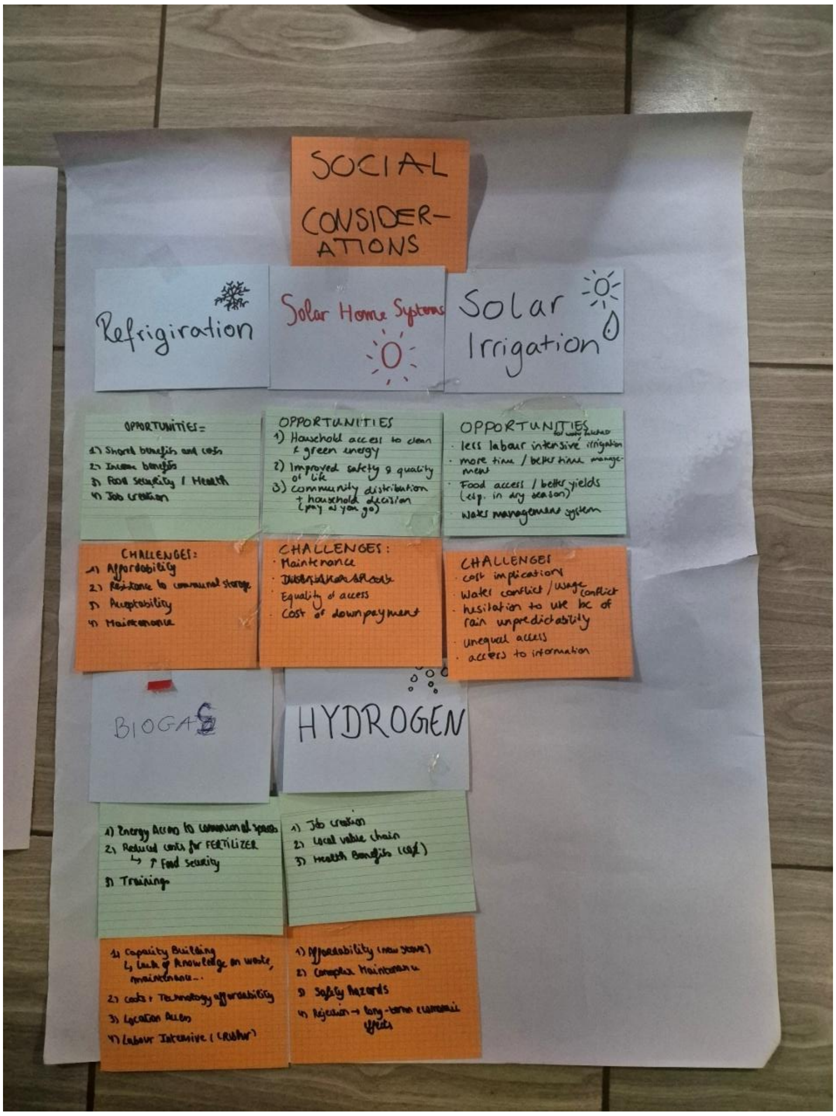

Figure 5: Poster of the social considerations highlighted during the Technology Workshop

Economic Dimension

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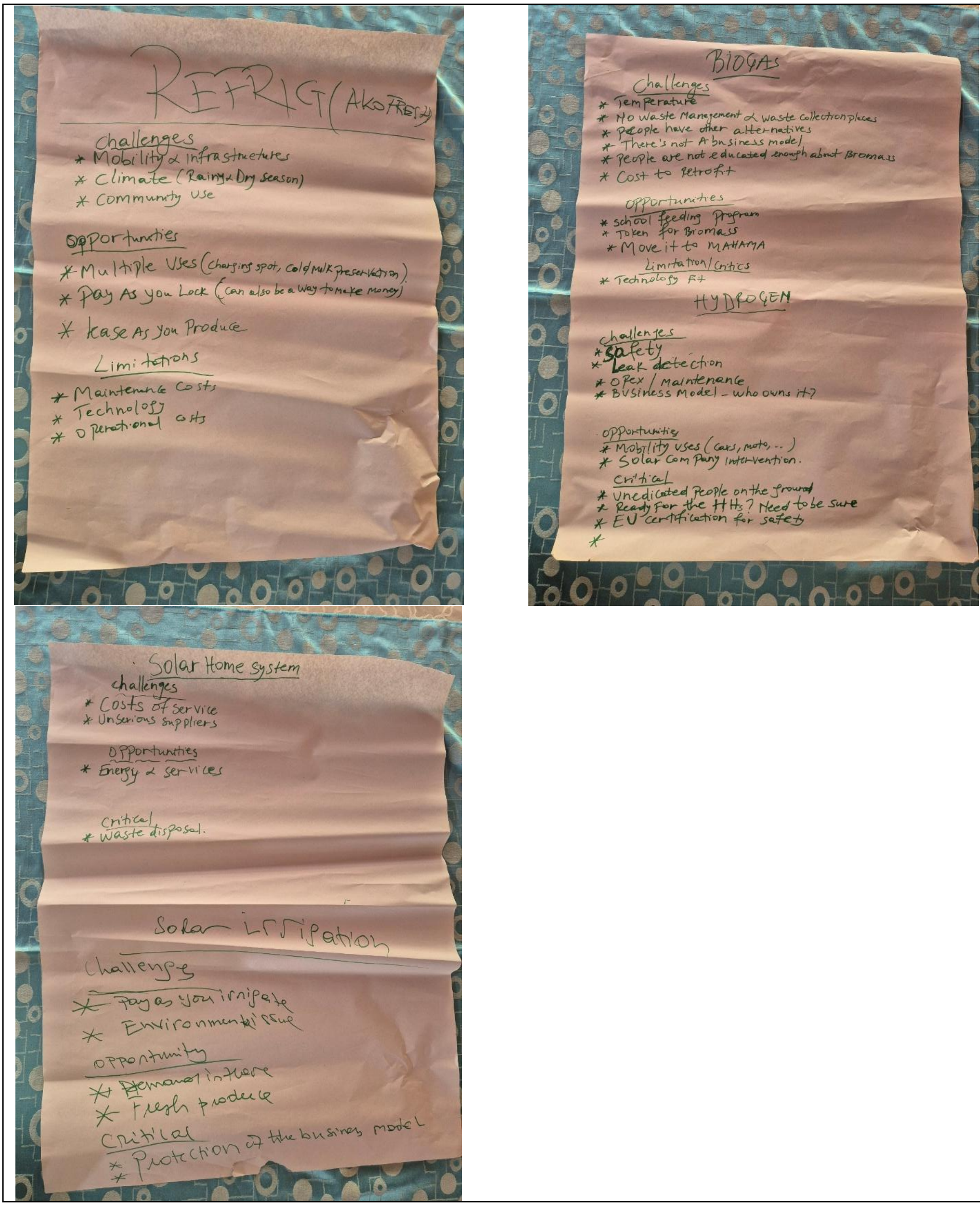

Figure 6: Posters of the economic considerations highlighted during the Technology Workshop

Regulatory Dimension

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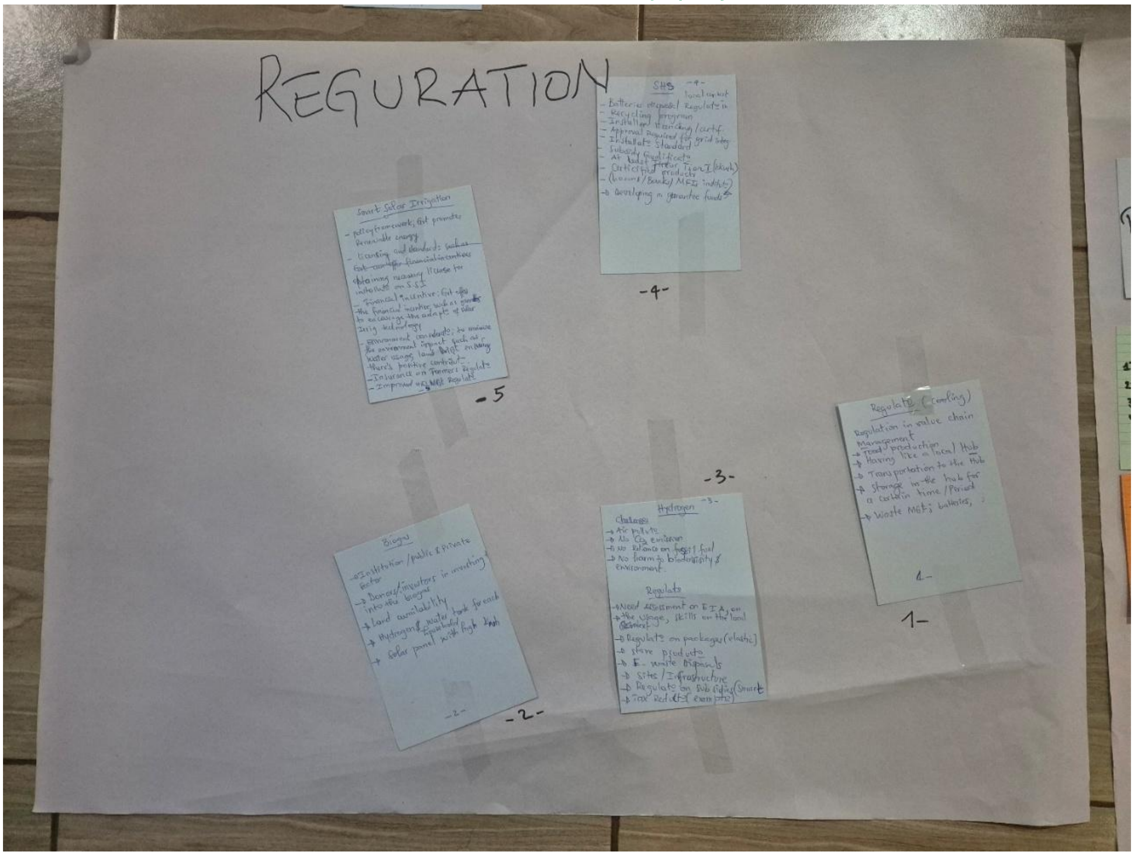

Figure 7: Poster of the regulatory considerations highlighted during the Technology Workshop

Project Implementation

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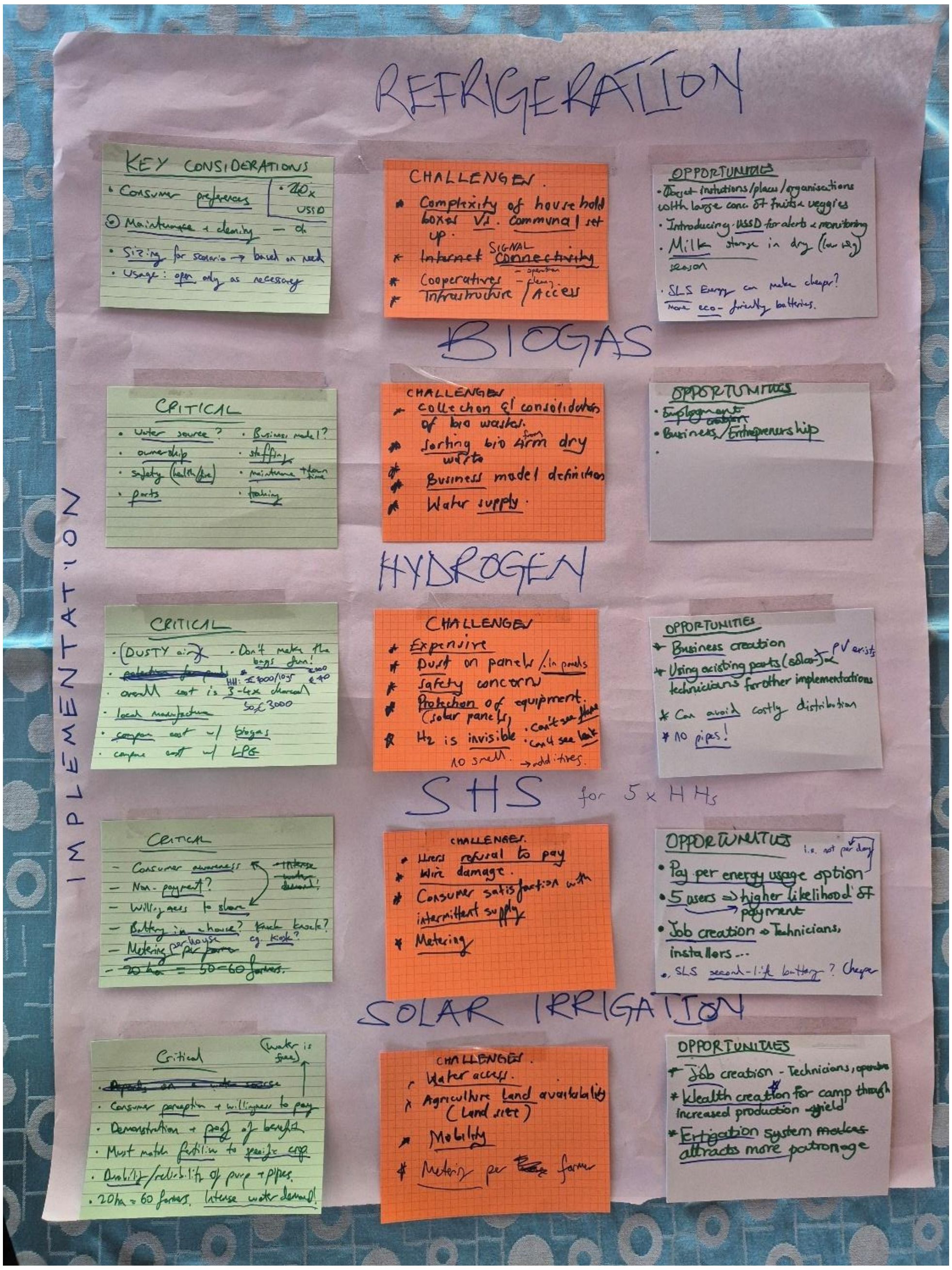

Figure 8: Poster of the considerations concerning the project implementation highlighted during the Technology Workshop

d. Online Group Results

The online group participated in the workshop through a shared documentation platform and followed the same structure as the on-site thematic groups. Their task was to reflect on each SUNNY technology and discuss critical aspects, potential challenges, opportunities, and additional considerations. The following section presents their consolidated inputs, structured by technology.

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Technology 1: Refrigeration

Important / Critical Aspects

- Why a mobile solution?
  - Potentially more expensive
  - Increased flexibility in cases of fluctuating demand
  - Logistics depend on road quality, seasonality, movement intervals
- Produce volumes (e.g., 33 kg/farmer/year): collected centrally or delivered individually?

Potential Challenges

- Connectivity, data storage, automated alerts
- Mobility-related maintenance (spare parts, staff, intervals)
- High cost of capital limiting expansion under PAYGo
- Non-payment risks for stationary systems

Opportunities

- Increasing system utilisation through additional services (e.g., phone charging)
- Using trailers instead of vehicles to reduce cost
- Cooperative ownership potentially lowering cost of capital

Other Aspects

- LTO batteries could be more robust than LFP

Points for Plenary

- Mobility as both challenge and opportunity
  - (+) Flexibility in meeting demand
  - (–) Higher costs and maintenance implications

Technology 2: Biogas

Important / Critical Aspects

- Homogeneous feedstock supply
- Safe handling of methane; risk of GHG leakage
- Water quality implications of the liquid fraction
- Influence of operating parameters (temperature, feed rate); staff training requirements
- Inputs: source and motivation for biowaste delivery
- Ownership and business models (who collects, who operates, who buys outputs?)
- End uses: electricity production vs. cooking

Potential Challenges

- Contaminated feedstock risking digester performance
- Ensuring standardised supply of organic matter and water
- Need for electricity for grinding or pumps

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- Odour impacts on surrounding households

Opportunities

- Converting waste into a valuable product, incentivising waste collection
- Possibility of immediate rewards for waste delivery
- Electricity or cooking applications
- Potential for local manufacturing
- Low-tech characteristics may allow user-driven design improvements
- Local labour participation in construction

Other Aspects

- Questions on alternatives to electric grinding; feasibility of manual systems
- Option to use starter bacteria culture to accelerate start-up
- Importance of waste collection and biogas distribution arrangements
- Potential need for larger storage to avoid losses

Technology 3: Hydrogen

Important / Critical Aspects

- Large local storage and mobile storage bags
- Requirements for safety guarding
- Safety distances vs. cost of household connection
- Certification questions: EU vs. African standards; relevance for imports
- Brand references (e.g., Cocsha)
- Local familiarity with gaseous cooking

Potential Challenges

- Importing technology in settings with limited regulation and standards
- Limited user familiarity with gaseous fuels
- Behavioural changes required for fuel handling and cooking
- Water consumption
- Centralised community cooking may conflict with household preferences
- Potential resistance or backlash from the LPG value chain
- Coordination with UNHCR regarding LPG subsidies

Opportunities

- Future medical oxygen supply (pending purity requirements)
- Building on LPG safety procedures and supply chain experience
- Integrating hydrogen system with microgrids to use surplus electricity

Other Aspects

- Cost-competitiveness with LPG due to distribution costs (but not with firewood)
- Fixed gas ratios required; dual-fuel stove considerations
- Storing hydrogen in LPG canisters requires compression and certification

Points for Plenary

- Cooking safety as a central concern

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- Link with LPG cooking behaviour and safety practices
- User habits, training, and existing supply chain structures

Technology 4: Solar Home Systems (SHS)

Important / Critical Aspects

- Audio feedback for users
- Multi-household approach
- Suitability for dispersed settlements
- 76 Wh battery capacity
- Battery lasts ~3 days (discussion on sizing adequacy)

Potential Challenges

- Decision-making on system placement
- E-waste, recycling, and disposal
- Scaling, marketing, and identifying customers
- Need for sales points, maintenance services

Opportunities

- Audio feedback supports low literacy and limited technical skills
- Business models: selling appliances upfront to stimulate energy demand
- Multi-household systems enabling PUE integration

Other Aspects

- Clarification needs: why one keypad per household?
- Data collection frequency
- Durability under local conditions
- Increasing affordability with increasing system size

Points for Plenary

- Energy services and PUE integration
- Durability as a key system requirement

Technology 5: Solar Irrigation Systems

Important / Critical Aspects

- Integration with other technologies (e.g., refrigeration) for value-chain strengthening
- Alignment with core business model; potential for external partnerships for add-ons (e.g., fertiliser distribution)

Potential Challenges

- Willingness to pay for water
- Low literacy or technical experience affecting uptake
- Increased water consumption due to easier access; need for efficiency measures
- Water source sustainability and potential impacts on other users
- Specific local conditions (e.g., river availability in Bidibidi)

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Opportunities

- Potential simplification of the system
- Integration with biogas systems (water input, fertiliser output)

Other Aspects

- Similar outstanding questions as for SHS

Points for Plenary

- Water–biogas integration
- Cross-technology question: how to design effective user trainings?

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IV. ENERGY NEEDS SPECIFICATION

This chapter presents the specification of energy needs as one of the central components of Deliverable D1.3. It outlines the methodological approach used to assess current energy use, future energy aspirations, and user-related factors relevant for the adoption of SUNNY technologies, and it presents the main results derived from this work. As such, the chapter contributes to the overall objective of the deliverable by translating contextual and user-related insights into a structured understanding of energy needs and related requirements. In this way, it provides an important basis for the further development of technological requirements, use cases, and subsequent activities in the SUNNY project.

1. Introduction and Objective

While assessing current energy use is relatively straightforward, anticipating future aspirations—especially in the presence of new technology options—is more complex, as usage patterns are shaped by social norms, cultural practices, ability to pay, perceptions of technology, and broader socio-economic factors. Evaluating needs alongside willingness to adopt, affordability constraints, and user preferences is therefore essential to ensure solutions are both technically viable and socially acceptable. Global frameworks such as the World Bank's ESMAP Multi-Tier Framework for Energy Access emphasize that energy planning must account for affordability, reliability, and service level, not just availability. Similarly, the IEA (2023) and SEforALL (2022) highlight that sustainable energy transitions in low-income and humanitarian contexts depend on aligning solutions with users' ability to pay and their perceived value of services. Linking these aspects enables the design of technologies and business models that are both desirable and financially feasible. The objective of the energy needs assessment is therefore to produce an evidence-based view of current use, future aspirations, and adoption potential, and to translate these insights into concrete, user-fit design and implementation requirements.

2. Methods

The assessment of energy needs for the SUNNY project is being conducted through a multi-step, collaborative process involving technology suppliers, local partners, and field organizations in Rwanda and Uganda. The following steps have been outlined and are currently being implemented or in preparation:

a. Baseline Evaluation of Available Technologies and Local Context

LUT has coordinated several consultation and discussion meetings with the SUNNY

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technology partners and other project partners to evaluate the current status of energy technologies. These discussions identified key data requirements for supporting technology upgrades and development of the technology partners. Baseline context data were also gathered through collaboration with local partners in Rwanda and Uganda to better understand local conditions and surroundings, and gain preliminary understanding of energy access challenges.

b. Definition of Data Needs and Methodologies

Following the baseline evaluation, the data requirements for each technology are defined. The need to link energy needs to users' willingness to pay was identified as a crucial factor in understanding consumer preferences for energy technologies. Additionally, the need for a deeper understanding of the energy context within the Uganda refugee camp setting became evident prior to implementing the end-user surveys.

As a result, Key Informant Interviews (KIIs) were identified as a critical method for gathering contextual insights in Uganda. By engaging with local organizations, the KIIs will provide a deeper understanding of community needs, enabling the precise definition of target groups for energy interventions.

In relation to user's data collection, a survey method was selected to collect both quantitative and qualitative data on user's current energy usage and needs, future aspiration, preferences as well as financial constraints that influence energy usage.

Conjoint analysis was identified as a key methodological approach to assess how households value various attributes of energy technologies in relation to their energy needs. Thus, this has been integrated in the survey. This approach was designed to comprehensively assess the energy demands of different households and to explore how various factors, including cost, reliability, and usage characteristics, shape their preferences for energy services.

The conjoint analysis component allows for a detailed exploration of consumer trade-offs and preferences, specifically in relation to energy needs. By systematically varying combinations of service attributes, such as price, reliability, night-time usage, and service levels, this method helps to identify the most cost-effective and desirable energy solutions for different household groups. Ultimately, such analysis helps to link energy demand with financial capacity, thereby informing the design of energy services that align with both the needs and preferences of the population. The attributes deemed

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most relevant for each technological solution were included in the conjoint analysis. For the SHS solution, these include: price, reliability, night usage, and total electricity usage level. The attributes for the cooking solution are: price, payment mechanism, storage duration (hydrogen bag), and pot size (relevant for stove design).

c. Questionnaire Development and Implementation

The questionnaire design was led by LUT through an iterative process, incorporating extensive information exchange between and feedback from technological partners and local organizations. This approach aimed to ensure both the relevance and cultural appropriateness of the questionnaires. The next step in the process is pilot testing phase, for each technology survey. This aims to ensure the clarity and effectiveness of the survey instrument, and refinement of questionnaires, addressing any ambiguities and improving its structure for broader implementation. This is followed by full scale implementation of data collection through surveys and questionnaires.

d. Data Analysis

Following the full-scale survey implementation, the data analysis phase will focus on processing and interpreting both the quantitative and qualitative data to address key research questions related to energy needs, preferences, and willingness to pay. Methods include:

- Statistical methods (e.g., descriptive statistics, regression analysis, conjoint analysis) and energy-system modeling for quantitative data to identify the most cost-effective and preferred energy technologies across different users and technologies. These analyses will provide insights into the relationship between users' willingness to pay and their energy needs, and determine the trade-offs households make regarding price, reliability, and service levels.
- Thematic analysis of open-ended survey responses and KIIs to identify key barriers, perceptions, and contextual factors influencing energy choices.

3. Results

Mahama camp (Rwanda):

The baseline evaluation has been successfully completed. Questionnaires for end-users have been designed, piloted, and are currently undergoing field survey implementation.

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The pilot survey, conducted with a small group of 13 participants, has provided initial insights into user preferences and willingness to pay. These preliminary findings will be further expanded and comprehensively analyzed following the full-scale survey implementation. Below are some of the insights from the pilot survey, which should be interpreted with caution due to the limited scope and nature of the pilot phase:

a. SHSs solution

1. Most households expressed interest in purchasing a Solar Home System (SHS), with those who did not cite income constraints as the primary barrier.
2. Over 50% of the households interviewed currently pay for electricity services from local shops mainly for phone or other battery devices charging. Therefore, reducing such expenditures emerged as a key motivator for purchasing an SHS.
3. The majority of participants indicated a willingness to share an SHS with neighbors. Among those open to sharing, there was a unanimous preference for equal payment and equal access to the system. This suggests the need for implementing shared systems in household clusters with similar energy needs. It also highlights the need for a technological solution that allows individual control of energy consumption, with the ability to cap usage once a household's limit is reached.
4. Desired appliances were largely limited to basic items such as mobile phones, TVs/radios, and lighting. However, discussions with local partners revealed that some households may be motivated to use an SHS for income-generating activities. This insight has been included in the updated survey. A few households also expressed interest in using a refrigerator. The full-scale survey will provide a clearer picture of the prevalent energy use patterns, and whether households willing to use higher energy consumption appliances are also willing to pay a higher price for these services.

Overview of current electricity usage of households with no electricity access at home

Among households without electricity access at home, a very high proportion (85.3%) rely on electricity outside the household. The majority of these households obtain electricity from local shops (81.3%), indicating a strong dependence on informal charging services for essential needs such as phone charging and small device use. Additionally, 26.3% access electricity through neighbors or family houses. Figures 8 and 9 provide an overview of the current lighting sources.

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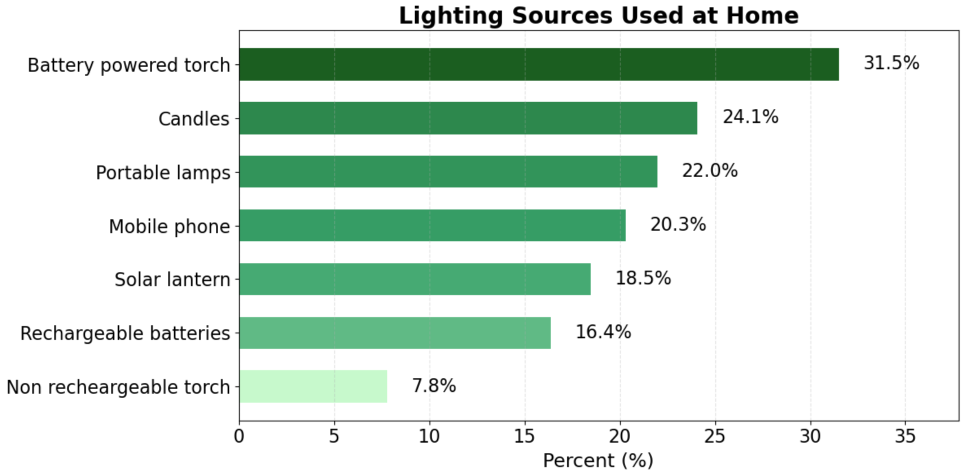

Figure 9. Lighting sources used at home.

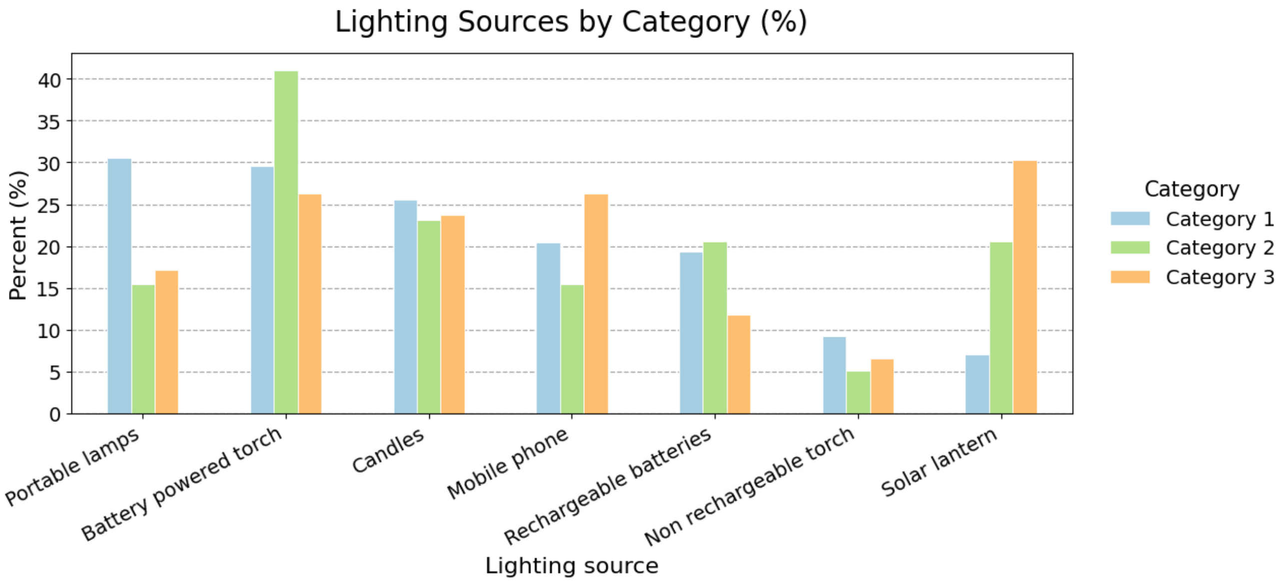

Figure 10. Lighting sources by category.

Current electricity expenditure of households with no electricity access at home:
Figure 10 presents the distribution of electricity expenditure across different payment frequency modalities, expressed as the percentage of respondents who reported paying for electricity. The most typical payment mechanism is monthly fixed payment with most common values of electricity expenditure around 1000 rwf/month. Figure 11 illustrates the estimated monthly electricity expenditure, including mean and median values with lower and upper bounds for each category.

Together, these figures provide a reference for understanding current household spending patterns on electricity and serve as a benchmark for assessing affordability

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and potential demand for alternative energy solutions.

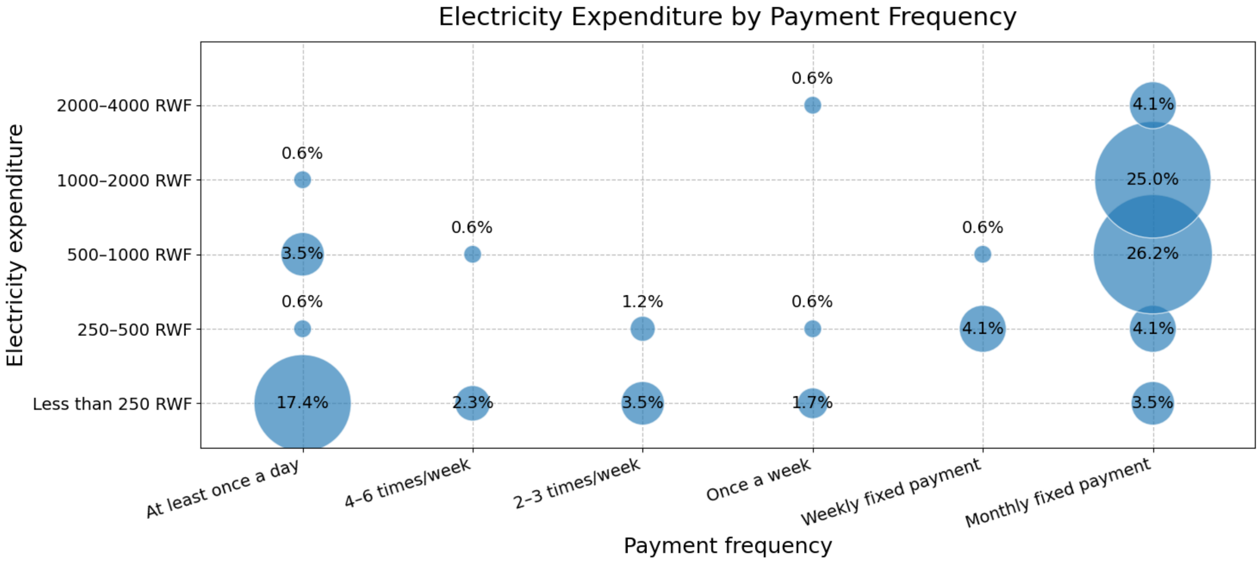

Figure 11. Electricity expenditure.

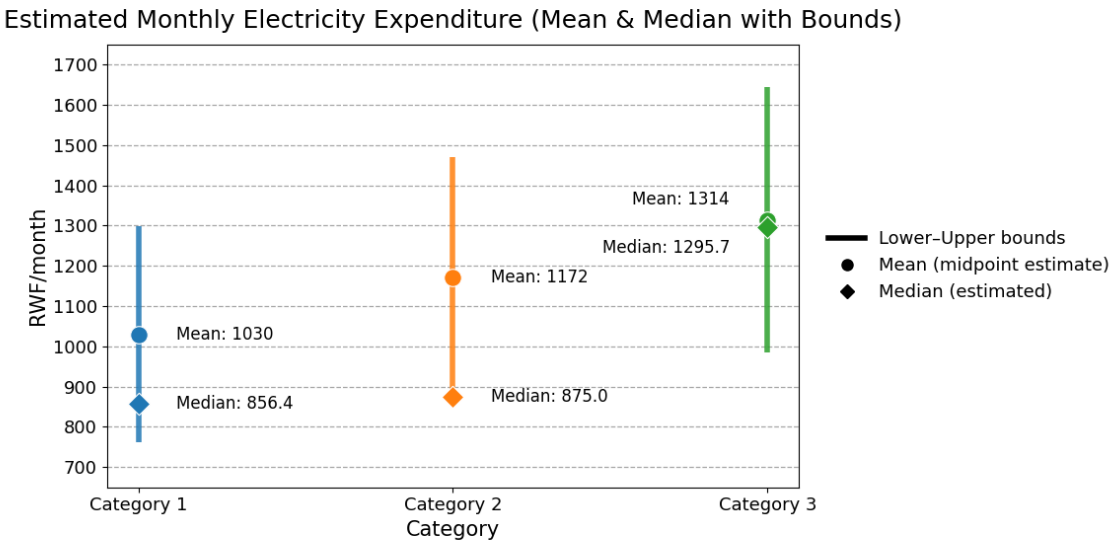

Figure 12. Estimated monthly electricity expenditure.

Willingness to adopt shared SHSs and link between affordability and level of services

The results indicate a very high willingness to purchase a Solar Home System (SHS), with more than 90% of respondents expressing interest in acquiring a system, as presented in Figure 12. This suggests strong demand for reliable household electricity solutions and

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confirms the relevance of SHS deployment in the target communities. In contrast, willingness to share an SHS is noticeably lower (Figure 13). While a majority remains open to sharing, a significant proportion of respondents express hesitation. The main concerns relate to potential conflict with neighbors, disagreements over usage or payments, and uncertainty regarding the ability of others to contribute financially. Some respondents also indicate a general reluctance to share household assets (Figure 14). These concerns highlight that, although shared systems may improve affordability, social and coordination risks must be carefully managed.

The importance of SHS attributes and the estimated uptake levels were derived from conjoint analysis, which evaluates how respondents trade off different system characteristics—such as price, payment modality, system capacity, and additional features—when making a choice. The analysis confirms that adoption decisions are sensitive to system design and pricing structure. While overall demand is high, successful implementation will depend on aligning service levels, payment mechanisms, and trust-building measures with household preferences and social dynamics.

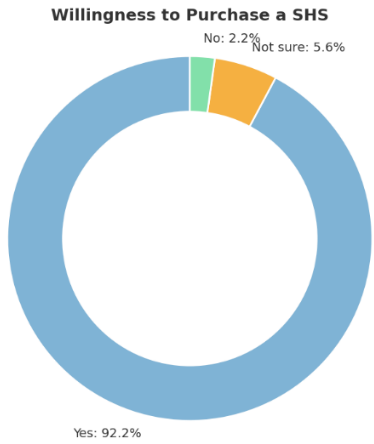

Figure 13. willingness to purchase.

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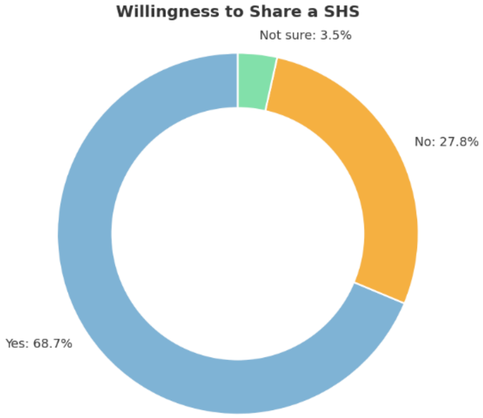

Figure 14. Willingness to share.

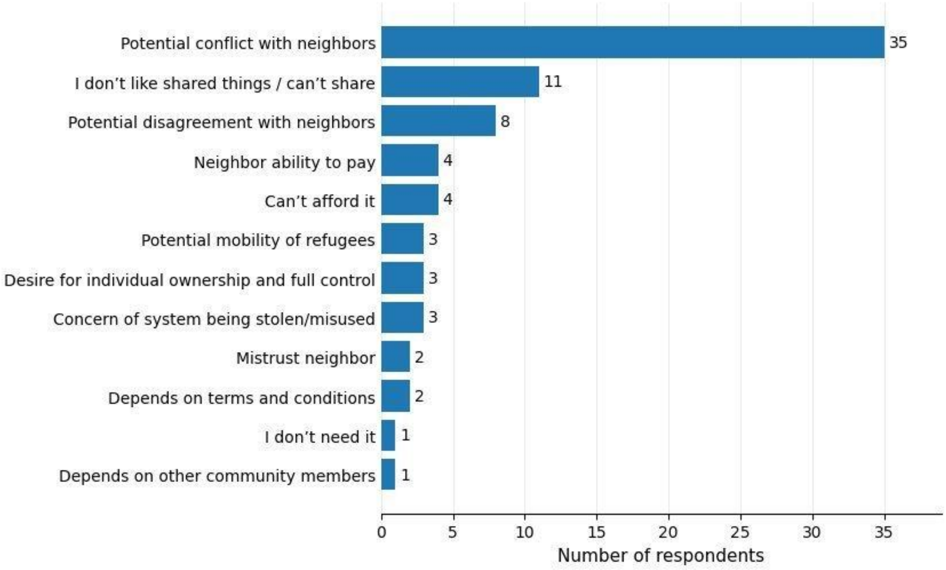

Figure 15. Concerns about using a shared SHSs.

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The importance of SHS attributes and the estimated uptake levels were obtained using conjoint analysis, which evaluates how respondents trade off different system characteristics (such as price, payment modality, capacity, and additional features) when making a choice. Overall, the results highlight that pricing strategy will play a decisive role in market penetration. Even modest increases in monthly payments significantly reduce predicted uptake, underscoring the need for carefully calibrated pricing, financing mechanisms and energy service levels to ensure accessibility.

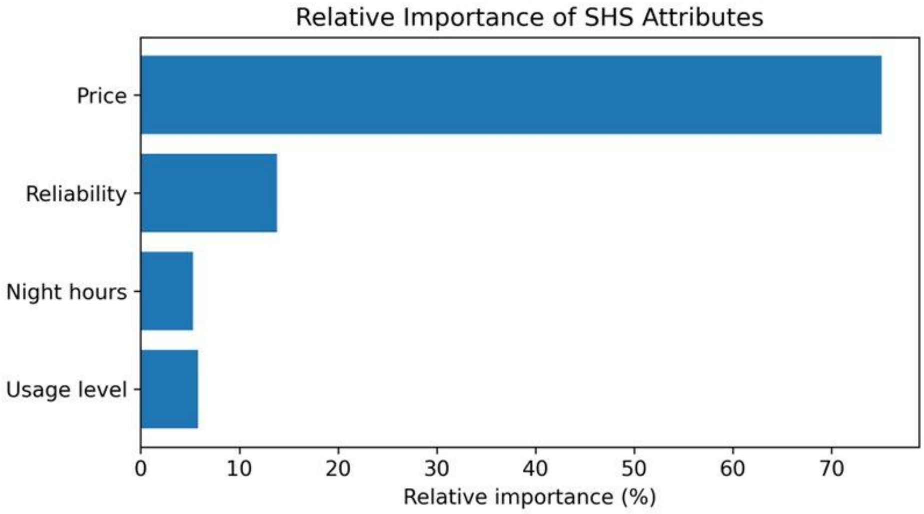

Figure 16. Results conjoint analysis.

Future appliance and electricity use aspirations

The results indicate that the primary aspiration among households is access to basic electricity services. The majority of respondents prioritize lighting and phone charging, followed by radio/TV, confirming that essential energy needs remain the dominant demand. These findings reinforce the importance of designing SHS solutions that reliably provide core services such as lighting, communication, and small entertainment devices.

At the same time, a smaller but significant share of respondents express interest in higher-energy appliances such as refrigerators, food processors, as well as other devices including flat irons, kettles, milling machines, electric cookstoves. This suggests emerging aspirations beyond basic access, particularly linked to improved household comfort and income-generating potential.

However, affordability remains a major constraint. The majority of respondents report that they would not be able to afford (more than 75%) these appliances upfront, with

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only a limited proportion indicating clear purchasing capacity, this is represented in Figure 17. This highlights a gap between aspirations and financial capability. While demand for enhanced energy services exists, it is currently constrained by limited purchasing power and the need for flexible financing or phased system upgrades.

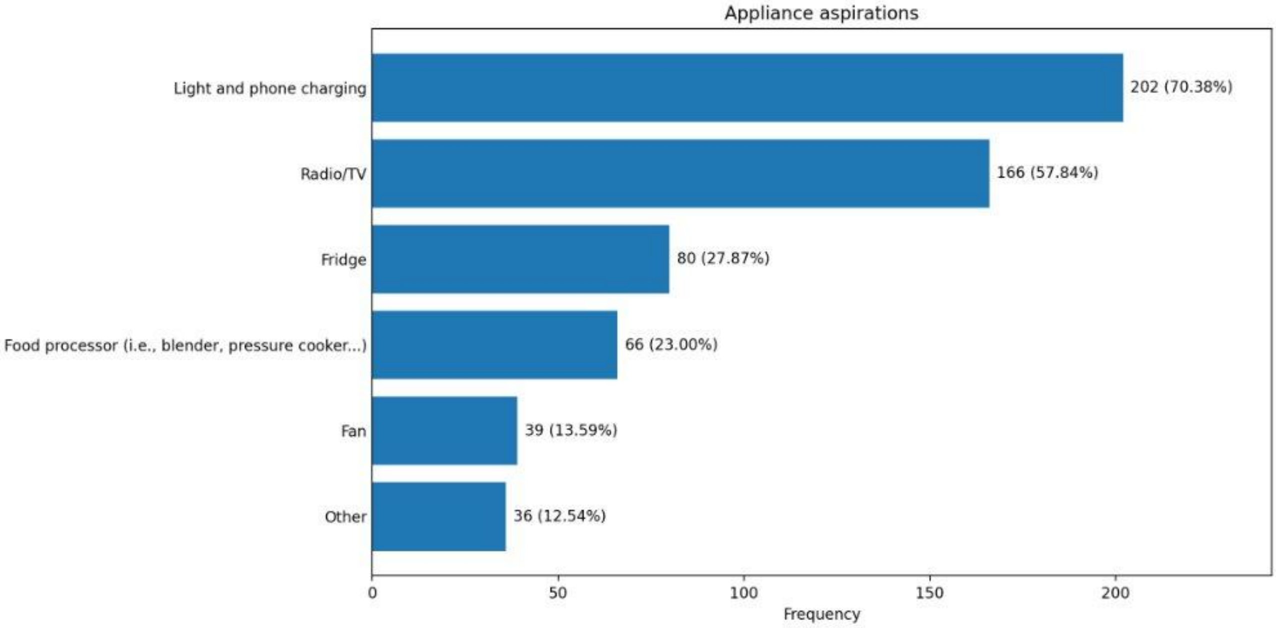

Figure 17. Future appliance aspirations.

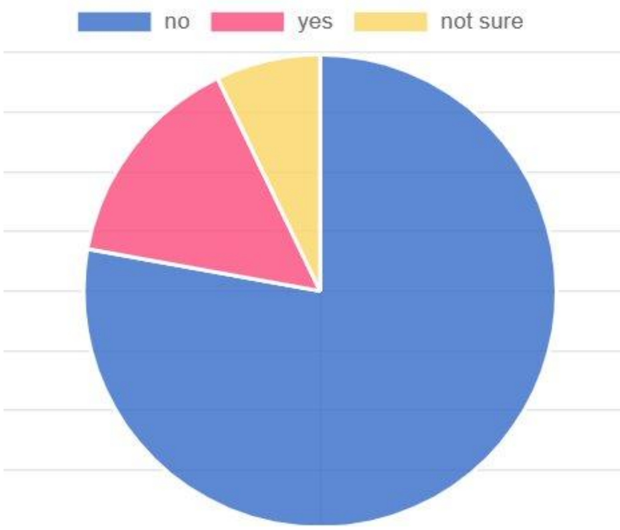

Figure 18. Households that can afford paying for the wished appliances.

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Interest in using SHSs for productive purposes is more limited. Slightly over 25% of respondents express willingness to use SHS systems for productive activities, while around half indicate no interest. Among those mentioning productive uses, the most common examples include small shop or restaurant applications (often refrigeration-related), phone charging businesses, hair salon, laundry or juice/blending businesses. This suggests that while productive use potential exists, it is not yet the primary driver of demand and may require targeted support, business development services, or higher-capacity systems to become viable.

Overall, the findings confirm that basic household energy services remain the immediate priority, while more advanced appliances and productive applications represent secondary, longer-term aspirations constrained mainly by affordability.

Current usage of Solektra's SHSs and feedback

The usage patterns of current Solektra's SHS users were used as a benchmark to understand realistic electricity consumption profiles and daily load distribution. The appliance usage data show that energy demand is concentrated in the late afternoon and evening hours (15:00–21:00), particularly for lighting and phone charging. Radio usage is more evenly distributed throughout the day but also peaks in the evening. These patterns are consistent with typical household routines, where energy demand increases after daytime activities.

To estimate representative consumption levels, average appliance power ratings were assumed based on survey data and common device specifications. Lighting was estimated at approximately 1–3 W per bulb (average use case), mobile phone charging at approximately 15 W during charging periods, and radio use at approximately 3 W. Based on the existing Solektra's SHS configuration (20 W panel with 76 Wh battery), an upgraded configuration of approximately 50 W panel capacity and 150 Wh battery storage was considered to reflect more stable and extended usage.

Using current users as a benchmark provides a realistic basis for modeling demand, as it reflects actual behavioral patterns rather than purely aspirational appliance use. A stochastic modeling approach was applied, using survey data. This method accounts for variability in appliance activation times, duration of use, and probability of concurrent operation, rather than assuming fixed deterministic schedules. The resulting average household load profile is presented in Figures 19 and 20. The modeled daily energy consumption is approximately 0.09 kWh per household, with a peak power demand of approximately 0.01 kW (10 W). The load curve shows clear evening peaks,

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corresponding to lighting and phone charging activity, and lower daytime demand levels.

Using stochastic modeling provides a more representative estimate of real household behavior and avoids overestimating system requirements based solely on theoretical maximum appliance ratings. This approach ensures that system sizing reflects probable usage patterns while capturing realistic diversity in demand.

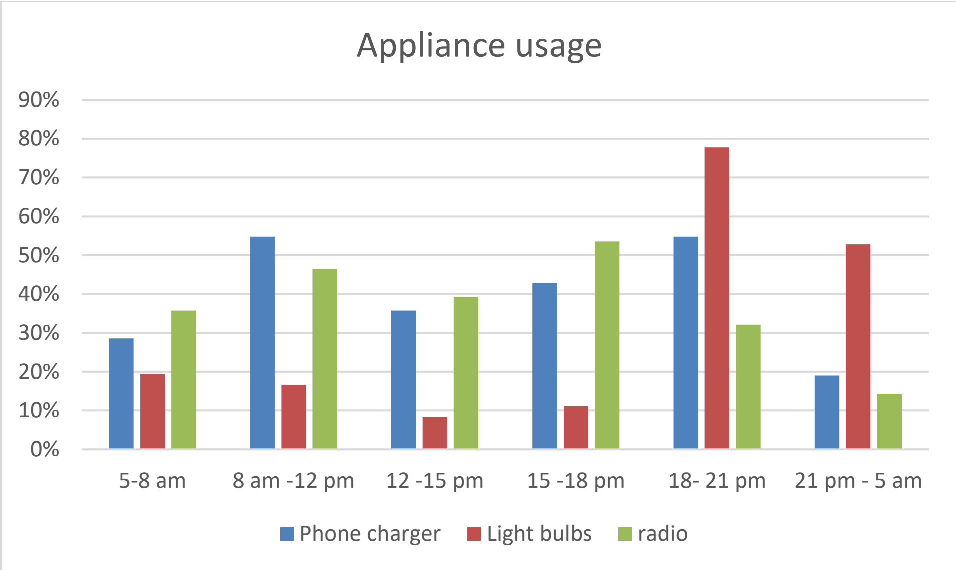

Figure 19. Electricity usage of current SHS owners.

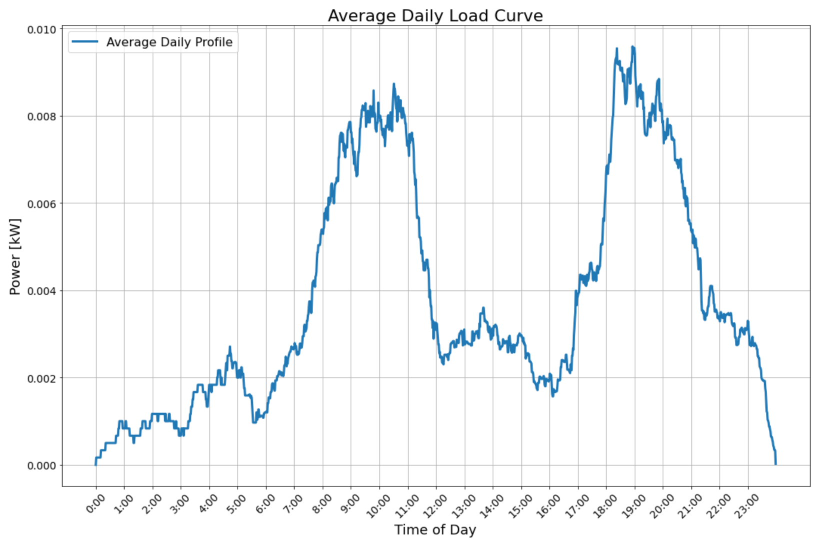

Figure 20. Daily Energy Consumption from Average Profile: 0.09 kWh Peak Power from Average Profile: 0.01 kW.

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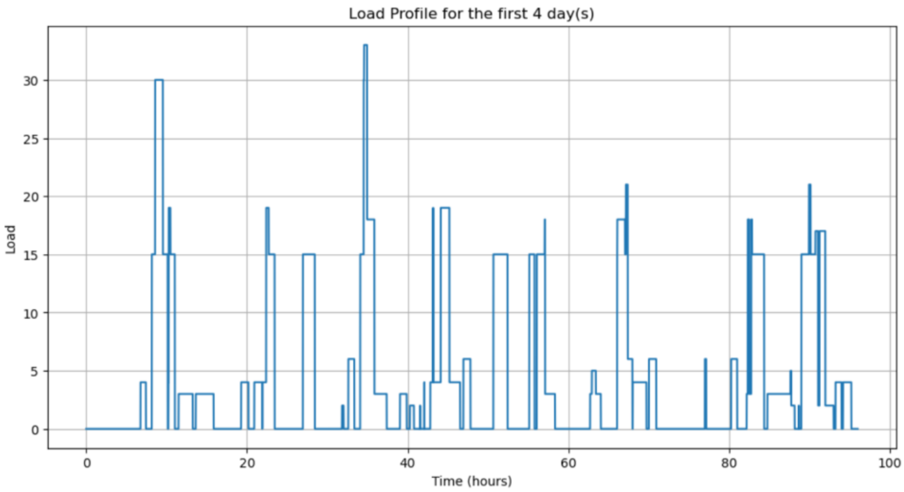

Figure 21. Load profile during four consecutive days.

Table 1 summarizes user feedback on current SHS performance, highlighting what works well, identified challenges, and suggested areas for improvement. Overall system reliability and lighting performance are positively rated, indicating that core functionality meets basic energy needs. However, battery performance, energy storage, maintenance response, and accessory quality emerge as areas requiring attention. Seasonal performance limitations during periods of low sunlight are also noted. These findings provide important considerations for system design improvements, service delivery, after-sales support, and potential product upgrades. While the core system is generally trusted, targeted technical refinements and service enhancements could significantly improve user satisfaction and long-term sustainability.

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Table 1. Feedback about Solektra SHSs from current users

Theme	What Works Well (%)	Challenges (%)	Suggestions (%)	Interpretation
Overall system performance / reliability	22.8%	0%	0%	Core system is reliable and trusted; not seen as a problem or priority for change
Lighting (brightness, duration, enough light)	33.3%	6%	4%	Strongest system feature with minimal complaints or improvement pressure
Battery & power storage	10.5%	12%	16%	Mixed performance; primary area where users want improvements
Performance in sunny season	10.5%	0%	0%	System performs best under optimal solar conditions
Rainy season / low sunlight	0%	4%	4%	System limitation linked to weather
Radio & bundled accessories	17.5%	6%	8%	Widely valued by users, but frequently affected by theft or damage, with requests for replacement of stolen items and upgraded packages including larger radios or additional appliances (e.g. TV, fan).
Customer service & support	5.3%	2%	8%	Generally positive, but expectations for improvement are growing
Maintenance & repair response	0%	8%	2%	Indicates a need to improve repair turnaround times and technician availability, not changes to the system design
Phone charger / cable quality	0%	4%	12%	Early warning signal: small issue now, strong improvement demand
Affordability & payment	0%	6%	4%	Raised by a smaller number of users, but critical for financially vulnerable households, including those who struggle with monthly payments or require special consideration due to disability.
Theft & security	0%	6%	4%	External risk requiring mitigation rather than system redesign
System expansion (TV, appliances)	0%	2%	8%	Aspirational demand reflecting growing energy needs

Monthly energy output solar PV

The estimated energy production from a 50 Wp solar panel was obtained using PVGIS (Photovoltaic Geographical Information System) data for the project location and is presented in Table 2. The results indicate moderate seasonal variation in solar generation. Average daily production ranges between approximately 0.18 kWh/day and 0.22 kWh/day, corresponding to monthly outputs of 5.5 kWh/month (lower production months such as February and November, associated with rainy conditions) and 6.8 kWh/month (higher production month such as July), as shown in Table 3.

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Monthly energy output from fix-angle PV system:

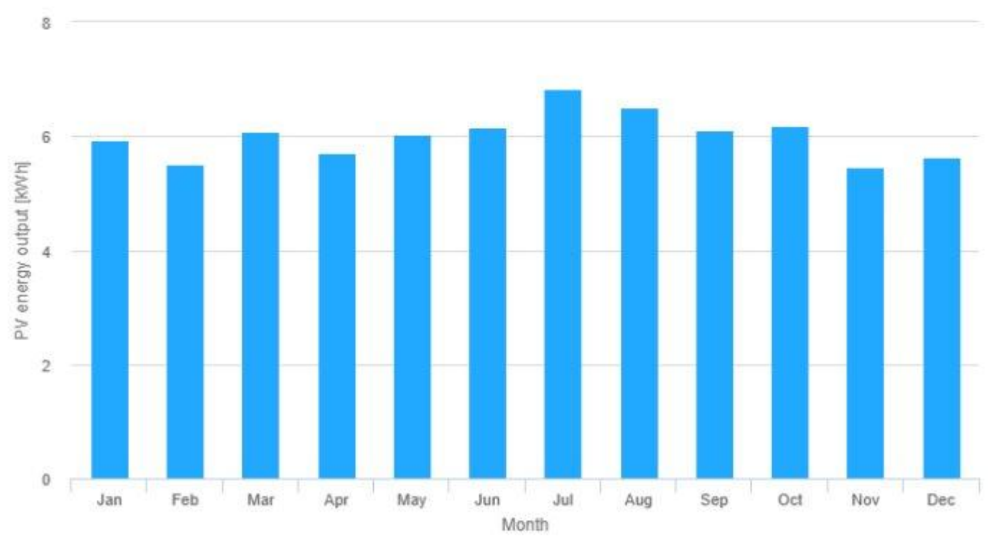

Figure 22. Estimated energy PV production with 50Wp Solar panel:

Table 2. Average daily PV output

	Average daily production
Higher energy output: July	6.8 KWh/month=0.22 Kwh/day
Lower energy output: February & November (rainy season)	5.5 Kwh/month =0.18 Kwh/day

SHSs sharing scenarios

Based on the estimated energy production, different operational scenarios were evaluated and presented in Table 3. The baseline scenario (Scenario 1) assumes five users with the same average electricity consumption as current Solektra's SHS households. Under this configuration, the system capacity is insufficient and the scenario is not technically feasible.
Scenario 2 considers five users with significantly reduced consumption. Although technically feasible under strict load limitations, this configuration would provide a very limited level of service and would require additional load reductions during the rainy season, making it less desirable in practice.

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Scenarios 3 and 4 both assume three users. In Scenario 3, moderately reduced energy consumption allows the system to operate under controlled usage conditions, though seasonal constraints remain. Scenario 4 builds on the same three-user configuration but explicitly incorporates load management during the rainy season. Under this approach, the system is technically feasible and recommended, provided that consumption is actively managed during lower solar production months.
Alternatively, sharing the system among five users could still be considered if the system capacity (panel size and battery energy storage) is expanded accordingly. Increasing generation and storage capacity would allow higher service levels while maintaining reliability throughout the year.

Table 3. Scenarios SHSs

Appliance Type	Rated Power (W)	Number of Units	Average Daily Usage (min/day)	Frequency of Use	Daily Energy Consumption (Kwh)	Peak Power (Kw)	Technical Assessment / Recommendation
Scenario 1: **Baseline_5 Users** (Current Solektra Consumption Profile)5 users with same energy use as current Solektra users)							
Bulb	2	2	315	Daily	0,45	0,05	System capacity insufficient. Scenario not technically feasible. Not recommended.
Mobile phone	15	1	280	Daily			
Radio	3	1	130	every 2-3 days during day time			
Scenario 2: 5 Users (Significantly Reduced Consumption)							
Bulb	mostly 1, sometimes 2	2	315	Daily	0,2	0,02	Technically feasible under strict load limitations. Electricity usage is very limitted. Additional load reduction required during rainy season. Not
Mobile phone	15	1	60	Daily			
Radio	3	1	60	every 2-3 days during day time			
Scenario 3: 3 Users (Moderately Reduced Consumption)							
Bulb	2	2	315	Daily	0,21	0,02	Technically feasible under controlled consumption. Additional load reduction required during rainy season. Recommended
Mobile phone	15	1	220	Daily			
Radio	3	1	80	every 2-3 days during day time			
Scenario 4: **3 Users** (Rainy Season Load Management Scenario)							
Bulb	mostly 1, sometimes 2	1	315	Daily	0,18	0,02	Technically feasible under controlled consumption. Recommended
Mobile phone	15	1	200	Daily			
Radio	3	1	80	every 2-3 days during day time			

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Recommendations

Camp vs. Host Community

- Only one host community was identified as interested in purchasing SHSs, as the other host communities already have access to the main electricity grid. The community name is Remanyundo.

System sizing strategy:

- Either reduce the number of users per system (e.g., from 5 to 3 users), or
- Increase solar PV and battery capacity to accommodate higher demand.

Flexible user allocation:

- Allow variation in the number of users per system to reflect differences in willingness to pay and electricity needs.
- Users willing to pay more (e.g., for productive uses or higher-energy appliances) could access larger or upgraded systems.

Modular and upgradeable design:

- Consider systems that can be expanded in capacity over time as users' energy needs, ability or willingness to pay increase.
- This would accommodate future aspirations for additional appliances or productive uses.

b. Hydrogen cooking solution

- Most of the households in the camp use LPG for cooking, nonetheless supply often runs out before the households are able to refill it for free. As a result, evaluating how long households take to finish LPG consumption can be instrumental to obtain an approximation for potential hydrogen usage.
- All households in the test sample currently use LPG for cooking, but most of them also use on charcoal and firewood. This may be due to the fact that once the LPG supply runs out, it is more cost-effective for them to switch to charcoal or firewood, rather than purchasing additional LPG. Understanding this behavior is crucial, and as such, this aspect has been incorporated into the updated survey. This will help clarify whether price is the primary motivator for this energy mix, or if other factors also influence their cooking fuel choices, which most likely also will influence the use of hydrogen for cooking.

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- In many cases, households pay for the alternative fuels other than LPG. By evaluating their energy expenditures on these alternative fuels, we can gain insights into their affordability levels as well as willingness to pay for alternative energy solutions.

The following household size categories are considered for the analysis of cooking energy needs:

- 1 (1-2 people) ~21%
- 2 (3-4 people) ~24%
- 3 (5-6 people) ~37%
- 4 (7+ people) ~18%

LPG and alternative fuel usage in households with access to free LPG

To establish a baseline demand assessment, the duration of a 6 kg LPG bottle is estimated using survey data disaggregated by household size. Figure 22 provides an overview of the average duration of a 6 kg LPG cylinder across household size categories. A clear correlation emerges between household size and LPG duration: smaller households tend to use LPG more slowly, resulting in longer cylinder duration, while larger households consume LPG more rapidly.

Households in category 1 show a higher share of cylinders lasting three to four weeks or longer, whereas households in categories 3 and 4 more frequently report shorter durations, typically between 10 and 21 days. The proportion of cylinders lasting a full month (26–30 days) decreases significantly as household size increases. This trend reflects higher cooking frequency and larger meal volumes in bigger households. Overall, the data confirm that LPG consumption scales with household size, with larger households experiencing shorter refill cycles and therefore higher effective fuel demand.

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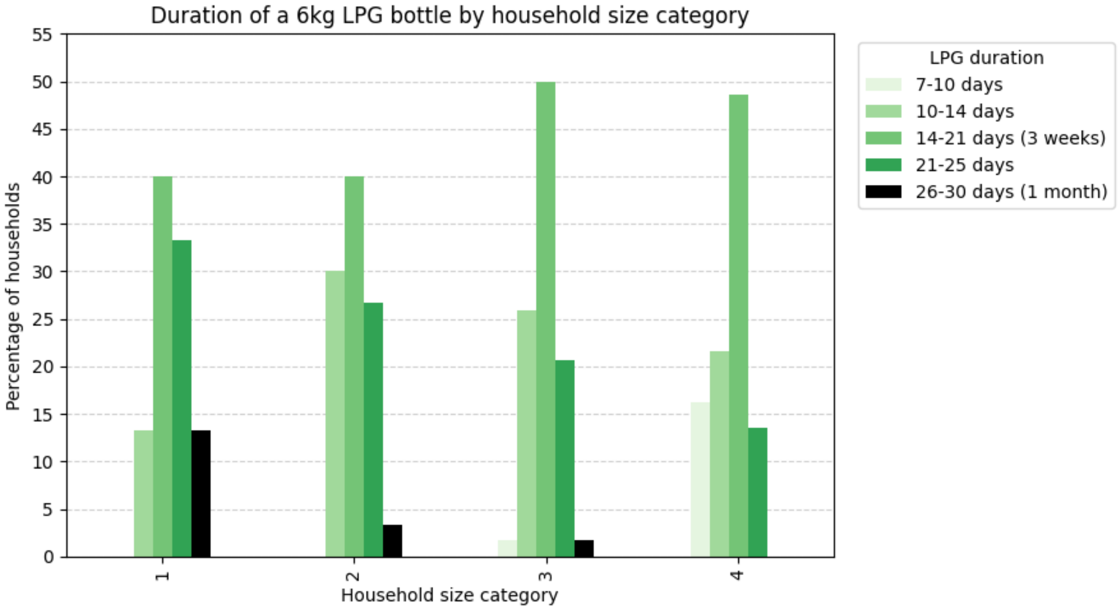

Figure 23. Duration of LPG bottle by household size.

Using ordinary least squares regression on data from 155 households, we estimate the relationship between household size and the duration of a 6kg LPG cylinder. Reported duration intervals were converted to numeric midpoints. Results show that each additional household member is associated with a statistically significant reduction of approximately 0.6 days in cylinder duration ($p < 0.001$). Although the model explains about 10% of the variation in reported duration, this level of fit is expected given the interval-censored nature of the outcome and heterogeneity in cooking practices. The results are presented in Figure 23 and Table 4.

Dependent variable: Estimated number of days a 6kg LPG cylinder lasts
Independent variable: Household size

$$\text{Days/6kg LPG bottle} = 20.54 - 0.62 \times \text{household size}$$

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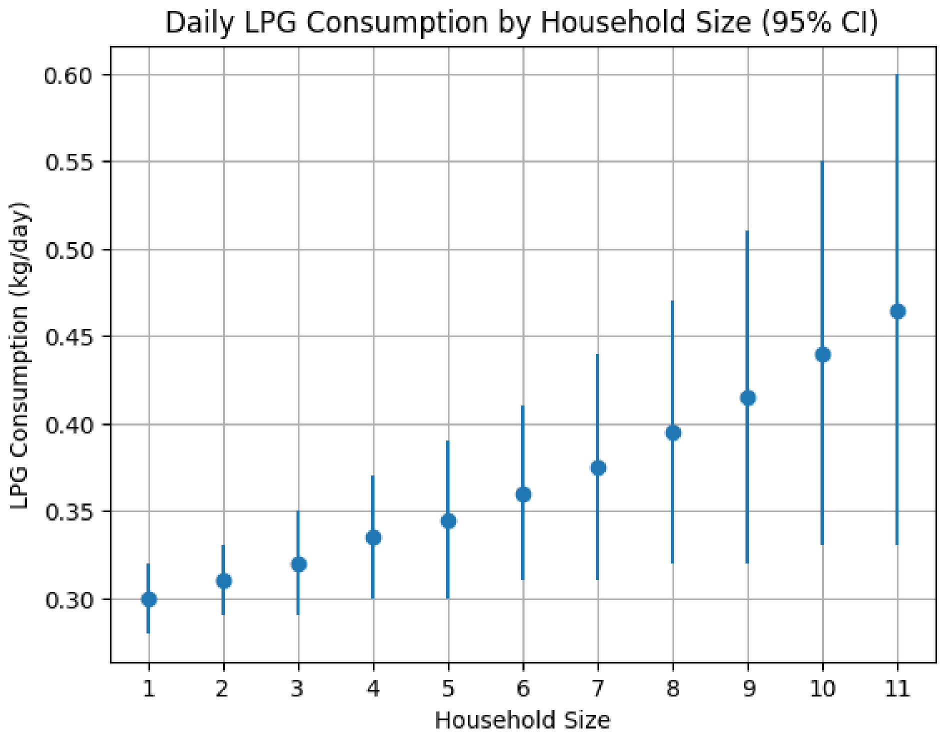

Figure 24. Results from OLS model: LPG consumption by household size.

Table 4. Estimated LPG consumption by household size

Household size	Estimated duration (days)	Estimated LPG consumption (kg/month)	Estimated LPG (kg/day)	95% CI (days)	95% CI (kg/month)	95% CI (kg/day)
1	19,9	9,10	0,3	[19.0 , 21.2]	[8.5 , 9.5]	[0.28 , 0.32]
2	19,3	9,30	0,31	[18.1 , 20.9]	[8.6 , 10.0]	[0.29 , 0.33]
3	18,7	9,60	0,32	[17.2 , 20.5]	[8.8 , 10.5]	[0.29 , 0.35]
4	18,1	10,00	0,33	[16.3 , 20.2]	[8.9 , 11.0]	[0.30 , 0.37]
5	17,4	10,30	0,34	[15.4 , 19.9]	[9.0 , 11.7]	[0.30 , 0.39]
6	16,8	10,70	0,36	[14.5 , 19.6]	[9.2 , 12.4]	[0.31 , 0.41]
7	16,2	11,10	0,37	[13.6 , 19.3]	[9.3 , 13.2]	[0.31 , 0.44]
8	15,6	11,50	0,38	[12.7 , 19.0]	[9.5 , 14.2]	[0.32 , 0.47]
9	15	12,00	0,4	[11.8 , 18.7]	[9.6 , 15.3]	[0.32 , 0.51]
10	14,3	12,60	0,42	[10.9 , 18.4]	[9.8 , 16.5]	[0.33 , 0.55]
11	13,7	13,10	0,44	[10.0 , 18.1]	[10.0 , 18.0]	[0.33 , 0.60]

Survey results indicated a clear fuel-stacking practice, mainly due to the limited amount of available LPG provided as well as the higher cost of it compared to other fuels. Households specially use alternative fuels when cooking dishes that take longer to prepare (such as beans) in order to save LPG. Nonetheless, cooking with gas was highly valued due to the easiness and time saving. Figures 22 and 23 show fuel usage patterns across household size categories, for households that receive LPG for free.

It can be seen that size category 1 (1 or 2 people) households rely almost exclusively on LPG, with very limited use of complementary fuels. In contrast, medium and larger households (size categories size 2–4) exhibit substantial charcoal use, making charcoal the dominant complementary fuel even when LPG is freely available.

Firewood use remains relatively low and is primarily collected without cost rather than purchased, particularly among larger households. Briquette use is limited overall but increases modestly with household size. Paid complementary fuel use is driven almost entirely by charcoal, especially among households with two or more members.

Overall, the results indicate that free LPG provision does not eliminate fuel stacking. Instead, complementary fuel use—particularly charcoal—persists and becomes more pronounced as household size increases. This highlights the presence of higher energy demands that are not currently meet, specially for the households with higher number of people (size categories 3 and 4).

Firewood use is largely unpaid across all household sizes, indicating that most households collect it rather than purchase it. Larger households show a higher share of firewood collected without cost. Charcoal use follows a clear fuel-stacking pattern: it is rarely used in single-person households but increases significantly in households of sizes 2 and 3, where around 45–47% report paid use, before slightly decreasing in size 4 households while remaining relatively high. Briquettes remain marginal overall, with only a slight increase in use as household size grows, and consistently lower adoption compared to charcoal.

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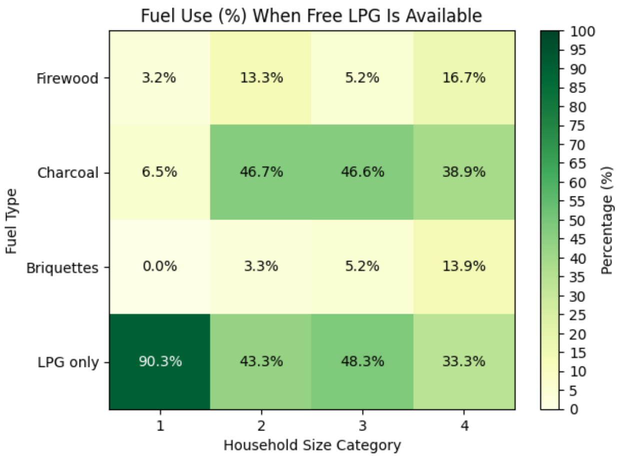

Figure 25. Fuel use when LPG is available.

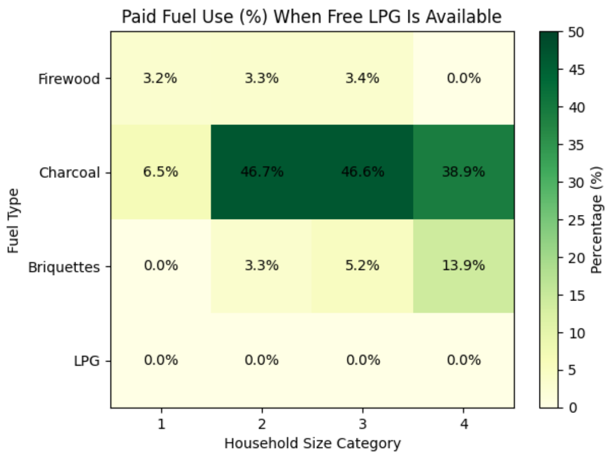

Figure 26. Paid fuel use when LPG is available.

Among households receiving LPG free of charge, fuel stacking remains widespread, particularly among larger households. Larger households are both more likely to stack fuels and to incur substantial weekly expenditures on non-LPG fuels, indicating that fuel stacking reflects cooking demand and capacity constraints rather than lack of access to LPG. Table 5 summarizes fuel expenditure patterns.

Table 5. Fuel expenditure in households that receive LPG

Household (HH) category size	HHs with additional fuel expenditure (%)	Mean weekly expenditure. Only HHs with additional expenditure (rwf)	Median weekly expenditure. Only HHs with additional expenditure (rwf)	Mean weekly expenditure. All HHs (rwf)	Median weekly expenditure. All HHs (rwf)
1	9,7	417	250	40	0

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2	51,2	982	750	474	0
3	51,7	1250	750	646	250
4	52,8	1566	1500	826	500

When the free LPG finishes only 5.8% of households report paying for it. Reliance on paid LPG remains low overall but increases slightly with household size. Approximately 8.3% of category 4 households and 7% of category 3 households report paying for LPG, while categories 1 and 2 remain below 4%. Among those who do pay, weekly expenditures are relatively high, averaging approximately 2,500–3,500 RWF per week, indicating that LPG remains a costly option for most households.

Fuel usage in households without access to free LPG

Figure 24 illustrates fuel-use patterns among households that do not receive complementary LPG, disaggregated by household size category. Charcoal emerges as the dominant fuel across all categories, with particularly high usage rates among medium-sized households (size 2–3). Firewood use increases with household size, suggesting greater reliance on traditional biomass among larger households. Briquette use is relatively limited in smaller households but rises substantially in the largest category. Paid LPG use remains present but does not dominate the fuel mix in any household size category. Overall, the results indicate continued dependence on solid fuels in the absence of complementary LPG provision, with fuel diversification patterns varying by household size.

Among the 66 households in the sample (in the no-complementary-LPG group), 16 households (24.2%) report positive LPG expenditure. However, exclusive reliance on LPG is rare. Only 2 households (3.0% of the total sample) report using LPG without any additional fuel use.

Figure 25 presents mean weekly fuel expenditure by household size among households that do not receive complementary LPG. LPG shows the highest expenditure per household in categories 1–3, indicating that households purchasing LPG tend to spend relatively large amounts when they rely on it. Charcoal also represents a substantial expenditure item across all categories, particularly among medium-sized households, confirming its role as a primary alternative fuel. Briquette expenditure is moderate and more evenly distributed, while firewood expenditure remains comparatively lower but increases slightly with household size. Overall, the results suggest that although LPG use is less widespread in this group, households that purchase it incur relatively high weekly costs compared to other fuels.

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Among households reporting positive LPG expenditure, LPG represents the largest share of weekly fuel spending, accounting for an estimated 55–65% of total fuel expenditure. However, most LPG users continue to allocate substantial resources to charcoal and, to a lesser extent, briquettes, indicating persistent fuel stacking rather than exclusive reliance on LPG. Firewood expenditure is comparatively limited within this subgroup, as shown in Figure 26 and Table 6.

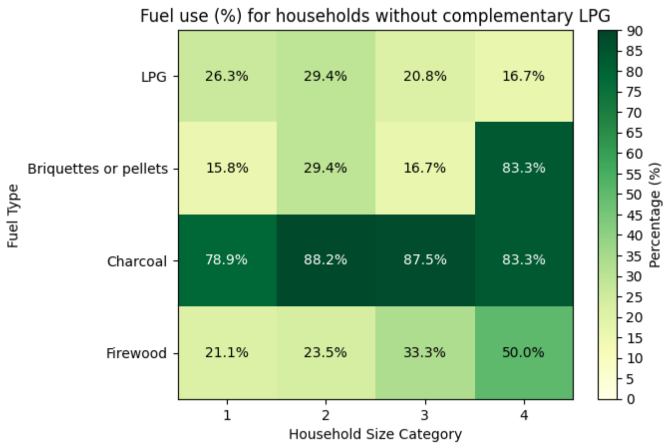

Figure 27. Fuel usage in households without complementary LPG.

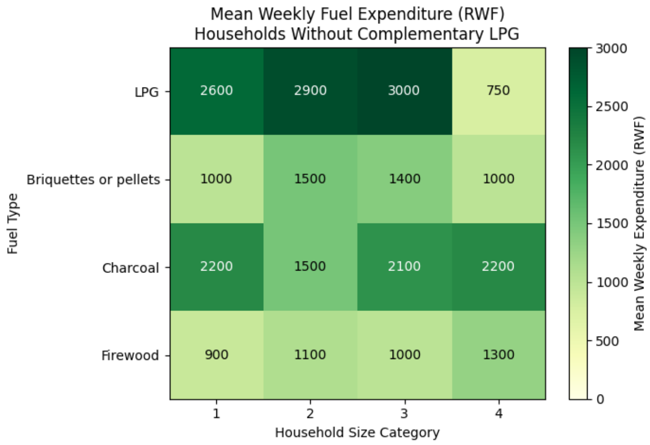

Figure 28. Weekly fuel expenditure in households without complementary LPG.

Table 6. Fuel expenditure in households without access to free LPG

Household (HH) category size	Mean weekly expenditure (rwf)	Median weekly expenditure (rwf)

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1	2303	2250
2	2985	2500
3	2781	2500
4	3542	3250

Cooking patterns

Cooking time data indicate no significant differences across household size categories, suggesting that meal preparation duration is relatively consistent regardless of household size. However, these values are based on self-reported estimates and should therefore be interpreted with caution, as respondents may approximate rather than precisely measure preparation time. Despite this limitation, clear patterns emerge: breakfast preparation time is consistently lower, as shown in Figure 28.

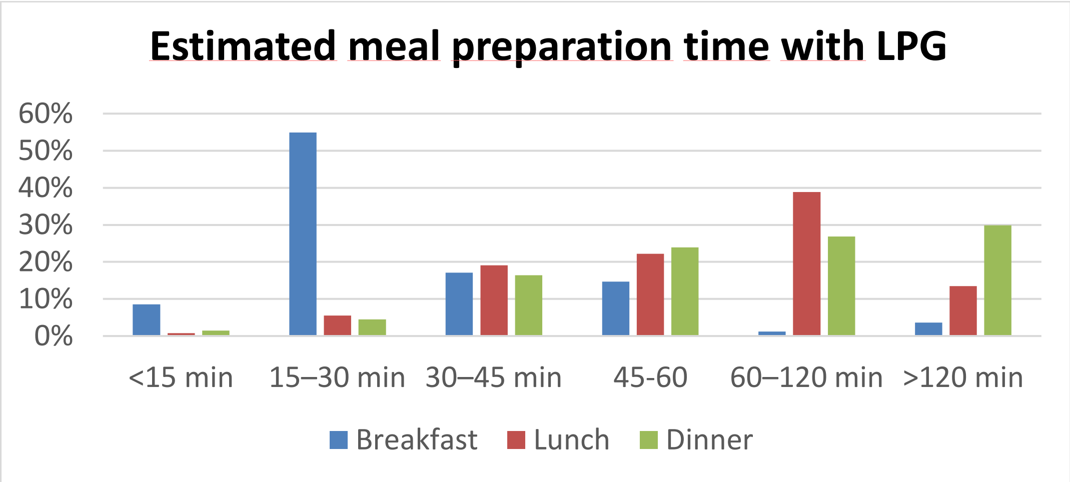

Figure 29. Meal preparation time.

Across 351 households, cooking frequency averages 1.8 times per day, with the median household cooking twice daily. Smaller households (1–2 people) typically cook once per day, while households with three or more members predominantly cook twice per day, with larger households more likely to cook three times daily. Lunch and dinner represent the main cooking events of the day, with only a minority of households reporting cooking for breakfast. The results are reported in Table 7.

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Table 7. Daily cooking patterns

HH size category	1 time/day	2 times/day	3 times/day
1	59.7%	36.1%	4.2%
2	38.6%	49.4%	12.0%
3	20.9%	61.2%	17.8%
4	28.6%	54.0%	17.5%

Furthermore survey responses indicate that households prefer flat-bottom cooking pots, which provide better stability and more efficient heat transfer on gas stoves. Smaller pot sizes (around 8 liters) were preferred for daily meal preparation. This has implications for stove and burner design, as hydrogen-compatible cooking solutions should accommodate flat-bottom cookware and typical pot sizes to ensure usability, safety, and efficient heat distribution.

Meals that require longer cooking times are typically prepared once or twice per week (Figure 29). These mainly include beans and cassava leaves. Among respondents who reported using LPG for these dishes, more than 50% indicated that cooking usually takes two hours or more (Figure 30).

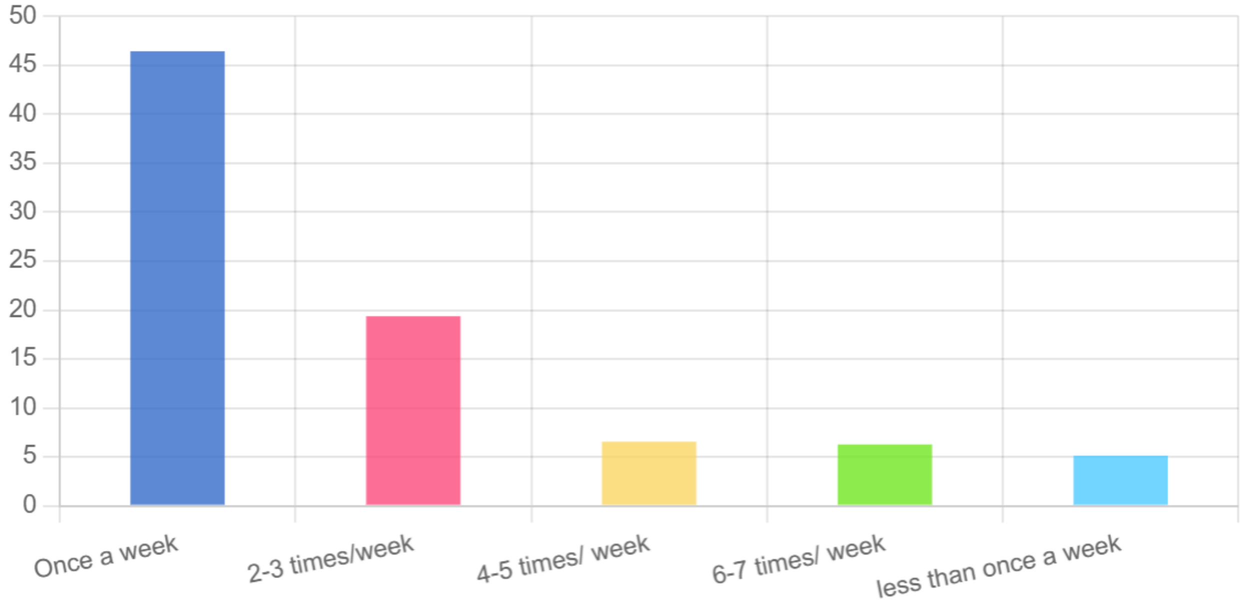

Figure 30. Frequency of preparation of long-cooking meals.

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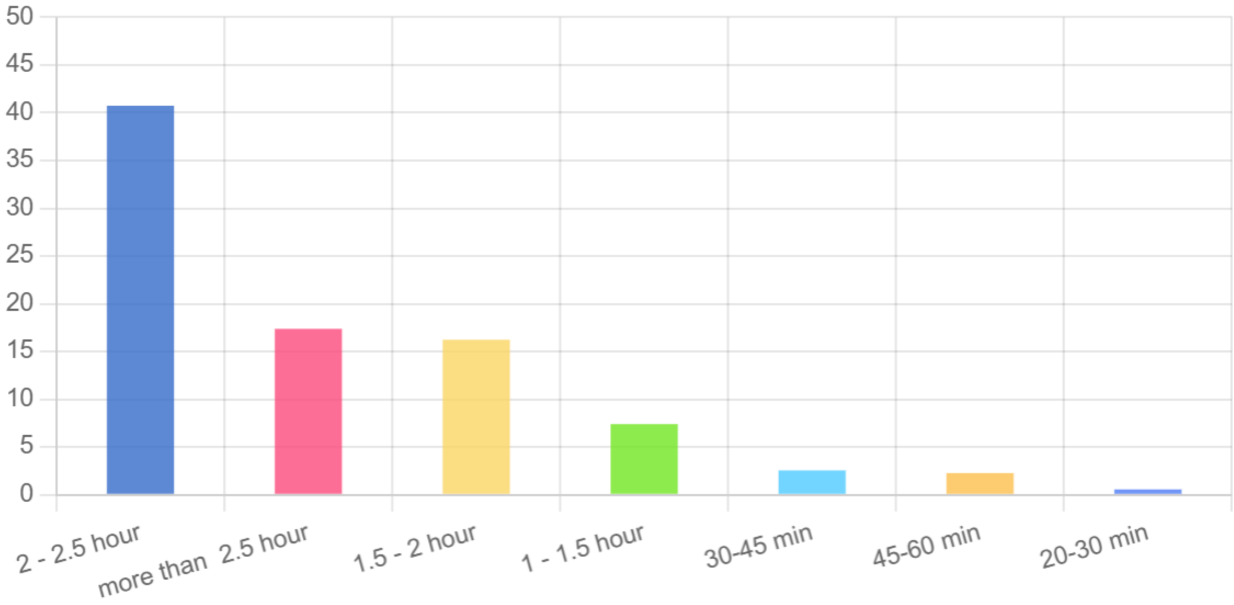

Figure 31. Duration of long-cooking meals.

Recommendations:

Based on the survey results and LPG consumption analysis, the following recommendations are proposed for the design of a hydrogen-based cooking solution:

1. **Prioritize larger households** (size categories 3–4, 5+ members): These households exhibit shorter LPG duration, higher charcoal use, and higher weekly fuel expenditures. Targeting them will maximize displacement of charcoal and address the highest unmet energy demand.
2. **Design for a minimum of one full day of cooking energy per unit, preferably two or more days:** Providing ≥2 days of cooking coverage improves reliability, reduces refill burden, and increases adoption probability. This means a minimum size that can cover the equivalent of 0.88 Kg of LPG, which corresponds to the LPG daily need for bigger households.
3. **Consider complementary use alongside LPG:** Several households that currently receive LPG expressed interest in having a second stove to cook with two pots simultaneously. In such cases, hydrogen may function as a complementary rather than replacement fuel, implying that total hydrogen demand in LPG-receiving households may be lower than full substitution estimates.
4. **Ensure the system covers high-energy meals (e.g., beans or cassava leaves):** Fuel stacking persists because LPG is conserved for quick meals, while charcoal is used for long cooking tasks. It is not clear whether fuel stacking will persist. Hydrogen must be capable of covering these high-energy cooking events to

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meaningfully displace charcoal.

5. **Ensure compatibility with existing cookware preferences:** Survey responses indicate that most households prefer small, flat-bottom cooking pots. Hydrogen stove design should therefore be compatible with this cookware to ensure usability, stability, and efficient heat transfer.

Bidibidi camp (Uganda):

The baseline evaluation resulted in the following findings and identification of needs to be addressed:

1. Cooking solution: The needs have been identified, to define the technology solution more precisely and to determine whether it will be designed for individual households or communal use, and accordingly finalize end-user surveys. This decision is closely tied to the availability of waste for biogas production, as well as the integration of biogas and hydrogen technologies.

2. Irrigation and cold chain solution: After preliminary discussions with SUNNY local partners, the needs were determined to identify key stakeholders and suitable locations for implementing a centralized energy system. This requires a thorough assessment of the target stakeholders, and infrastructure availability. Engaging with stakeholders, including local cooperatives, agricultural organizations, and supply chain actors, will be crucial to evaluate specific energy needs and ensure the system's feasibility and sustainability. Additionally, it is important to evaluate the local agricultural and supply chain dynamics to ensure that the system can be effectively integrated.

3. Irrigation solution: Water availability has been identified as a potential challenge, necessitating further analysis and discussions with local stakeholders to identify most suitable demonstration sites and before the survey implementation to final users is to be carried out.

c. Biogas solution

The preliminary proposed pilot site for the biogas system is Locopio Technical School, subject to final confirmation. The school accommodates approximately 200 students and staff, creating a concentrated and consistent demand for cooking energy.

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Currently, the school relies heavily on firewood for cooking, which presents both. Additionally, the institution offers training curricula in energy and agriculture, providing an excellent opportunity to integrate the biogas system into practical learning activities and hands-on student training. The site was identified by REFUESE during the waste assessment. Although the volume of waste generated is not entirely stable, multiple differentiated and viable sources of biodegradable waste were identified, with the potential to be supplemented through additional feedstock collection from nearby households.

Cooking energy needs

This analysis estimates the daily cooking energy required to provide meals to 200 students under two scenarios. Results are presented as useful cooking energy (delivered to the pot/food), in kWh/day and MJ/day and then compared to the equivalent biogas volume, in m³/day.

The estimated energy demand per meal is derived from published reports on cooking practices in Ugandan schools[1] and from studies assessing the implementation of School Feeding and Nutrition Programmes in Uganda[2]. Boarding schools typically offer breakfast and lunch, with some also providing meals for learners in the early morning and evening. Overall, most are plant-based meals with ugali/posho, rice, cassava or sweet potato being dominant staples with beans the main protein *(Fungo, 2023).*[1] Table 8 provides an overview of typical school menu in Uganda.

Table 8. Typical school menu (Fungo, 2023)

Day	Morning Tea	Breakfast	Lunch	Dinner
Monday	Black Tea	Porridge	Posho & Beans	Posho & Beans
Tuesday	Milk Tea	Porridge	Posho & Beans	Posho & Beans
Wednesday	Black Tea	Porridge	Posho & Beans	Posho & Beans

[1] Modern Energy Cooking Services (MECS). (2025). Uganda cooking in schools brief. https://mecs.org.uk/wp-content/uploads/2025/09/Uganda-Cooking-in-Schools-Brief.pdf
[2] Fungo, R. (2023) 'Implementation of the School Feeding and Nutrition Programmes in Uganda and the Contribution of School Meals to Recommended Dietary Allowances (RDAs) of Children: Challenges and Opportunities'. African Journal of Food Science, vol.17, no.5. https://academicjournals.org/journal/AJFS/article-full-text-pdf/35C3C0770705[1]

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Day	Morning Tea	Breakfast	Lunch	Dinner
Thursday	Black Tea	Porridge	Posho & Beans	Posho & Beans
Friday	Black Tea	Porridge	Posho & Beans	Posho & Beans
Saturday	Milk Tea & Mandazi	Porridge	Rice & Meat	Rice & Beans
Sunday	Milk Tea	Porridge	Cassava & Beans	Rice & Beans

Based on typical cooking practices and school meal compositions in Uganda, the estimated useful cooking energy demand varies depending on the number of meals provided per day. For a single lunch consisting primarily of posho and beans, the required useful energy is relatively modest. However, in a full boarding school setting—where tea, breakfast, lunch, and dinner are prepared daily—the cumulative energy demand increases significantly. The table 9 summarizes the estimated useful energy requirements per student and the corresponding total daily energy demand for 200 students under the two scenarios considered.

Table 9. Estimated energy needs for cooking

Scenario	Useful Energy per Student	Equivalent (kWh per Student)	Total Energy for 200 Students
A. Lunch Only (Posho & Beans)	1.0 – 1.5 MJ/student/meal	0.28 – 0.42 kWh/student	56 – 84 kWh/day
B. All Boarding (Tea + Breakfast + Lunch + Dinner)	2.25 – 3.5 MJ/student/day	0.63 – 0.97 kWh/student/day	126 – 194 kWh/day

Biogas output

To estimate the potential daily biogas production, a set of operational and contextual assumptions has been established. These assumptions are based on observed waste generation patterns at the school, anticipated participation from nearby households, and typical characteristics of organic waste streams in similar rural settings. The objective is to determine a realistic and conservative estimate of the amount of feedstock available to supply a small-scale biogas digester. The key assumptions applied in this assessment are outlined below:

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- Direct contributing population to the system: estimated participation of 240 people, taking into account not only students, but also families from nearby households.
- Estimated percentage of potentially usable organic waste: 70%, considering kitchen, manure and agricultural waste.
- Estimated total amount of waste generated by the group: 72 kg/day.
- Estimated useful organic fraction to feed the digester: 50.4 kg/day, which is in line with the observation that the useful volume available for a small plant in the current context is around 50 kg/day.
- As for the input composition, a generic mixture based on typical waste available in the environment has been considered, as shown in Table 10:

Table 10 Bidibidi environment waste parameters.

Kind of waste	Dry matter (DM)	Volatile solids (VS over DM)
Manure	20%	80%
Agricultural waste	25%	80%
Kitchen waste	15%	80%

The estimation allows us to calculate a reasonable organic matter loading rate for a low-scale biodigester aimed to produce biogas for cooking in a limited resources context, as Bidibidi settlement. Resources seasonality, scarcity of water and transport restrictions has been taking into account in the design parameters of the biogas device. In addition, the design and dimensioning of the biogas plant has been carried out taking into account both the waste generated by the population of the area and the need for local management that avoids transporting waste over long distances. It has been foreseen that the waste managed in the plant will be generated in the vicinity of the facility, being processed in a simple and efficient way.

Based on the characteristics of the mixture, and considering an average methanogenic potential of 550 L/kg of degraded volatile solids, and an estimated volatile solids removal of 46%, the biogas production estimated is presentend in Table 11:

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Table 11. Estimated biogas production

Biogas production	550	L/kg MV
Volatiles removal	46	%
Biogas generation	2027	m^3/a
	5,6	m^3/d
CH4 content	55	%
Density	1,13	Kg/m^3
Lower Heating Value	5,47	kWh/m^3

Based on the assumed feedstock input, the system is expected to generate approximately 5.6 m³ of biogas per day, equivalent to about 2,027 m³ per year. With an estimated methane (CH_4) content of 55%, the biogas has a lower heating value (LHV) of 5.47 kWh per m³. This results in a total daily energy potential of approximately 30.6 kWh/day, corresponding to about 110 MJ/day of energy available in the produced gas.

Coverage comparison:

The actual useful cooking energy delivered to the food will depend on burner performance and overall heat-transfer efficiency. Typical biogas stove efficiencies range between 50–60%. These efficiency factors have not been applied in the present calculation in order to maintain a conservative comparison based strictly on the energy content of the produced biogas.

The projected biogas output would cover approximately 37–67% of the estimated daily cooking energy demand under the lunch-only scenario. In contrast, under the full-boarding scenario—where tea, breakfast, lunch, and dinner are prepared—the same level of biogas production would meet approximately 16–24% of the total daily cooking energy requirement. These figures indicate that while the system could substantially offset firewood consumption in a limited-meal configuration, it would serve as a partial energy supplement in a full-boarding context.

Recommendations:

The following recommendations are proposed to enhance the technical performance, operational reliability, and overall impact of the proposed biogas system.

- **Verify the full waste collection potential** at the school and in surrounding households. Higher recoverable organic waste volumes could significantly increase energy coverage.
- **Establish an integrated waste management system**, including source

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segregation, reliable and targeted collection from clustered households, consistent digester feeding, and clear operational responsibilities to ensure stable and predictable biogas production.

- **Determine the hydrogen production potential** as part of a combined energy solution, assessing how hydrogen integration could increase overall gas output and usable cooking energy
- **Implement a structured biogas allocation and use plan:** Engage the school administration for defining energy priorities, including agreement on which cooking activities or meals should be covered by biogas under the projected production levels, ensuring that system operation aligns with the school's actual energy needs and planning.
- **Improve biogas use efficiency** through appropriate stove selection, operator training, and cooking practices.

d. Irrigation and cold storage

The present assessment builds on the preliminary assessment conducted in Bidibidi by UMAK and is complemented by desk-based research. It provides an initial estimation of potential energy needs based on an overall overview of the camp conditions.

The analysis should be considered a baseline assessment and planning framework. Final system sizing will require the definition and detailed characterization of specific demonstration sites. Once site selection is completed, the technical parameters and energy requirements can be refined accordingly.

Water access and agriculture context

Current watering practices are largely manual and heavily dependent on rainfall. Watering cans are the most commonly used method, while only a small proportion of respondents reported accessing boreholes or streams for irrigation. Surface water availability is limited, resulting in primary reliance on boreholes and shallow wells. Water scarcity and the long distances required to fetch water emerged as major constraints. Respondents frequently highlighted the limited number of boreholes and the lack of appropriate irrigation equipment as key challenges. The time and labor required for water collection significantly restrict the ability to expand agricultural production, particularly during the dry season.

These findings support the design of shared irrigation systems, including centralized pumping, water storage tanks, and distribution networks that minimize labor and reduce hauling distances.

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Perceptions of Irrigation vs. Cold Storage

Key Informant Interviews (KIIs) indicate that the perceived urgency of irrigation is significantly stronger than that of cold storage. Irrigation is widely seen as a direct production enabler. Respondents emphasized that it:

- Increases crop yields and enables dry-season production
- Generates immediate and visible income benefits
- Reduces dependency on rainfall
- Benefits a large share of the community, as most households are engaged in agriculture

Cold storage, nonetheless, is viewed primarily as a post-production improvement. While considered useful, its perceived necessity depends on increased production volumes and improved market access. These findings suggest that cold storage should be introduced alongside strengthened market linkages to ensure value capture. Cold storage can generate sustained benefits if paired with effective aggregation mechanisms, buyer connections, and coordinated harvesting and sales scheduling. Without reliable market outlets, storage capacity alone is unlikely to translate into increased incomes. However, when combined with strong market linkages, such as aggregation systems, off-take agreements, access to market information, quality standards, or reliable transport, the integration of irrigation and cold storage has substantial potential to improve food security while significantly enhancing income generation and value capture for producers.

Site-specific crop mix and water demand

Energy requirements for both irrigation and cold storage depend on the specific crops cultivated at the demonstration site. The crop mix directly influences:

- Irrigation water demand assumptions
- Seasonal production patterns
- Cold storage temperature requirements
- Overall system energy demand

The system design should therefore remain site-specific and flexible to accommodate potential shifts in crop composition over time. The dominant crop at Bidibidi is maize, followed by cassava, beans, and leafy greens, with smaller shares of sorghum, groundnuts, and other crops. Initial assumptions implies that the systems would serve

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approximately ~50 farmers. To estimate irrigation water demand for the 50-farmer, a weighted-average crop water requirement is obtained based on a report by Food and Agriculture Organization of the United Nations[3]. The water requirements are presented in Table 12:

Table 12. Water requirement by crop

Crop	Percentage	Net water (m³/acre/day)
Maize	29.68%	19.4–29.1
Cassava	17.18%	12.9–26.7
Beans	14.84%	18.6–27.9
Greens	12.50%	16.2–24.3
Sorghum	3.90%	16.2–26.7
Groundnuts	1.56%	18.6–27.9
Other (Simsim, cow peas, blank)	20.3%	-

The average net irrigation water demand per acre is 17.17–27.46 m³/acre/day. This is derived as a weighted average based on the existing cropping pattern. For each crop, the lower and upper bounds of the reported net water requirement were multiplied by the respective percentage share of cultivated area. Summing these weighted values produced representative lower and peak dry-season water demands per acre.

- **17.17 m³/acre/day** represents lower dry-season demand (i.e., lower temperatures, higher humidity, reduced evapotranspiration)
- **27.46 m³/acre/day** represents peak dry-season demand.

Two implementation scenarios are considered:

- **Scenario A** assumes 0.5 acre per farmer, corresponding to a total cultivated area of 25 acres.
- **Scenario B** assumes 1 acre per farmer, corresponding to a total cultivated area of 50 acres.

2

[3] Allen, R. G., Pereira, L. S., Raes, D., & Smith, M. (1998). *Crop evapotranspiration: Guidelines for computing crop water requirements* (FAO Irrigation and Drainage Paper No. 56). Food and Agriculture Organization of the United Nations. https://www.fao.org/3/x0490e/x0490e00.htm

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Irrigation technology

Daily pumping energy is calculated as follows:

$$E_p\left(\frac{\text{kWh}}{\text{day}}\right) = \frac{p\, g\, V_g\, H_t}{3.6 * 10\, \eta},$$

Where:

- E_p = energy required (kWh/day)
- ρ = water density (≈ 1000 kg/m³)
- g =gravitational acceleration (9.81 m/s²)
- V_g = gross water volume pumped per day (m³/day)
- H_t = total dynamic head (m)
- η = overall pump efficiency

Table 13 represents energy demand under different dynamic head values (Ht).

Table 13. Irrigation energy needs.

Scenario	Total acres	Total net water need per day (m3/day)	Gross water need (m3/day)	Energy need lower bound (kWh/day)	Energy needs higher bound (kWh/day)
Scenario A	25	429 – 687	537-859	1,46 x Ht/η	2,34 x Ht/η
Scenario B	50	859 – 1,373	1073-1716	2,92 x Ht/η	4,68 x Ht/η

An overall pump efficiency of 70% is considered, representing a medium-sized, properly selected and maintained electric irrigation pump operating near optimal conditions. Assuming a representative total dynamic head values of 20 m and 30 m, the resulting energy demand ranges from approximately 42–100 kWh/day for Scenario A (0.5 acre per farmer) and 84–200 kWh/day for Scenario B (1 acre per farmer). Table 14 presents a summary of the energy needs by scenario.

Table 14. Irrigation energy needs by scenario

Scenario	η	Ht (m)	Energy need lower bound (kWh/day)	Energy needs higher bound (kWh/day)
Scenario A	70%	20	41.8	66.9

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Scenario A	70%	30	62.7	100.3
Scenario B	70%	20	83.5	133.6
Scenario B	70%	30	125.3	200.4

The current results provide a pre-feasibility energy range and a scalable calculation framework. Once site-specific measurements are collected, the same model can be updated to produce accurate final system sizing without altering the underlying methodology.

Several technical inputs needed to convert water demand into energy demand, which should be measured once the final demonstration site is confirmed. For the final sizing of the irrigation system, the parameters described above should be obtained:

- **Total Dynamic Head (H_t, meters):** the total "height/pressure" the pump must overcome. It includes (i) the vertical lift from the water level to the outlet, (ii) elevation to any storage tank, (iii) pressure needed at the irrigation system (e.g., drip lines), and (iv) pipe friction losses.
- **Pump–motor efficiency (η, decimal):** the fraction of electrical energy that is converted into useful hydraulic energy. It depends on pump type and operating point; typical values are 0.45–0.60.
- **Pumping schedule / flow (Q or hours/day):** determines how large the pump and inverter must be (nominal and peak power). If pumping is limited to fewer hours per day, nominal and peak power must increase to deliver the same daily volume.

Cold storage technology

Most of the crop mix currently cultivated at Bidibidi (maize, cassava, sorghum) does not typically require cold storage. Cold storage is mainly relevant for crops such as greens, tomatoes, fresh vegetables. Given the current crop mix, only a subset of cultivated area (primarily horticultural crops such as greens and fresh vegetables) are considered for this assessment to directly utilize cold storage. Energy demand assessment and validation framework is build based on existing knowledge about the agriculture practices, to support final technical dimensioning once the demonstration site parameters including specific crops cultivated, seasonal production cycles, and market linkage development.

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Greens currently represent approximately 12.5% of cultivated area. Conservative yield assumptions of 8–12 tons per acre per production cycle (90-day harvest window) were applied to estimate daily intake. This range aligns with FAOSTAT[4] reported yields for common vegetable crops in Uganda and reflects achievable productivity under irrigated, moderate-input smallholder production systems. The assumption represents a mid-range performance level, above rainfed low-input conditions but below intensive commercial horticulture, thereby providing a realistic and prudent basis for cold-room intake modelling. The potential maximum daily intake is presented in table 15.

Table 15. Potential maximum daily agricultural product intake

Scenario	Greens Area (acres)	Daily Yield per Acre (kg/day)	Potential maximum daily Intake (kg/day)
Scenario A (25 acres total)	3.125	89 – 133	278 – 417
Scenario B (50 acres total)	6.25	89 – 133	556 – 833

These values represent potential daily intake requiring cooling under the current crop mix. Actual cold-room intake will be lower, depending on the share of produce routed through cold storage (sales timing, household consumption, and service uptake).

Total cold-room energy demand consists of: (i) structural and operational heat gains (transmission through insulation, air infiltration during door openings, internal fans and controls), and (ii) product cooling load required to reduce incoming produce from ambient temperature to storage temperature. This decomposition follows standard refrigeration engineering practice[5].

Energy demand is composed of two components:

$$E_{total} = E_{base} + E_{product}.$$

3

[4] Food and Agriculture Organization of the United Nations. (2024). *FAOSTAT statistical database: Crops and livestock products*. https://www.fao.org/faostat/en/#data/QCL

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The product cooling component of cold-room energy demand is estimated using standard refrigeration load calculations. The thermal energy required to cool incoming produce is:

$$Q = m \cdot cp \cdot \Delta T,$$

where:

- m = mass of product (kg)
- cp = specific heat capacity of fresh product (for leafy vegetables typically 3.5–4.0 kJ/kg·K)
- ΔT = temperature reduction from ambient to storage conditions.

To convert thermal energy to electrical energy, the refrigeration system efficiency is represented by the coefficient of performance (COP), such that:

$$E_{product} = \frac{Q}{COP}$$

Assuming a temperature reduction of 20–25 K (e.g., ~25–30°C ambient down to ~5–10°C storage) and a refrigeration COP of 2–3, the resulting electricity requirement for product cooling is approximately 0.007–0.014 kWh per kg of intake.

Because not all harvested products will be routed through cold storage (some will be sold immediately, consumed, or otherwise not stored), an uptake factor *f* is introduced to represent the share of potential daily production that is actually delivered to the cold room. The cold-room daily energy demand is therefore estimated as the sum of a typical baseline load and the intake-dependent product cooling load:

- **Typical baseline load:** E_{base}=22 kWh/day (transmission through insulation, infiltration due to door opening, and auxiliaries such as fans/controls).
- **Intake-dependent load:** scaled by *f* and the 0.007–0.014 kWh/kg factor above.

Under these assumptions, the total daily energy demand ranges shown in Table 16 are obtained for the two agricultural area scenarios.

[5] ASHRAE. (2018). *ASHRAE handbook—Refrigeration (2018 SI edition)*. American Society of Heating, Refrigerating and Air-Conditioning Engineers. https://studylib.net/doc/27863662/2018-ashrae-handbook---refrigeration-si

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Table 16. Cooling energy demand estimation

Scenario	Uptake factor (*f*)	Total Daily Energy Demand (kWh/day)
Scenario A (25 acres)	0.30	22.6 – 23.8
	0.50	23.0 – 24.9
	0.70	23.4 – 26.1
Scenario B (50 acres)	0.30	23.2 – 25.5
	0.50	23.9 – 27.8
	0.70	24.7 – 30.2

In typical operation, the cold-room baseline load (22 kWh/day) dominates the total energy demand, while the product cooling component increases approximately linearly with the uptake factor *f.*

Under Scenario A (25 acres), daily cold-room energy demand is expected to range between 22 and 26 kWh/day, depending on operational discipline. Under Scenario B (50 acres), daily demand increases to 23.2–30.2 kWh/day, reflecting higher intake from larger cultivated area. Energy demand scales primarily with:

- Expansion of horticulture share (influencing $E_{product}$)
- Daily intake levels (influencing $E_{product}$)
- Operational management such as door control and insulation effectiveness (influencing E_{base})

Solar resource

Monthly irradiation has been obtained using PVGIS. The lowest solar yield occurs around June–July, which coincides with the cloudier/wetter period in Yumbe (West Nile), while the highest yield occurs around December–February, which aligns with the drier season and clearer skies in Northern Uganda, as presented in Figure 31.

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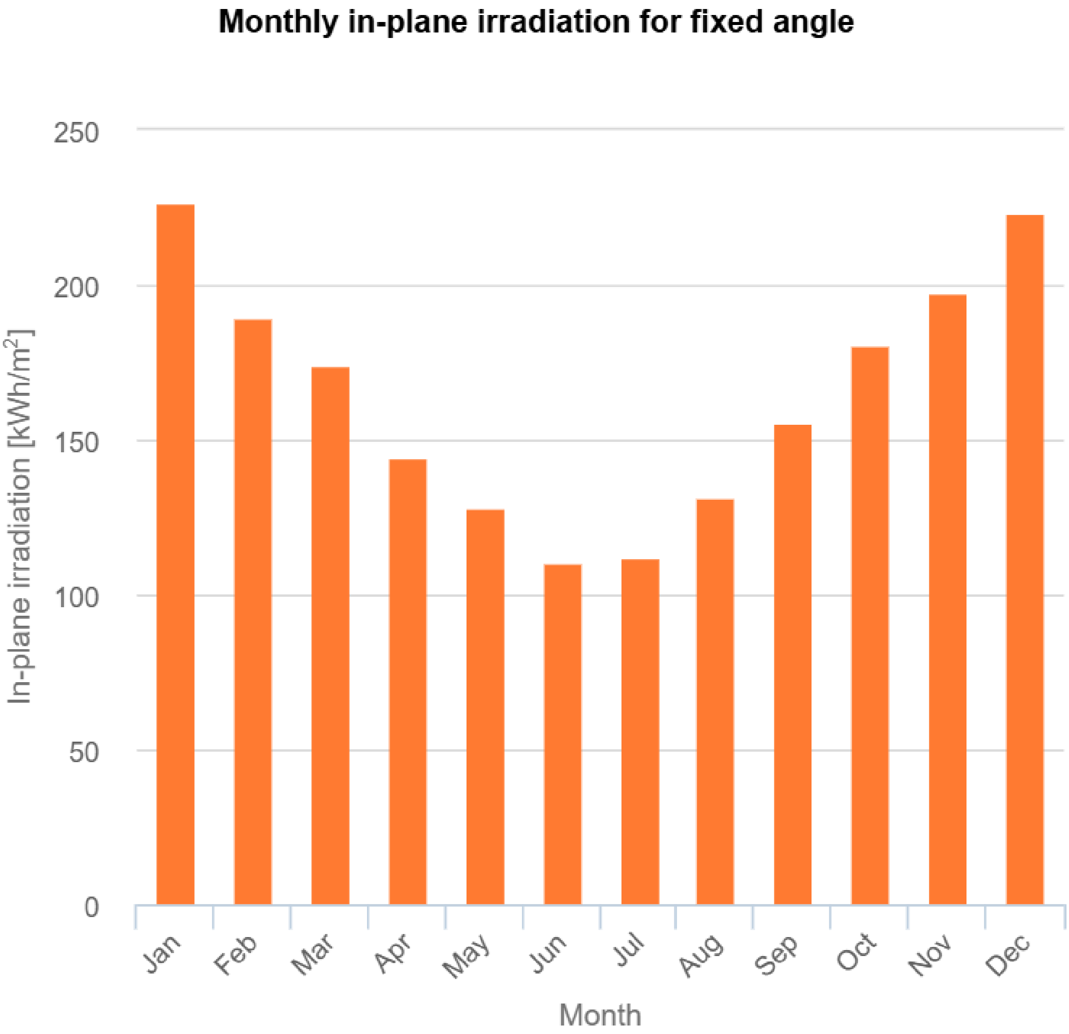

Figure 32. Monthly solare irradiation in Uganda

Recommendations

Based on the scenario-based assessment, the estimated daily electricity demand of the cold room under typical operation (baseline load of 22 kWh/day plus intake-dependent cooling) ranges approximately from 23 to 30 kWh/day, depending on the cultivated area and the share of production routed through cold storage. Using the provided monthly PV output data for Uganda, an 8 kWp system is expected to generate approximately 44 kWh/day during high-solar months (≈5.5 kWh/kWp/day) and about 21–22 kWh/day during the lowest-solar month (≈2.7 kWh/kWp/day). This indicates that the system is generally sufficient to operate the cold room during most of the year. During the lowest-solar period, however, PV production approaches the estimated daily refrigeration demand, meaning that reliable operation will depend on efficient cold-room management and appropriate battery sizing.

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Seasonal complementarity between irrigation and refrigeration strengthens the technical case for integration. The lowest solar yield coincides with the rainy season, when irrigation demand is naturally reduced. As a result, available PV capacity can be prioritized for cold storage during this period. Conversely, during the dry season—when irrigation demand increases—solar production is higher, providing additional generation capacity. This seasonal diversification of loads supports the feasibility of integrating irrigation and cold storage under a shared system.

Furthermore, the system should allow for phased growth and modular cold room capacity, enabling incremental expansion as production volumes and market access improve. This approach reduces upfront investment risk while maintaining flexibility for future scaling. It should also be paired with strengthened market linkages, including aggregation mechanisms, buyer agreements, and coordinated harvesting and delivery schedules, to ensure that increased production and improved storage translate into higher and more stable incomes.

The final system sizing should incorporate a Water–Energy–Food (WEF) nexus perspective, ensuring that water availability, energy generation capacity, agricultural production targets, and post-harvest handling needs are jointly optimized. This integrated approach will help balance seasonal resource variability, improve overall system efficiency, and enhance long-term economic and environmental sustainability.

Once the final demonstration site is selected, the following parameters must be confirmed to define the final sizing of the irrigation and cold storage systems:

- Static water level and borehole depth – to determine the actual vertical lift (total dynamic head component).
- Pipe routing, length, and diameter – to calculate friction losses and refine total dynamic head.
- Required operating pressure at irrigation emitters (especially for drip systems) – to ensure adequate delivery pressure.
- Elevation of storage tank (if applicable) – to account for additional head requirements.
- Final pump selection and manufacturer datasheet efficiency – to refine overall pumping efficiency (η).
- Final crop composition, total cultivated land area, and average daily intake (kg/day) which is also related to market linkages – to validate irrigation demand and cold storage throughput assumptions.
- Cold room final insulation specification, and refrigeration system COP – to verify baseline refrigeration load assumptions.

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- Door opening frequency and usage pattern estimation – to assess infiltration-related heat gains and refine total cold-room energy demand.

4. Discussion and implications for the SUNNY project

The assessment of energy needs, aspirations, and adoption potential provides critical insights for tailoring SUNNY technological solutions to end-user contexts in Rwanda and Uganda. The findings will inform not only current consumption patterns but also preferences, willingness to pay, and potential barriers to adoption. For the SHS solution, besides current consumption patterns, insights into shared use, appliance prioritization, and energy expenditure inform both system design and deployment strategies. For cooking technologies, understanding households' fuel switching behavior and affordability constraints will guide the technology and delivery design, storage solutions, and payment mechanisms. Similar approach will be implemented to evaluate energy needs in Uganda in relation to the other SUNNY technologies. Beyond technology design, the assessment informs broader project activities, including the development of use cases (Task 1.4), ICT-based supervision and monitoring systems (Task 3.3), and the design of business models (WP7) that align with users' financial capacities, thereby supporting higher uptake and sustainable utilization of the technologies.

5. Summary and outlook

This task has made progress in terms of the preliminary assessment to ensure the collection of relevant data for each of the technologies and alignment with the other SUNNY tasks. Initial data collection and preparatory activities are currently underway in both Rwanda and Uganda. Efforts are ongoing to finalize surveys, engage key stakeholders, and analyze the findings to support subsequent project planning and implementation.

The exercise has:

- Assessed the current status of technology solutions and identified requirements to evaluate the suitability of potential upgrades in collaboration with the SUNNY technology partners and local organizations.
- Evaluated data requirements beyond current energy usage to understand future energy use aspirations and support the upgrading of each technology solution.

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- Conducted regular coordination with other task partners to ensure that the energy needs assessment is aligned and supportive of dependent deliverables.

- Rwanda: Designed surveys, conducted pilots, and commenced full-scale implementation.

- Uganda: Mapped the camp context and identified relevant stakeholders to support end-user identification; prepared draft surveys.

Planned activities for the forthcoming months:

- Complete stakeholder identification and implement KIIs for the Uganda camp.

- Reassess data collection needs and methods in Uganda based on KIIs findings and update end-user surveys accordingly.

- Conduct comprehensive analysis of the collected data.

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V. ENVIRONMENTAL REQUIREMENTS SPECIFICATION

This chapter presents the environmental requirements specification as one of the central components of Deliverable D1.3. It first introduces the objective of this component and then outlines the methods used to define environmental requirements and ecodesign-related indicators for SUNNY technologies. This is followed by the presentation of the main results, a discussion of their implications for the SUNNY project, and a brief summary and outlook.

As such, the chapter contributes to the overall objective of the deliverable by translating sustainability-related considerations into a structured set of requirements relevant for the development and adaptation of SUNNY technologies. In this way, it provides an important basis for technology refinement in later project stages and complements the analysis of energy needs and use cases presented in the other core components of D1.3.

1. Introduction and Objective.

Environmental performance of SUNNY energy technologies was assessed through the development of an evaluation framework specifying relevant indicators. The use of Ecodesign KPIs aligns international projects with global sustainability frameworks, including the Paris Agreement, the Sustainable Development Goals (SDGs), and evolving EU Green Deal and circular economy regulations. The following guidelines and KPIs are informed by internationally recognized tools and methodologies that assess product sustainability and circularity. Specifically, they draw from the French Repairability Index, the iFixit Repairability Criteria, the Material Circularity Indicator (MCI) developed by the Ellen MacArthur Foundation, and relevant standards such as ISO 14006 and ISO 20887:2020, which highlights disassembly as part of product development. For projects like SUNNY, which operate at the intersection of innovation, social cohesion, and environmental justice, such indicators are essential tools to deliver meaningful, scalable and responsible impact.

The research project aims to facilitate the livelihoods of displaced and underserved communities through energy solutions. However, in refugee settlements, waste handling infrastructure is often limited. Ecosystems are fragile, and service continuity is vital. Ecodesign KPIs are important to ensure that energy, water, cooking, and storage systems are not only functional and cost-effective but also durable, repairable, circular, and adapted to the local environmental and social realities for every demo site: Mahama Camp, Rwanda, and Bidibidi, Uganda.

To provide a framework for environmental requirement specification, tailored to each

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technology, REFUSE adapted international frameworks to the local context, structured into four key ecodesign categories based on the preliminary data collected through WP1 and WP2. The toolkit includes definitions and design principles to guide the development of sustainable products and services. Two main research questions were addressed: (1) How can energy solutions avoid adding to existing waste and pollution problems in refugee and host communities? (2) What environmental KPIs ensure systems are durable, circular, and repairable under local conditions?

2. Methods

Environmentally conscious development of SUNNY technologies throughout WP3 will be ensured throughout the SUNNY project by:

- Acknowledging a shared definition of eco-design adapted to the local context.
- Grounding performance evaluation on the baseline assessment developed through WP1 research on Bio waste valorization practices and WP2 research on Dry waste handlign and valorisation value chains in Yumbe District, Uganda and Mahama District, Rwanda.
- Providing technical assistance and network support to SUNNY technology providers to improve performance throughout WP3.
- Assessing the effective improvement in environmental standards and in the avoidance of negative environmental externalities throughout WP6.

The Ecodesign Toolkit was designed to help technology providers design and evaluate systems with low environmental impact, improved durability, and stronger circular value. The toolkit includes a range of Key Performance Indicators (KPIs) developed based on existing ecodesign frameworks and on observations from the field. The aim of the Toolkit is to provide a simple set of themes, and indicators adapted to the implementation areas of the SUNNY Project. The Toolkit is structured into four categories, thematic areas grouping a list of KPIs. The categories include:

1.	**Nature-Based Design, Environmental Footprint**	This theme addresses the extent to which the design of SUNNY technologies limits environmental impact on ecosystems, reduces resource use (materials, water, land), and enhances climate adaptation. It prioritizes local, natural, or low-impact materials and designs that integrate well with fragile ecosystems.

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2.	Durability and Repairability	This theme evaluates how well SUNNY technologies are designed for long-lasting use, easy repair with standard tools and accessible documentation, and minimal resource consumption for mainteenance. It prioritizes modularity, availability of parts, and ease of disassembly, contributing to reduced environmental impact over the product life cycle.
3.	Recyclability & End of life Management	This theme measures how well SUNNY technologies are designed for responsible end-of-life handling, including reuse, recycling, and safe disposal. It ensures materials can be recovered locally and hazardous waste is minimized.
4.	Service Orientation	This theme measures how well SUNNY technologies are designed for responsible end-of-life handling, including reuse, recycling, and safe disposal. It ensures materials can be recovered locally and hazardous waste is minimized.

The Toolkit is a simple matrix presenting the 4 themes and the related indicators, in a table where columns present and assess KPIs:

- Criteria - the KPIs relevant to each themed category.
- Grade - the numeric value assigned based on the Evaluation.
- Justification - a descriptive explanation of how the grade was chosen.
- Materiality - the assessment of relevance, significance of this KPI for the solution.
- Weight - Relevance of the KPI based on the Materiality. Automatically calculated.
- Score - Number assessing Grade and Materiality. Automatically calculated.

Grade and materiality respond to two different questions: How well does the solution perform on this dimension? How much does this dimension matter in this specific context? The **Grade** refers to the performance level of a product or solution against a specific sustainability criterion. It is a quantitative score, typically on a scale from 0 to 4, used to evaluate how well a solution meets the defined standards. For example, a solution that uses ≥70% locally sourced materials might score a 4, while one using <10% scores a 0. The **Materiality** refers to the relevance or significance of that criterion in the specific project or context. It determines how important the criterion is for decision-making or comparison across alternatives. Not all KPIs are equally material. For example, recyclability might be more material for electronic systems, while water efficiency is more material in drought-prone areas. This dual structure ensures a better prioritisation of design improvements, avoids misinterpretation (high scores in low-impact areas), and provides a tailored and transparent sustainability assessment.

Designers, engineers, or technical teams were requested to assess grades. They evaluate the

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technical specifications and features of the product against a defined scoring rubric. For example: A solar water pump that uses 70% recycled materials would be graded a 4 on "embodied circularity". Project leads, sustainability managers, or local stakeholders were requested to assess materiality. They decide how relevant each ecodesign criterion is to the specific project, community, or region. For example: In a desert area, water usage may be highly material, while in a flood-prone region, water use may be less critical than corrosion resistance. The main references for using both concepts include:

- GRI Standards: Widely used for sustainability reporting and stakeholder-driven materiality analysis.
- EU Ecodesign Directive and ISO 14062: Address environmental design integration and performance measurement.
- Life Cycle Sustainability Assessment (LCSA): Integrates performance scoring with materiality-based weighting.

The **weight** represents the relative importance of each criterion or category in the final assessment score. While the grade reflects how well a solution performs on a given indicator, the weight adjusts its influence based on contextual priorities (like climate, project goals, user environment). In the toolkit, "weight" is calculated automatically. The weight helps amplify or reduce the impact of certain KPIs. It helps tailor the toolkit to different settings (e.g. durability may weigh more in remote areas). The **Score** is calculated by multiplying the grade and the materiality. There is NO target to reach, each technology provider will witness different outcomes and improvements throughout the project. There is no comparison with other sector providers not between different technologies.

a. Theme 1: Nature-based design, environmental footprint

This category focuses on minimising ecological degradation, limiting negative environmental impact on ecosystems, promoting localised and treaceable material sourcing, reducing toxicity, integrating nature-based and low-tech solutions, and enhancing both climate mitigation and adaptation capacities. Designing technologies using locally sourced, low-impact, and renewable materials significantly reduces the greenhouse gas emissions and environmental degradation associated with long-distance transportation and industrial processing. By avoiding the use of toxic substances and minimising dependence on water-intensive processes, these guidelines help protect fragile local ecosystems and biodiversity, in a context where extreme vulnerability highly affects community members. Moreover, local sourcing does not only mitigate negative environmental externalities. It fosters livelihood creations and local value chain diversification, strengthening. For SUNNY technologies such as biodigesters and hydrogen cooking systems, this approach promotes the use of regionally available materials (e.g. agricultural waste) and supports water-efficient operation of solutions as solar-powered cold storages and irrigation systems.

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Table 17: Description of the elements in the theme Nature-Based design, environmental footprint

Description	Scoring
1.1 Local material sourcing	
This criterion evaluates the proportion of total material mass that is sourced locally (within a defined radius, such as 100 km). Local sourcing reduces transport-related emissions, supports regional supply chains, and builds economic resilience in the community. It also increases traceability and contextual appropriateness of the materials used in design. A project sourcing the majority of its materials nearby will score higher, while heavy reliance on internationally imported goods reduces environmental performance and earns a lower score. *The percentage of material mass locally sourced determines the score.*	≥70% = 4 50–69% = 3 30–49% = 2 10–29% = 1 <10% = 0
1.2 Use of natural/low-impact materials	
This KPI assesses the share of total material weight that comes from environmentally preferable sources that are renewable, biodegradable, and non-toxic. The goal is to shift away from finite, synthetic, or energy-intensive inputs. The indicator is based on the total weight of materials used. It encourages designs that emphasise natural, low-impact resources rather than chemically treated or fossil-fuel-derived components. *The higher the proportion of such materials, the better the environmental outcome.*	≥70% = 4 50–69% = 3 30–49% = 2 10–29% = 1 <10% = 0
1.3 Toxicity potential	
This criterion evaluates how much of the product or system includes hazardous substances defined and listed under the EU REACH Regulation. These materials can cause long-term environmental and health harm. The goal is to substitute such substances with safer, inert, or naturally benign alternatives. Projects that fully eliminate or nearly eliminate these substances are rewarded with top marks, while high reliance on them signals environmental and regulatory risks. *The lower the percentage of mass containing REACH-classified hazardous substances, the higher the score.*	<1% = 4 1–5% = 3 5–10% = 2 10–20% = 1 20% = 0
1.4 Local water risk sensitivity	
This KPI measures the solution's dependence on water resources, particularly in areas of high local water stress. Products or processes that minimise or eliminate process water use are critical for resilience and ecological sustainability in drought-prone regions. Designs using dry processes will receive the highest scores, while those requiring constant or excessive water input are graded lower. *Solutions are scored on a*	Very low or no water use = 4 Low = 3 Moderate = 2 High = 1 Very high = 0

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qualitative basis, depending on their water intensity. No quantitative assessment is included seen the diversity of solutions and scales.	
1.5 Nature-based or low-tech integration	
This criterion evaluates how effectively a solution incorporates natural systems or low-tech, nature inspired design features to minimise environmental impact. Nature-based elements can include passive cooling, rain gardens, vegetative shading, and other designs that mimic ecological processes rather than relying on mechanised systems. The more the product relies on natural or passive mechanisms, the better it supports sustainable infrastructure and climate resilience. A methodology for the evaluation of the impact of nature-based integrations is provided by the EU. *The level of integration determines the qualitative score.*	Extensive = 4 Significant = 3 Partial = 2 Minimal = 1 None = 0
1.6 Climate change mitigation potential	
This KPI measures the reduction in greenhouse gas emissions achieved by the design compared to a conventional baseline. It's directly tied to carbon intensity and the broader climate targets of the Paris Agreement. For example, switching from a diesel generator to solar power represents a strong mitigation intervention. Clear documentation of emissions savings through alternatives or innovations is necessary to earn higher marks. *The percentage reduction in GHG emissions defines the score.*	80% = 4 60–80% = 3 40–60% = 2 20–40% = 1 <20% = 0
1.7 Climate change adaptation support	
This criterion measures how well the design helps communities or systems adapt to climate change impacts such as extreme heat, flooding, or drought. It emphasises resilience-builploding features, like elevated platforms to avoid floods, reflective surfaces that reduce overheating, or water-harvesting systems that increase system independence. Designs that enhance local resilience against climate risks will score highly, especially in vulnerable geographies. *Solutions are graded qualitatively and are based on the designed technology itself, not on its usage and outputs.*	Strong support = 4 Moderate = 3 Limited = 2 Minimal = 1 None = 0
1.8 Footprint of material sourcing	
This KPI checks whether raw materials are sourced from areas of high ecological sensitivity. The goal is to avoid contributing to biodiversity loss, deforestation, or degradation of protected habitats. Traceability and responsible sourcing certifications support better performance. Are all materials, articles necessary for the realization of the technology fully	No risk = 4 Low = 3 Medium = 2 High = 1 Very high = 0

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traced? Is the production value chain certified with internationally recognized standards (e.g. Fair Trade Certification, ISO 20400 self-assessment on Sustainable Procurement, Responsible Minerals Assurance Process Certification)?. Sourcing from unverified international suppliers, especially in ecologically vulnerable zones, automatically ranks the solution as "High" or "Very High" risk. *Sourcing risk is assessed qualitatively as follows.*

1.9 Circularity of material sourcing	
This criterion evaluates the proportion of the total material weight derived from the acquisition of recycled and/or reused inputs from recycled or reused inputs, including both post-consumer and post-industrial content. The goal is to promote circular material flows that reduce reliance on virgin resources, lower environmental impacts, and align with sustainable production principles. High circularity supports zero-waste design strategies by extending the life of materials and minimizing extraction of finite resources. It also reduces energy demand and greenhouse gas emissions associated with primary material production. Moreover, formal recycling and reuse systems foster livelihood creation in the recycling sector, particularly in developing economies, and enable resource valorization by transforming waste into valuable inputs instead of landfill or incineration. To ensure credibility, recycled or reused content should be verified by recognized certification schemes or through auditable supply chain documentation. *The higher the share of recycled or reused material, the better the score.*	≥70% = 4 50–69% = 3 30–49% = 2 10–29% = 1 <10% = 0

b. Theme 2: Durability and repairability

This category ensures that products are built to last, can be easily maintained, and reduce the need for premature disposal, aligning with the principles of resource efficiency and extended product responsibility.
A design that prioritises longevity, modularity, and ease of maintenance leads to a significant reduction in material consumption, emissions, and waste over a product's lifecycle. Durable and easily repairable systems reduce the frequency of replacements, lower logistical demands, and support local capacity for upkeep in far and resource-constrained refugee settlements. Incorporating local repairability and resilience to harsh environmental conditions enhances service continuity, user trust, and cost-efficiency while minimising the project's environmental footprint.
Durable and repairable are "relative" concepts. Within the Yumbe and Kirehe Districts, local repair technicians operate minimal services, counting on a mix of different aspects: knowledge of the technology and its components, tools availability, energy access, financial constraints. Durability is threatened by the complexity of living in isolated rural areas. Specific issues related to the

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geography and lack of services undermine the life expectancy of technologies, facing broad issues that span from the high presence of rats biting electric wires to intermittent heavy rains causing massive soil erosion and flooding.
Together with partners CTEN, the University of Makerere, Practical Action Rwanda, the University of Rwanda, ReFuse interviewed 25+ technicians in Bidibidi Refugee Settlement in the Yumbe District, Uganda, and in Mahama Refugee Camp in the Kirehe District, Rwanda. Most technicians met were men (over 90%). Some of the non representative, non scientifically or statistically gathered information is presented. Only 15% of people interviewed operate in a market stall, 21% owns a workshop or repair space, while 32% operate from home and 9% move around their villages to provide services. The key repair challenges reported include:

1. A lack of spare parts necessary for maintenance, replacement of components (70%);
2. Lack of appropriate tools for dismantling, repairing (70%). Tools - including basing items as screwdrivers - are sometimes rented or borrowed from local networks.
3. Lack of electricity to provide services (65%). Only 10% has regular grid access, 70% have limited access relying on photovoltaic energy or batteries, power banks.
4. The absence of repair manuals (60%), particularly for rapidly developing solutions and new technologies emerging in the market;
5. An excessive cost of spare parts (50%) both for them to access and for customers to afford, often supplied from far;
6. Poor access to information and training (30%) due to the lack of a smartphone or laptop to access repair videos, connectivity issues, language barriers and more;
7. A limited market for repair and maintenance services (30%).

Table 18: Description of the elements in the theme Durability and repairability

Description	Scoring
2.1 Design lifetime	
This criterion assesses how long the system or product is expected to operate effectively in the local environment. It encourages teams to factor in real-world conditions such as UV exposure, dust, humidity, and inconsistent maintenance relevant for remote or humanitarian contexts. Long service life ensures better environmental return on material inputs and reduces the need for frequent replacements. To achieve a top score, teams must use robust materials, test durability under local climate stressors, and document field-proven lifespans. *The expected operational lifespan under field conditions determines the score.*	≥15 years =4 10:14 years=3 5:9 years =2 <5 years =1 <3 years =0
2.2 Ease of disassembly	

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This KPI measures how simple it is to take apart the system to access key components such as filters, wiring, or batteries. Solutions that allow easy disassembly reduce the time, effort, and risk of damage during maintenance. Avoiding glues, permanent seals, or overly complex designs increases repairability and component reuse. Systems with fewer, intuitive disassembly steps score higher. A non-statistically representative survey proved that local technicians have the knowledge to disassemble diverse items including: mobile phones, laptops, radios, solar home systems, photovoltaic panels, solar lamps, batteries, engines and more.

Yet, not all technicians are capable of disassembling all, and most have a limited experience between 1 and 3 years of work (40% of the 25+ technicians met). 24% of technicians learned how to repair from family and friends. 38% are self-taught and count on online videos - when internet is available, they have access to a smart device and electricity is on - to learn. Only 35% participated in a formal Vocational Education and Training opportunity and learned through the support of an NGO. *Grading is based on the number of steps required to access components.*

<10 steps = 4
10:20 steps=3
21:30 steps=2
31:40 steps=1
>40 steps = 0

2.3 Tools required for maintenance and repair

This criterion looks at whether the tools required for field maintenance are standard, affordable, and locally available. Using specialised or proprietary tools creates dependency, increases downtime, and excludes local technicians from carrying out repairs independently. Solutions that use screwdrivers, pliers, and other readily available tools will perform best on this indicator.

All tools standard=4
Mostly standard=3
Standard and proprietary=2
Mostly proprietary=1
All proprietary=0

Technicians met in Yumbe, Kirehe Districts reported owning:

- A screwdriver or a set of such: 22%;
- A multimeter: 17%;
- A hot air gun: 6%;
- A battery tester: 11%;
- Basic manual tools: 7%;
- A soldering gun: 20%.

Scoring is based on tool accessibility.

2.4 Spare parts availability

This KPI assesses how quickly spare parts can be sourced, especially in emergency or low-infrastructure settings. Local stocking, standardisation, and modularity all help improve availability and reduce downtime. Teams should aim to establish local inventories or design systems around readily available components. Interviewed

<1 week = 4
1–2 weeks = 3
2–4 weeks = 2
4 weeks = 1
Not available = 0

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technicians reported that they source spare parts:

- From local shops in their villages (30%);
- Traveling to the main town within the district: Yumbe or Arua in Uganda, Kirehe in Rwanda (65%);
- From moving sellers reaching their villages (35%);
- Ordering them through sales agents (25%);
- Reaching the capital Kampala, Kigali (15%);

Spare part lead time is measured as follows.

2.5 Spare parts cost	
This criterion measures the cost burden of spare parts relative to the total system value. Affordable spares support long-term usability, especially in resource-constrained communities. Consider delivery costs to field locations, not just base price, when grading. *Cost is scored as a percentage of product value.*	<10% = 4 10–20% = 3 21–30% = 2 31–50% = 1 >50% = 0
2.6 Repair documentation	
Clear, accessible repair instructions empower end users and local technicians to perform troubleshooting and repairs independently. Visual or multilingual content, both printed and digital, is crucial for inclusivity. Top scores are awarded when guides include step-by-step visuals, are available offline or via QR codes, and are translated into local languages. Currently, identified technicians acquire knowledge through open access online sources (25%), NGO-offered training (30%), learning from fellow technicians (55%), repair manuals and books (10%) - scarcely available. *Availability and format determine the score.*	Public, free, detailed = 4 Public, free, partial = 3 Available on request = 2 Paid access = 1 No info = 0
2.7 Modularity	
This criterion measures the share of the system that can be repaired or replaced in modules rather than as a whole. Modularity reduces waste, repair time, and total lifecycle cost while enabling system adaptability. Teams should document modular elements and their interfaces to demonstrate this. *Scored by percentage of system designed with replaceable modules.*	≥80% = 4 60–79% = 3 40–59% = 2 20–39% = 1 <20% = 0
2.8 Remote support	
This KPI captures whether the technology provider offers real-time or asynchronous technical guidance via mobile platforms. In remote or underserved areas, WhatsApp or SMS-based support can significantly	Full (diagnostics + guidance) = 4 Partial = 3

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reduce system downtime. Low-bandwidth, offline-compatible resources like troubleshooting trees are strongly encouraged. *Scoring is based on level of remote support.* •	Minimal = 2 One-time only = 1 None = 0
2.9 Upgradeability	
Upgradeability reflects whether the design allows for future improvements without replacing the entire system. This supports long-term adaptability, reduces environmental impact, and enables incremental capacity building. Avoid closed systems that cannot evolve with changing needs or technologies. *Designs are graded based on upgrade potential.*	Fully upgradeable = 4 Mostly = 3 Partial = 2 Minimal = 1 None = 0
2.10 Resilience to environmental conditions	
This KPI evaluates how well the system withstands local environmental stressors such as heat, wind, rain, or corrosion. Using field-tested materials like UV-resistant plastics, rust-proof coatings, and waterproof enclosures ensures reliability and safety. Document IP ratings, stress testing, or real-world validation for a strong score. *Score is based on percentage of components meeting environmental durability standards.*	≥90% = 4 70–89% = 3 50–69% = 2 30–49% = 1 <30% = 0

c. Theme 3: Recyclability and end of life management

This category evaluates how a product or system is designed to support responsible recovery, reuse, and recycling at the end of its life cycle. It addresses environmental and health risks by minimising hazardous waste, while also promoting circular resource flows through reuse, second-life applications, and integration of recycled materials. This category reduces pollution, landfill burden, and the extraction of virgin materials. It promotes circularity by ensuring products can be responsibly dismantled and processed at end-of-life, even in settings where formal waste infrastructure may be limited. SUNNY systems such as SHS, solar batteries, and hydrogen cooking components benefit from these principles by allowing safe handling of e-waste and recovery of high-value materials. Second-life potential and take-back mechanisms ensure cleaner transitions, reducing toxic waste and reinforcing sustainable exit strategies for deployed technologies.

Both Kirehe and Yumbe Districts totally lack sanitary disposal options and formal (public or private) source sorting. Organized solid waste collection does not systemically cover both regions. Informal actors (non-registered companies, individuals lacking permits or formal authorizations) are the only ones operating highly needed collection and sorting services that divert valuable secondary materials, fueling recycling value chains. Their work has a clear

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positive environmental footprint, yet exposes them to financial threats, health hazards, unstable working conditions, community stigma and more. The interconnection between eased recyclability and safe disposal of technologies and social impact is of uttermost importance. End of life handling of mixed municipal, hazardous waste foresees disposal in uncontrolled dumpsites where materials are exposed to weather agents, with probable leaching of materials in soils. Combustion of solid waste in open spaces as well as in informal dumpsites is witnessed in both Uganda, Rwanda. Preventing disposal through ecodesign practices is a compelling moral obligation to mitigate environmental and human health hazards.

Table 19: Description of the elements in the theme Recyclability and end of life management

Description	
3.1 Recyclability	
This criterion evaluates the percentage of the system's total mass that can be recycled through existing local infrastructure. Recyclability, at this lifecycle stage, covers end-of-life handling, ensuring that materials re-enter production loops instead of ending up in landfills or open dumps. Avoiding mixed or composite materials simplifies recycling and reduces processing costs. Designs should document material composition and prove local recyclability pathways to score well. Localizing the concept of recyclability means defining which materials can be diverted based on the knowledge of informal waste collectors, as formal (public or private) source sorting systems do not exist. A range of materials that are gathered by informal networks and sent to valorisation facilities or traded as secondary raw materials is presented for the Yumbe and Kirehe Districts.	
Kirehe District, Rwanda. The market relies on informal scrapyards within and outside refugee settlements, with most traders selling to a larger intermediary who buys and resells large volumes of recyclables, and fewer directly linked to a recycling factory on the way to Kigali. Materials gathered include:	≥80% = 4 60–79% = 3 40–59% = 2 20–39% = 1 <20% = 0
3.2 Reusability, second life potential	
Reusability measures the extent to which components (like casings, wiring, solar panels) can be reused as-is, without significant reprocessing. This indicator also targets the end-of-life stage. It promotes resource efficiency and reduces energy consumption associated with recycling. Durable and standardised designs support repurposing across different applications and user groups. Teams should map potential reuse paths and design for physical robustness to earn higher grades. Similarly, second-life potential refers to the ability of system components to be used in a new function once their primary use ends. For example, batteries that no longer support pumps may still power lights. Systems with inherent adaptability are better suited to	≥50% = 4 30–49% = 3 15–29% = 2 5–14% = 1 <5% = 0

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circular economies. Design teams should outline repurposing options and test component performance in secondary uses. *The score reflects the percentage of reliable components that can be reused directly.*

3.3 Hazardous materials share

This assesses the share of system mass made up of hazardous substances that cannot be locally recycled, reused like lithium batteries, PVC wiring, or components including heavy metals. These remaining materials would necessarily end up in informal dumping sites if not other recovery mechanism is possible. Reducing hazardous content is essential for environmental and human safety, especially where proper disposal is limited. Compliance with local and international regulations, such as the Basel Convention, is a minimum requirement. Clear documentation and material tracking are essential to justify a high rating. *Grading reflects the mass percentage of hazardous materials, deducting the weight of recyclable, reusable mass from the total weight, combining indicators 2.1, 2.2. The indicator differs from 1.3 as Toxicity potential is also possible for materials that are sent to recycling, reused.*	<1% = 4 1–5% = 3 5–10% = 2 10–20% = 1 >20% = 0

3.4 Ease of material separation

This criterion evaluates how easily different materials (like metals and plastics) can be separated during dismantling. Design choices such as avoiding permanent adhesives and reducing joint complexity significantly improve material recovery efficiency. Systems with tool-free access or minimal fasteners will score highest in this area. Refer to Indicator 2.3 to assess the possibility to effectively separate components with locally available tools, therefore excluding industrial, complex separation processes. *The number of steps required to fully separate recyclable materials determines the score.*	<10 steps = 4 10–20 = 3 21–30 = 2 31–40 = 1 40 = 0

3.5 Local disposal/recycling chain

This KPI considers whether adequate and compliant recycling or disposal services are identified locally or regionally. Linking to nearby facilities improves circularity and reduces transportation-related emissions. Stronger scores require demonstrated engagement with waste management actors, possibly under a written agreement. Partnerships or contracts with local recyclers enhance scoring potential. *Scoring reflects proximity and availability of disposal infrastructure for the different materials, elements present in the technology.*	Full local capacity = 4 Partial = 3 Available in region = 2 Only national-level access = 1 None = 0

3.6 Takeback schemes at End Of Life (EOL)

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This measures whether manufacturers or vendors retrieve used products for proper end-of-life processing. Take-back schemes are crucial in humanitarian or rural contexts where users lack access to disposal channels. Including prepaid return logistics or engaging last-mile partners increases viability. Vendors must demonstrate clear pathways for collection, ideally supported by logistics networks. *Grading is based on scheme existence and cost to users.*	Yes, free = 4 Yes, with fee = 3 Informal = 2 None = 0
3.7 Materials, components identification	
This evaluates whether materials are clearly labelled for sorting and recycling. Using global standards and clear identification labels (like ISO 11469 for plastics) improves recovery efficiency and supports waste workers in identifying how to process materials safely and effectively. Visible, standardised material codes directly on the product components are required for full points. *Grading is based on material labelling coverage.*	All parts = 4 Most = 3 Partial = 2 Minimal = 1 None = 0
3.8 EOL documentation	
Clear EOL documentation supports users and recyclers in dismantling and recycling systems responsibly. This includes printed and digital guides made accessible in local languages, including illustrations or video tutorials. Clear EOL documentation enables informed disposal, reuse even in low-tech contexts. Content should be shared openly, e.g. printed or via QR codes, websites, or messaging platforms. *Scoring reflects the detail and accessibility of EOL guides.*	Public and detailed=4 Public basic=3 On request=2 Minimal=1 None=0

d. Theme 4: Service orientation

This category examines the degree to which a technology is embedded in a service-based delivery model rather than being sold as a stand-alone product. Service orientation shifts the focus from ownership to access, prioritising long-term functionality, preventive maintenance, and lifecycle support. In low-resource or humanitarian settings, where spare parts, technical skills, and formal disposal pathways are limited, service-based approaches can be critical for reliability, affordability, and sustainability.

Well-designed service models extend system lifetimes, avoid premature abandonment, and reduce environmental burdens by ensuring that equipment is repaired, upgraded, or recovered before reaching end-of-life. They also strengthen local economies through job creation, skill development, and the retention of value within communities. For SUNNY technologies—such as solar-powered cold storage, irrigation pumps, or hydrogen stoves—service-based delivery can enable shared access, build trust, and embed circularity into the business model itself. Moreover, they reinforce the connection between technology partners and customers.

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In both Yumbe (Uganda) and Kirehe (Rwanda), examples include solar irrigation systems managed by farmer cooperatives with pooled maintenance funds, cold storage units run as community services with trained local operators, or hydrogen cooking systems leased to households with routine servicing included - thanks to a network of local technicians. These models reduce the burden on individual users to troubleshoot complex systems, while also ensuring that components are refurbished or replaced in a timely manner.

Table 20: Description of the elements in the theme Service orientation

Description	Scoring
4.1 Service model	
Assesses whether the technology is provided through an integrated service package—covering installation, operation, and long-term support—rather than a one-off sale. Strong models often involve cooperatives, NGOs, or local social enterprises that remain locally accountable for performance over time. This approach reduces downtime, prevents improper handling, and helps ensure safe end-of-life recovery. In Yumbe, for instance, some PAYG solar companies manage customer relationships through village-based agents, guaranteeing both functionality and proper battery disposal. *Grading is based on the level of service integration and delivery model.*	Full service (including maintenance, upgrades)=4 Partial service (e.g. only O&M)=3 Product + optional service contract=2 Product sales with informal support=1 Product only=0
4.2 Maintenance contract	
Evaluates the existence and accessibility of formal agreements for scheduled servicing and repairs. These contracts provide users with predictable costs, clear response times, and guaranteed access to skilled technicians. In rural Rwanda, for example, cooperative-managed cold rooms with mandatory, scheduled maintenance agreements have shown higher uptime and lower failure rates than individually owned units without such arrangements. *Grading is based on how formalised and accessible the maintenance contract is to users.*	Mandatory standard contract=4 Standard optional contract=3 Available upon request=2 No formal standard contract=1 No agreement=0

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4.3 Buy-back schemes	
Examines whether providers have mechanisms to retrieve systems or components at end-of-life, ensuring that valuable parts are reused or recycled, and hazardous materials are not abandoned in local dumpsites. In contexts where no formal waste infrastructure exists, such as Yumbe or Kirehe, this may involve collection points in trading centres or scheduled recovery visits by the supplier's logistics partners. *Grading is based on the extent and formalisation of buy-back or recovery practices.*	Formalised scheme: 4 Partial buy-back (limited components or locations): 3 Informal practices only: 2 None: 0
4.4 Pay-per-use and leasing models	
Considers the availability of access-based business models that reduce upfront costs for users, such as leasing irrigation pumps to farmer groups during peak seasons or charging cold storage users per crate stored. These models are especially effective in low-income or refugee-hosting communities, where capital investment is a barrier but demand for reliable services is high. *Grading is based on the availability, maturity, and uptake of pay-per-use or leasing models.*	Standardised offering: 4 Available on request: 3 Piloting only: 2 Minimal user uptake: 1 None: 0
4.5 Warranty Duration	
Looks at the duration and terms of guarantees provided by the manufacturer or service provider, signalling confidence in product quality and a commitment to resolving issues after deployment. In humanitarian supply chains, warranties covering both parts and labour can be critical in ensuring systems remain operational beyond the initial funding cycle. *Grading is based on the length of the warranty offered for the system or product.*	≥5 years: 4 3–4 years: 3 2 years: 2 1 year: 1 <1 year or none: 0
4.6 Components replacement services	
Assesses how quickly and efficiently faulty components can be replaced, minimising downtime for users whose livelihoods may depend on the technology. In Yumbe, where agricultural output is highly seasonal, delayed pump repairs can result in missed planting windows; in such cases, service agreements with local spare-part depots significantly improve resilience. *Grading is based on the typical turnaround time for component replacement, estimated as an average for the different components present in the technology.*	<1 week: 4 1–2 weeks: 3 2–4 weeks: 2 4 weeks: 1 None: 0
4.7 Remote monitoring	

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Evaluates the use of tools—such as SMS-based alerts, mobile apps, or IoT sensors—that allow for early detection of faults, performance tracking, and reduced need for on-site visits. In Kirehe, solar cold rooms with remote temperature monitoring have helped operators act before spoilage occurs, avoiding significant food loss. *Grading is based on the type and depth of remote monitoring functionality provided.*	Comprehensive (real-time alerts, dashboard): 4 Partial (scheduled checks): 3 Basic (e.g., SMS or manual): 2 Minimal (ad hoc calls only): 1 None: 0
4.8 Service impact on lifetime	
Assesses the documented effect of service provision—through preventive maintenance, upgrades, and user training—on extending the operational life of the system. Where providers remain actively engaged, systems tend to operate for years longer, reducing the need for premature replacements and lowering the volume of waste requiring management. *Grading is based on the documented increase in system lifetime due to the service model.*	≥50% extension: 4 30–49%: 3 10–29%: 2 <10%: 1 No documented impact: 0

3. Results

The baseline Ecodesign evaluation highlights significant variability among the five technology providers, reflecting different maturity levels in environmental integration and local adaptability. Each spider graph presented in the Deliverable illustrates a distinct environmental performance profile across the four thematic categories — *Nature-Based Design & Environmental Footprint, Durability & Repairability, Recyclability & End-of-Life Management,* and *Service Orientation.*

Akofresh (Solar Cold Storage):
Akofresh demonstrates balanced performance across all categories, particularly in *Durability & Repairability* and *Service Orientation*. The system benefits from modular design and local repair potential, with accessible components and a community-based service model. However, *Nature-Based Design* indicators reveal limited use of low-impact or recycled materials, suggesting room for improvement in material sourcing and embodied circularity. Future work under WP3 should focus on integrating locally available insulation materials and enhancing the traceability of components.

Metanogenia (Biogas Systems):
Metanogenia scores highest in *Nature-Based Design*, reflecting its strong reliance on

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local and natural inputs — notably agricultural residues — and its inherent circularity in waste-to-energy conversion. Nonetheless, the toolkit highlights weaknesses in *Durability & Repairability* due to the limited standardisation of components and lack of documented repair procedures. Integration with local vocational programmes and improved modularity could substantially enhance long-term resilience and community ownership.

Solektra – Irrigation Systems:
Solektra's solar irrigation units show medium-to-high performance in *Durability* but modest scores in *Environmental Footprint*. Metal-based structures provide robustness yet reduce recyclability and increase embodied emissions. Local assembly and service contracts in Yumbe can strengthen their *Service Orientation*, but future iterations should explore hybrid structures using lighter and recycled materials to reduce transport and lifecycle impact.

Solektra – Solar Home Systems (SHSs):
The SHS units perform well in *Service Orientation*, benefiting from existing PAYG (pay-as-you-go) models that support long-term operation and local maintenance. Yet, *Nature-Based Design* remains limited due to imported components and lack of local sourcing. Their small size and modular nature, however, represent an opportunity for integrating reuse and take-back schemes, which will be refined under WP3 and WP6 to enhance recyclability and reduce electronic waste.

Solhyd (Hydrogen Cooking Systems):
Solhyd's technology exhibits strong innovation potential but low baseline scores in *Nature-Based Design* and *Recyclability*. The current design relies heavily on imported metallic components with low local circularity potential. Nevertheless, *Service Orientation* and *Durability* are promising, reflecting well-engineered components and stable performance under stress conditions. The next development phase should prioritise substitution of non-recyclable materials and define take-back and end-of-life strategies.

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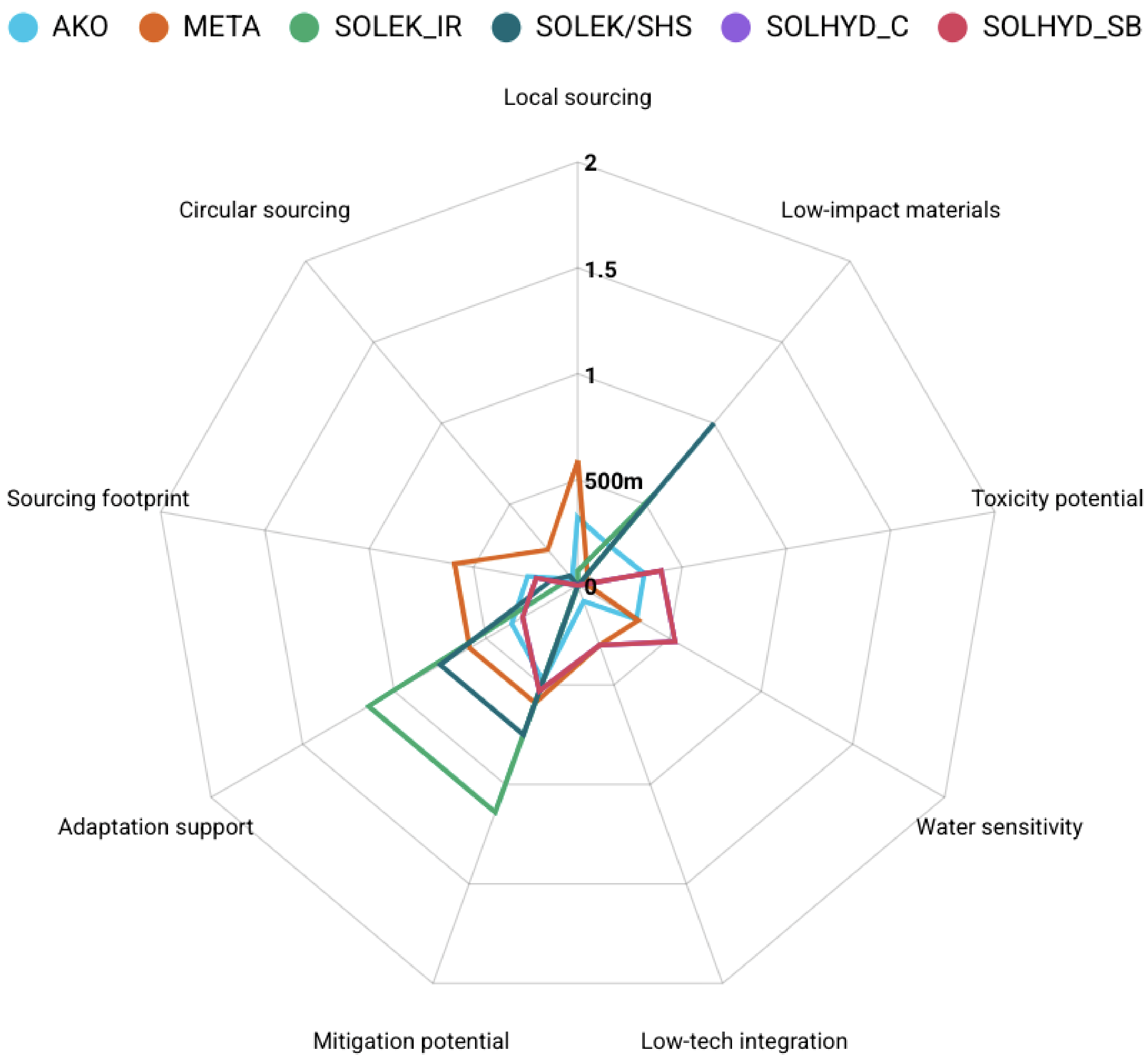

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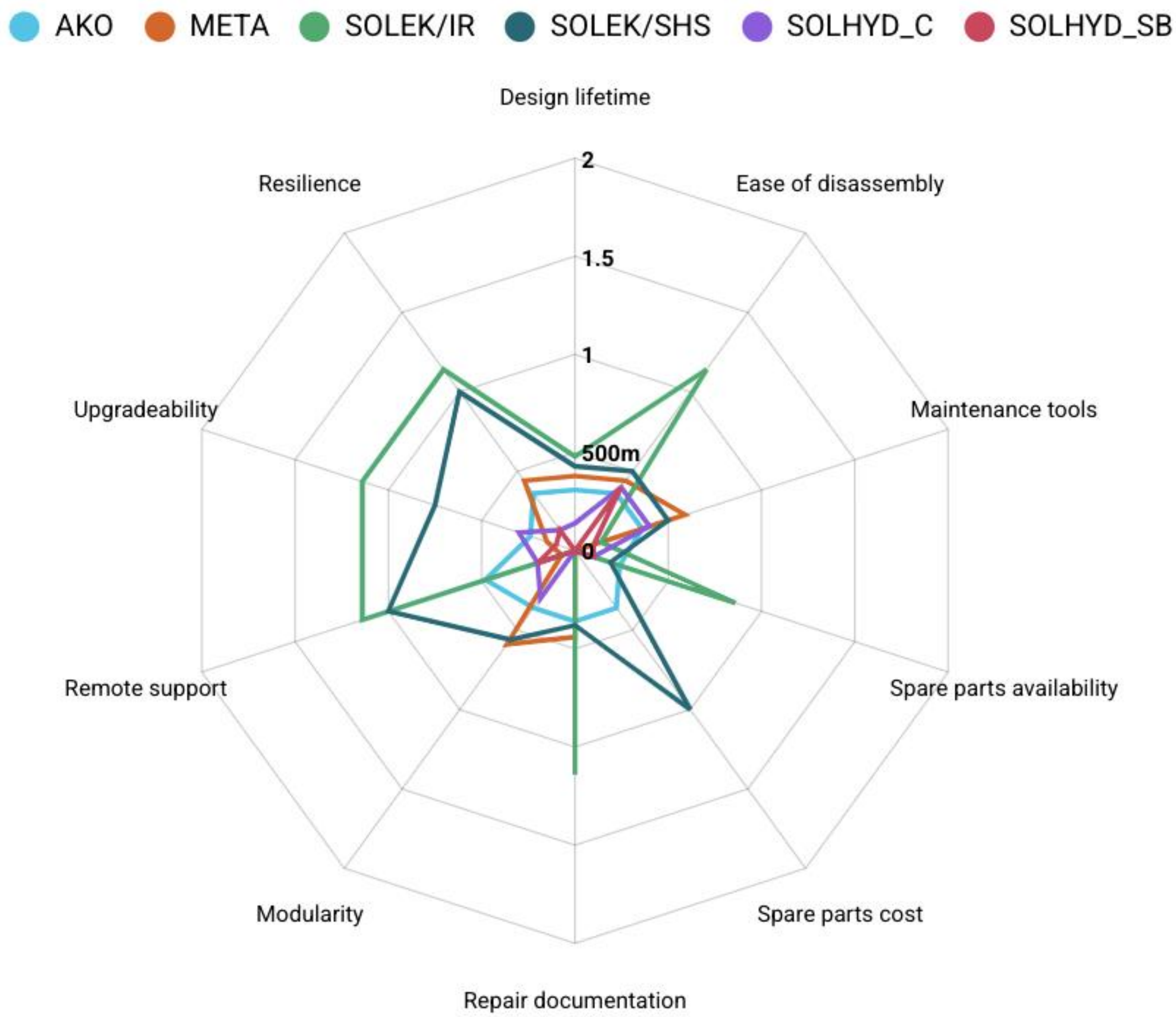

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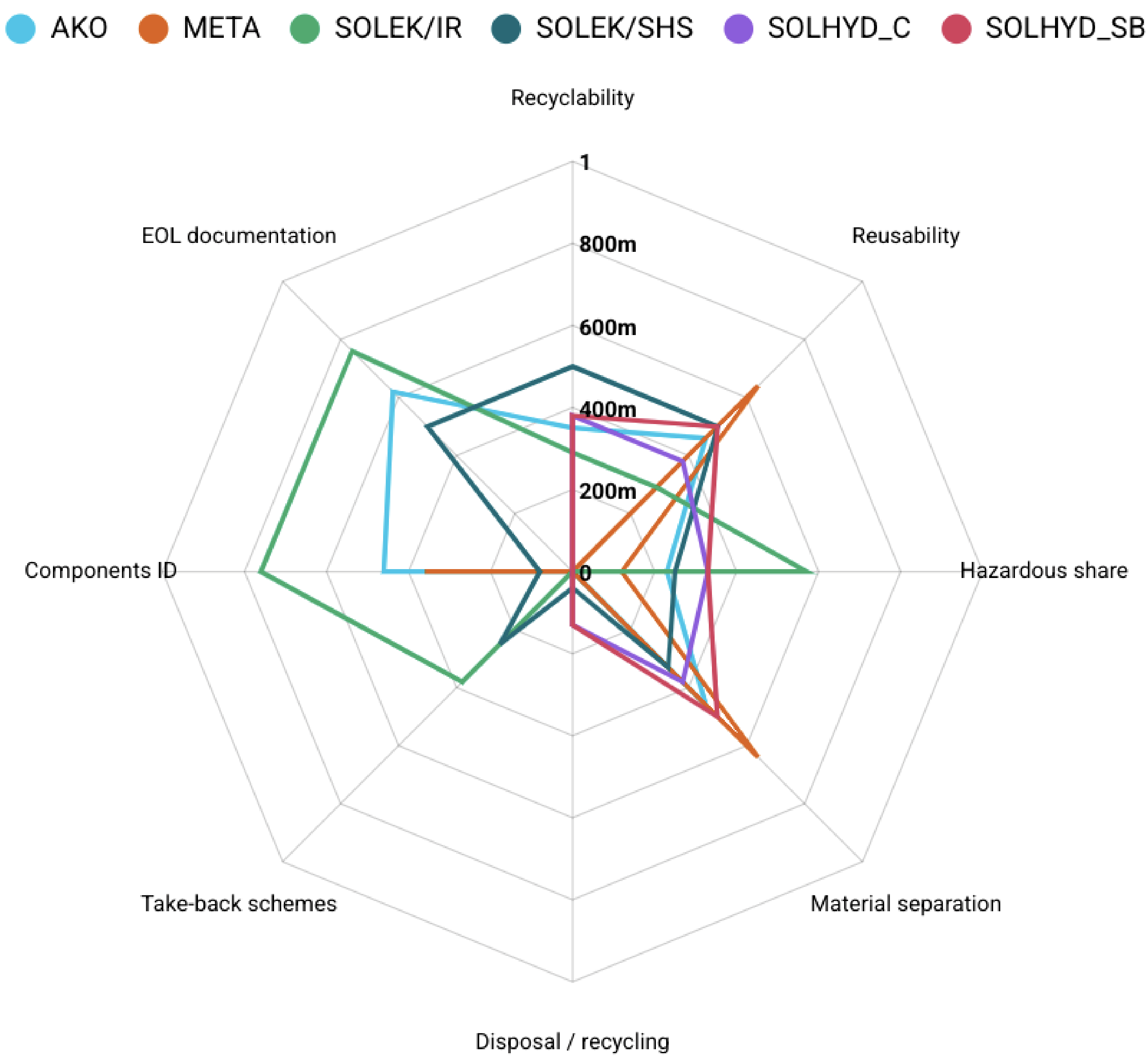

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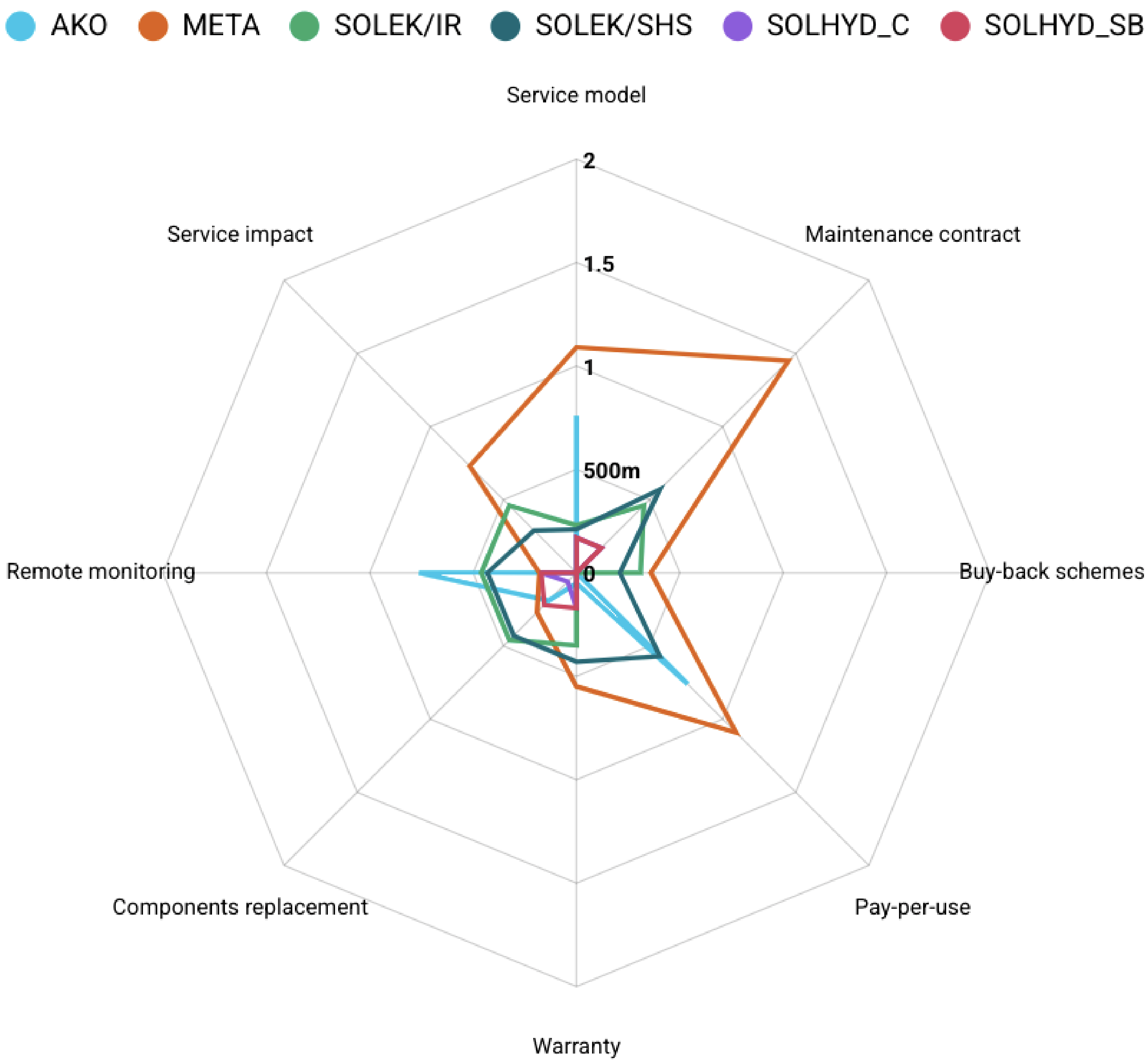

4. Discussion and implications for the SUNNY project

Overall, the results confirm the toolkit's capacity to differentiate environmental maturity among solutions while guiding targeted improvements. The application of materiality weighting proved effective in adapting the evaluation to local contexts, ensuring that indicators such as *repairability, spare-part availability,* and *service delivery models* are prioritised in fragile environments like Mahama and Bidibidi. These findings will directly inform WP3 (Technology Adaptation) and WP6 (Evaluation Processes), ensuring that SUNNY's technological portfolio evolves towards context-responsive circularity and environmental resilience.

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5. Summary and Outlook

The baseline Ecodesign assessment, conducted through the REFUSE Environmental Requirements Specification toolkit, establishes the first harmonised sustainability benchmark for SUNNY technologies. The exercise has:

- Validated the relevance of four thematic areas for humanitarian energy solutions;
- Demonstrated the usability of a materiality-based evaluation integrating both global standards and local constraints;
- Provided baseline spider graphs serving as reference points for performance improvements during WP3 and WP6.

The forthcoming phases will:

- Align identified gaps with the circular value-chain analysis in WP2.3;
- Support technology partners in adopting design improvements and local sourcing strategies;
- Monitor environmental performance during pilot implementations in Rwanda and Uganda;
- Refine the toolkit into a decision-support tool for procurement and scaling of low-impact technologies across future SUNNY sites.

Ultimately, the approach ensures that environmental sustainability becomes a measurable, adaptable, and iterative dimension of SUNNY's technological innovation — embedding ecodesign principles from prototyping to deployment.

6. Literature

- EU Ecodesign Directive (Directive 2009/125/EC)
- ISO 14006:2020 – Environmental management systems: Guidelines for incorporating ecodesign
- ISO 14062 – Integration of environmental aspects into product design and development
- ISO 20887:2020 – Sustainability in buildings and civil engineering works: Design for disassembly and adaptability
- Ellen MacArthur Foundation, *Material Circularity Indicator (MCI)*
- GRI Standards – Global Reporting Initiative: Materiality and sustainability reporting
- iFixit Repairability Index
- French Repairability Index (Indice de Réparabilité)
- Life Cycle Sustainability Assessment (LCSA) framework
- Basel Convention on the Control of Transboundary Movements of Hazardous

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Wastes and Their Disposal

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VI. USE CASES

This chapter presents the use cases as one of the central components of Deliverable D1.3. It first introduces the objective of the use-case work and then outlines the methods used for their development. This is followed by the presentation of the use cases, and a brief summary and outlook. The complete description of all use cases is part of the annex.

1. Introduction and Objective

The goal of this document is to describe the use cases to be implemented in each SUNNY demonstration site: (1) the Mahama refugee camp and local host community in Rwanda and (2) the Bidibidi refugee settlement, local farmers, and population in Uganda.

In the context of Horizon Europe projects, Andres et al. (2023, 442) define a use case as "a sequence of transactions that yields a measurable result of value for an actor". The system performs a use case when an actor uses the system. Usually, a system's complete functionality is made up of several use cases, which in turn contain a range of scenarios that describe a set of possible actions.

Use cases are defined during the initial stages of the SUNNY project to provide a general orientation. As such, they are subject to changes over the duration of the project. The use cases are listed in Table 21.

Table 21: Overview of use cases in the SUNNY project

#	Technology	Lead Partners	Location	Use Case
1	Solar Home Systems	SOLEK	Rwanda	Multi-Household Solar System for Electricity Access in Off-Grid Communities
2	Hydrogen Cooking	SOLHYD, SOLHYDAIR	Rwanda	Valorise locally produced hydrogen for clean cooking through tailored hydrogen cookstoves and develop low-cost, frugal storage solutions
3	Biogas Production	META	Uganda	Low-tech biogas plant for communal use
4	Agricultural produce refrigeration	AKO	Uganda	Refrigerated food storage unit with improved remote operation through IoT
5	Sollar irrigation system	SOLEK	Uganda	Smart solar irrigation system to improve water efficiency and increase yields

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2. Methods

Guidelines for use cases in Horizon Europe projects are provided by the standard IEC 62559-2 (IEC 2015). Based on this standard, the BRIDGE use case repository (Alacreu et al. 2021) is an attempt to standardize and collect use cases (essentially energy-related activities or interventions) from European projects.

An important limitation of the template for the BRIDGE repository is that it is primarily geared towards European contexts. Activities related to "energy access", which are highly relevant in the SUNNY context, are not sufficiently included. Furthermore, the SGAM model from the standard IEC 62559-2, which is used to describe the system architectures of the demo solutions, is purely technical and does not reflect behavior and usage patterns or the interaction of users with the system (and the resulting consequences for the business case).

The SUNNY project is mission-driven and interdisciplinary rather than purely technical. Energy is only the means to an end such as livelihood and sustainable development. Therefore, while we use the IEC 62559-2 standard as a general guideline, we have chosen to deviate from it in some aspects. We adapt the existing approach to the characteristics and requirements of the SUNNY contexts, adding non-technical categories that are important for a full understanding of the SUNNY use cases. The following categories were added to the template:

- Socio-economic, ecological, and business objectives;
- User story; Ecological KPIs from REFUSE's Ecodesign Toolkit;
- Socio-economic, environmental, and business use case conditions;
- Socio-economic and business requirements.

Data for this deliverable is collected through workshops with the technical partners in the SUNNY project.

3. SUNNY use cases

This section presents excerpts from the use case drafts developed for this deliverable. For the full template, refer to the annex.

a. Rwanda: Solar Home Systems

1) Name of the use case:

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"Multi-Household Solar System for Electricity Access in Off-Grid Communities"

2) Short description:

The modular Solar Home System (SHS) concept is designed to enhance energy access and affordability for refugee and host communities in Rwanda. The improved SHS transitions from the earlier H2G and H3G versions (76 Wh) to a higher-capacity 150 Wh modular system. This enables connection of small appliances and shared use among several households. The design integrates LUT's new IoT-enabled PCB, allowing remote monitoring, performance analytics, and fault detection. The improved solution extends the scope of an individual SHS to serve five households. This enables investment costs to be shared, resulting in a reduction of 75% in investment costs per household for equal loads. Moreover, SUNNY will implement innovative financing models, such as pay-as-you-go systems, microloans, possibility to have different tariffs, subsidies, and cross-subsidies to make SHS even more accessible for communities with limited financial resources.

The SHS solution is informed by socio-economic and affordability surveys, currently being conducted across Mahama refugee camp and host communities. These surveys aim to identify energy behaviors, willingness to pay, and affordability thresholds. Eco-design and sustainability KPI development ensure that the SHS model aligns with circular economy principles.

3) User story:

- As a resident of Mahama refugee camp, I want a solar home system to get access to electricity.
- As a resident of Mahama refugee camp, I want to switch to renewable electricity to improve the air quality in and around my family's home.
- As a resident of Mahama refugee camp, I want a low-cost solar home system so that I can afford it.
- As a resident of Mahama refugee camp, I want to share the cost of a solar home system with my neighbours so that I can afford it.

4) Narrative of the use case:

The SHS are an improvement on an existing system and have already been installed in 5 refugee camps by SOLEKTRA. Solar home systems have made significant strides in providing clean and reliable energy to households in off-grid and rural areas. SHS typically consist of photovoltaic (PV) panels, a battery storage unit, and various electronic components to distribute the generated energy. An important limitation to their developments is capacity: Current designs are limited to serving individual households and do not allow for system extensions to satisfy growing energy needs.

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SUNNY will provide a modular solution through which the storage capacity is increased from 76 Wh (current state of the art) to 150 Wh. The improved solution extends the scope of an individual SHS to serve up to five households. Thus, it bridges the gap between SHS and minigrids, which are often too costly and require extensive organisational efforts. The resulting synergies allow for a connection of households with basic loads, which currently is uneconomic and simultaneously expands the maximal loads a SHS can provide to an individual household, beyond what is currently possible. Maintenance and Support: Irregular intervention by maintenance technicians leads to longer downtimes and shorter system lifespans. To remedy this, IoT (Internet of Things) technology will be integrated to remotely monitor system performance, diagnose issues, and provide timely maintenance. The use of IoT functionality will go beyond monitoring through the control of different load levels at different times (e.g., shared utilisation of basic loads and alternating access to higher loads). Knowledge transfer to technicians and users will also contribute to this challenge.

Recent improvements in SHS includes: i) Efficiency: Advances in PV technology have improved the efficiency of solar panels, allowing them to capture more sunlight and convert it into electricity. ii) Battery Storage: Lithium-ion and other advanced battery technologies have increased energy storage capacity and lifespan, ensuring uninterrupted power supply even during cloudy days or nighttime. iii) Energy Management: Smart controllers enable efficient energy distribution, optimising power usage and extending the lifespan of batteries. iv) Appliance Compatibility: Modern solar home systems are designed to power a range of appliances, from LED lights and mobile chargers to fans and small televisions.

- Business Actors: SOLEK (System Owner), Local Technicians, Local Community/Household Users, Mobile Money Providers (MTN/Airtel), LUT (IoT Data Management Partner)
-

These actors define and sustain the SHS business model: SOLEK designs and operates the systems; LUT provides IoT data management; local technicians ensure after-sales service; users pay for energy through mobile money; and telecom partners process transactions.

- Operator: SOLEK Backend Team / PAYG Operator

Operates the PAYG platform, activates and monitors devices, processes user data, and coordinates maintenance responses.

- Logical Actor: PV Production Unit (Solar Panels), Storage Unit (Battery), IoT System

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(PCB + Modem), Distribution Line

Together these logical actors form the SHS hardware ecosystem: panels generate energy, batteries store it, the IoT system monitors and reports performance, and the distribution line connects multiple households in a shared system model.

5) Project KPIs and reference to use case objectives

Table 22: Project KPIs and reference to use case objectives – Solar Home Systems in Rwanda

Project KPIs			
ID	***Name***	***Description***	***Reference to mentioned use case objectives***
1	CAPEX reduction compared to existing alternative	Target: 75%/household	Increase access to affordable and reliable energy for refugee and host households.
2	OPEX reduction compared to existing alternative	Target: 60-70%/household	Increase access to affordable and reliable energy for refugee and host households. Test shared-use PAYG models to lower per-user energy costs.
3	Percentage increase in lifetime of products used in the demonstrator locations	Target: 40%	Promote circular-economy principles through eco-design supported by HUDARA. Extend equipment lifespan and minimize electronic waste through real-time monitoring and preventive maintenance.
4	Storage capacity enhancement of the SHS	Target: From 76 to 150 Wh	Demonstrate modular upgrade capacity from 76 Wh to 150 Wh and assess shared-use configurations among households.
9	GHG emissions mitigated with SUNNY solutions	Target: 0.5 tCO2eq/year *500 users	Reduce reliance on kerosene and diesel generators, cutting household CO_2 emissions by approximately 0.5 tons/year per unit.
17	Number of people benefiting from an enhanced access to energy	Target: 500	Increase access to affordable and reliable energy for refugee and host households.
23	Reduction of respiratory diseases due to solar lighting, and cleaner cooking fuels	Target: 50%	Reduce reliance on kerosene and diesel generators, cutting household CO_2 emissions by approximately 0.5 tons/year per unit and improving air quality.
25	Percentage of energy solutions replaced by clean technologies in the demonstration sites	Target: 10%	Reduce reliance on kerosene and diesel generators, cutting household CO_2 emissions by approximately 0.5 tons/year per unit.

6) Diagram of the use case

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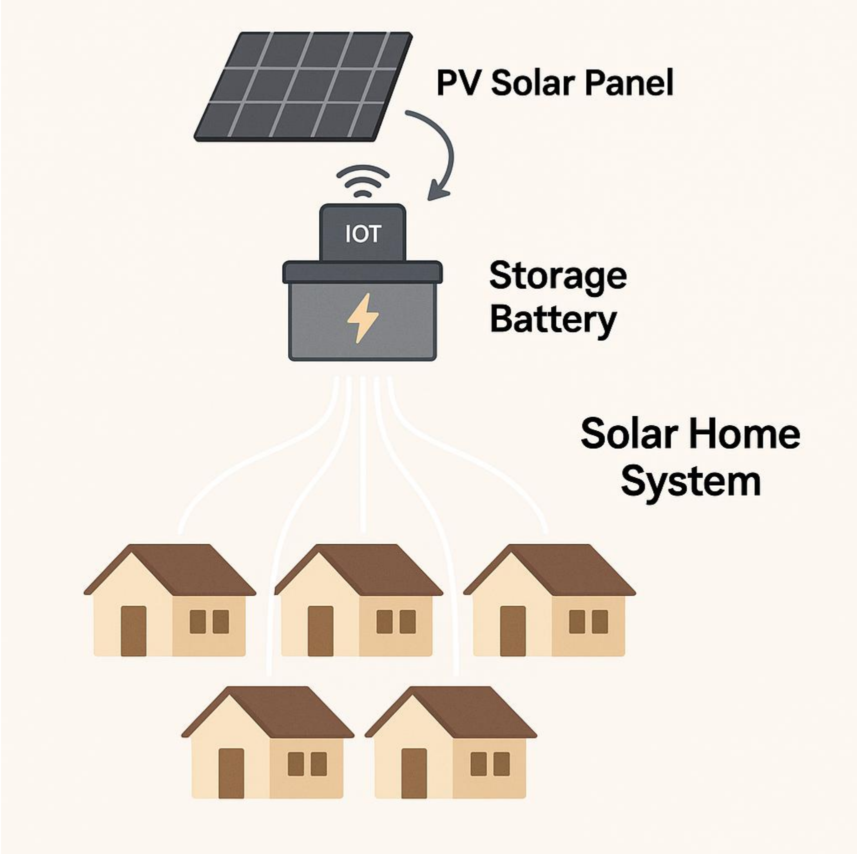

Figure 33:Schmatic representation of the use case: Multi-Household Solar System for Electricity Access in Off-Grid Communities

b. Rwanda: Hydrogen cooking

a) Name of the use case:

"Valorise locally produced hydrogen for clean cooking through tailored hydrogen cookstoves and develop low-cost, frugal storage solutions."

b) Short description:

Most of the traditional cooking solutions rely on liquefied petroleum gas (LPG), wood and charcoal, which leads to high CO2 emissions and a major health hazard. Solar hydrogen clean cooking combines the benefits of existing alternatives (solar cookers, biogas) and LPG, with the added benefits of local off-grid production capacities and low-cost energy storage solution, enabling to accelerate the spread and uptake of clean cooking technologies. The starting point is a stand-alone, low-maintenance and safe hydrogen panel producing hydrogen out of sunlight and water collected from airborn humidity . The hydrogen gas is temporarily stored at low pressures in proximity to the production site. This gas can be burned in tailored hydrogen cookstoves using specific hydrogen diffusion burners. Gas transport from the production location to end-user can be

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achieved via a microgrid system (underground tubing) or with mobile gas bags. This unique technology will be further refined and adapted to the local African context through a combination of design considerations for a low-tech low-pressure cookstoves, storage and transport solutions. Local distribution will be performed from a small hydrogen production station by filling tire tubes or gas bags, while leaving room for new contextual insights and product modifications by local stakeholders. A flexible-volume, mobile hydrogen storage solution combined with local fuel production and innovative payment models such as leasing and PAYG will enable households to reliably secure the basic need of having Fuel For A Day. meet end-user acceptance, the design of the hydrogen technology and appliances will be adapted and improved by co-creation. This participatory user-centric design process will result in a user-friendly, robust, low-tech and low-cost application of the hydrogen technology transferring solar energy to the cookpot.

c) User stories:

- As a resident of Mahama refugee camp, I want to switch to a clean cooking fuel to improve the air quality in and around my family's home.
- As a resident of Mahama refugee camp, I want to switch to a renewable, low-cost fuel so that I no longer have to buy expensive LPG.
- As a resident of Mahama refugee camp, I want a clean cooking stove that functions like the one I am used to so that I do not have to change my habits and can keep following my cultural requirements and traditions.
- As a resident of Mahama refugee camp, I want an efficient and fast cooking stove to limit the time spent cooking meals every day
- As a resident of Mahama refugee camp, I want to switch to a locally produced clean cooking fuel to limit the time spent collecting firewood, or time spent to go and buy charcoal or LPG
- As a resident of Mahama refugee camp, I want to be able to buy variable volumes of hydrogen gas depending on daily need and purchasing capacity, to be able to also cook on the days with minimal income and always having Fuel For A Day
- As a resident of Mahama refugee camp, I want to share a cookstove with other households or use a community kitchen to lower the or avoid the cost of buying (at once or spread over a longer period) a hydrogen cookstove myself
- As a resident of Mahama refugee camp, I want to use a clean cooking system so that I can help combat deforestation, global warming and climate change

d) Narrative of use case

Most of the traditional cooking solutions in Sub-Sahara Africa rely on liquefied petroleum gas (LPG), charcoal and wood, which lead to high CO2 emissions and a major health hazard. Solar hydrogen combines the benefits of existing alternatives (solar cookers,

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biogas) and LPG, with the added benefits of local off-grid production capacities and low-cost energy storage solution, enabling to accelerate the spread and uptake of clean cooking technologies. The main problems associated with the introduction of innovative cooking systems are i) Social acceptance of the solution by end-users. To remedy this problem, SUNNY will implement two types of cookstoves: existing LPG stoves will be refitted in hydrogen compatible stoves, and new cookstoves will be designed to be usable with hydrogen, biogas, and LPG. In this way, end-users will not have to change their habits completely, targeting positive feedback from users of over 80% for single gas cookstoves; ii) High upfront costs. In SUNNY, refitting existing cookstoves aims at reducing upfront costs for end-users by 80%. In addition, a new low-tech storage solution using tire inner tubes will be researched and developed with the aim to reduce the storage costs by 90%. Moreover, innovative financing mechanisms such as leasing schemes, pay-as-you-go models or microcredits will be developed to overcome the problem of high upfront costs. Furthermore, in the case of refugee camps , the significant operating costs, such as distribution of LPG in refugee camps in Rwanda, are borne by humanitarian organisations such as the UNHCR. With the hydrogen solution, the operating costs are expected to be close to zero at the end of the project.

Hydrogen solar panels are a patented technology developed by SOLHYD that absorbs water out of the air during the night and produces hydrogen by harnessing solar energy during the day. The starting point is a stand-alone, low-maintenance and safe hydrogen panel producing hydrogen out of sunlight and airborne humidity. The hydrogen gas is temporarily stored at low pressures in proximity to the production site. This gas can be burned in tailored hydrogen cookstoves using specific hydrogen diffusion burners. Gas transport from production location to end-user can be achieved via a microgrid system (underground tubing) or with mobile gas bags. A solar hydrogen panel can be adapted to a specific climate by tuning the water vapor collection (most critical in dry climate) and the solar hydrogen splitting functions (most critical in less solar regions). This unique technology will be further refined and adapted to the local African context through a combination of design considerations for a low-tech low-pressure cookstoves, storage and transport solutions. Local distribution will be performed from a small hydrogen production station by filling tire tubes or gas bags, while leaving room for new contextual insights and product modifications by local stakeholders. Within SUNNY, this design of the existing multi-burner cookstoves will be modified for low-tech single and multi-fuel stoves providing the robust safety inherently required in hydrogen systems. However, the gas flow and burner mechanism of a propane stove cannot be used with hydrogen gas. Hence, research and experiments will be conducted to determine the modified design that best assures safety and reliability in the burning of hydrogen gas within a domestic environment. The safe handling and burning of hydrogen gas are paramount considerations in the hydrogen cooking design: the burner

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muffles the sound produced by ignition and creates an even flame spread. Additionally, flame arresters and blowback devices are installed on the gas storage side for guaranteed safety. The technical upgrades of the hydrogen panels performed during the project will be the following: i) incorporation of sensors in the panels for remote monitoring (from Europe) of the performance of the hydrogen panels; ii) practical evaluation of an original idea for short distance low pressure hydrogen transportation combining a small hydrogen production park, filling station of inner tubes of tires of trucks and tractors, and connections to hydrogen cookstoves; iii) Admixing of solar hydrogen with other fuels like biogas; iv) Design of a multifuel cookstoves running either on hydrogen, biogas or mixtures, depending on availability and preferences, especially because in refugee camps cultural contexts are diverse. To gain acceptance of a new technology, the cooking preferences need to be respected and cookstoves need to be flexible to suit all kinds of cooking habits. The number of burners (one pot cooking or multiple), the cooking times and temperatures are important, especially since the delivery of fuel (hydrogen or biogas) is limited by the volume available and the maximum pressure off the system. To meet end-user acceptance, the design of the hydrogen technology will be adapted and improved by co-creation. This participatory user-centric design process will result in a user-friendly, robust, low-tech and low-cost application of the hydrogen technology transferring solar energy to the cookpot. The improvement of the technology will be combined with establishing collaboration with local stakeholders, and with demonstration and training at the MALLS.

For the hydrogen cooking solution preliminary tests will verify the safety aspects. This step will be dedicated to the finalization of the Hazard and Operability (HAZOP) study and the Standard Operating Procedure (SOP) for the household case and the solar hydrogen hub case. The HAZOP assessment will assist in formulating step-by-step emergency procedures in the case of accidental hydrogen release and detection, while the SOP is dedicated to the description of the safe operation and transfer of hydrogen from the solar hydrogen panel to the gas bag and through the piping system for the two cases. The HAZOP and SOP will be jointly constructed and shared with the respective living lab partners.

Site preparation, commissioning and testing of the household installation will be done at the demonstration site, according to the designed SOP. Technical validation of the clean cookstove will be done against the baseline tests performed in the EU. These validation tests include the assessment of hydrogen flow rate from the solar hydrogen panel, pressure testing of the gas bag, and NOx measurement of the cook stove flame. A full 100 h extended performance test will be done to assess hydrogen generation rate, re-usability of the hydrogen gas bag and the inner tubes of truck tires, and cooker thermal efficiency. Testing of the sensor incorporated in the hydrogen panels for monitoring hydrogen production and warning of failures will be performed at demonstration site. In

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addition, hydrogen storage in tubes of big tires will be tested through the assessment of maximum pressure, leakages, mode of quick connection to hydrogen filling station and cookstove, ease of transportation by rolling and ease of filling and emptying operations.

e) Project KPIs and reference to use case objectives

Table 23: Project KPIs and reference to use case objectives – Hydrogen cooking in Rwanda

Technical KPIs			
ID	**Name**	**Description**	**Reference to mentioned use case objectives**
1	CAPEX reduction compared to existing alternative	Target: 80%	Technical and socio-economic objectives
2	OPEX reduction compared to existing alternative	Target: 80%	Technical, socio-economic and business objectives
3	Percentage increase in lifetime of products used in the demonstrator locations	Target: 20%	Technical and ecological objectives
7	Improved energy efficiency of the hydrogen panels	Target: 400L of H2 per day at 13% efficiency	Technical objectives
9	GHG emissions mitigated with SUNNY solutions	Target: 1 tCO2eq/year *400 users	Technical, socio-economic, ecological, business objective
17	Number of people benefiting to an enhanced access to energy	Target: 400	Socio-economic and business objective
23	Reduction of respiratory diseases due to solar lighting, and cleaner cooking fuels	Target: 50%	Socio-economic objective
25	Percentage of energy solutions replaced by clean technologies in the demonstration sites	Target: 10%	Business objective

f) Diagram of use case

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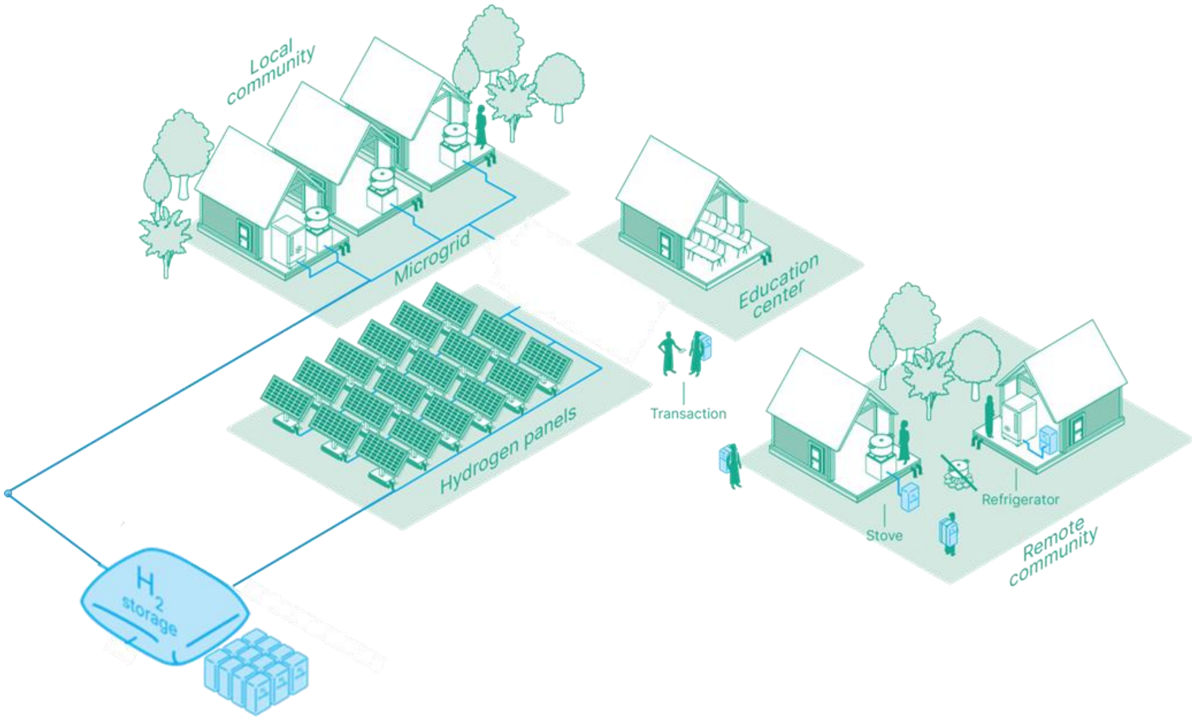

Figure 34: Schematic representation of the use case: Valorize locally produced hydrogen for clean cooking through tailored hydrogen cookstoves and develop low-cost, frugal storage solutions.

c. Uganda: Biogas production from waste

1) Use case title

"Low-tech biogas plant for communal use"

2) Short description

META aims to develop, implement, and operate small-scale biogas systems adapted to the local realities of African communities, using organic waste generated within local infrastructure. The overall goal is to improve access to energy, strengthen local waste management systems, and produce organic fertilizer in a sustainable, affordable, and culturally acceptable way. Although biogas is a highly relevant solution, most existing biogas technologies are not well adapted to local needs. They are often expensive, prefabricated on a global scale, poorly integrated into local value chains, and sometimes lack cultural acceptability. SUNNY addresses this gap by proposing a frugal, decentralized, and locally adapted approach, bringing biogas solutions to communities where such systems have not previously been feasible.

The project will develop small-scale biodigesters made with at least 70% locally sourced materials, designed to be robust, easy to operate, and affordable. The systems will be adapted to the types of organic waste available in each community and will rely on

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simple processes rather than complex or costly technologies. The approach involves collecting and manually sorting organic waste, preparing it for anaerobic digestion, and converting it into biogas and digestate through a natural biological process (anaerobic digestion). The biogas will mainly be used for cooking and thermal applications, enabling users to reduce reliance on traditional fuels and supporting income-generating activities, such as food processing. The digestate will be reused as a high-quality organic fertilizer, closing the local nutrient cycle.

3) User stories

- As a resident of Bidibidi refugee camp, I want to use clean fuels to save money and reduce my dependence on fossil fuels.
- As a resident of Bidibidi refugee camp, I want an energy solution that uses cheap materials so that I can afford it.
- As a resident of Bidibidi refugee camp, I want an energy solution that uses locally sourced materials so that energy is always available.
- As a resident of Bidibidi refugee camp, I want the local waste management infrastructures to be improved to reduce health hazards.
- As a resident of Bidibidi refugee camp, I want to spend my time on other duties than risking my life looking for firewood.

4) Narrative of use case

Using organic waste from local infrastructure via low-tech biogas digesters improves energy access, produces fertilizer, and improves local waste management infrastructures. Even though highly relevant, most of the biogas generation devices are not adapted to the African local needs, cultural acceptability, purchasing power and value chain. Some solutions are emerging such as The Waste Transformers involved in the Green Deal project ENERGICA which is still under development and is more relevant to an urban context with a lot of waste, and the biodigesters developed by Flexi Biogas Solutions, one of the market leaders in biodigesters in East Africa, but they are limited in their consideration of the local value chain, because of their prefabrication on a global scale.

SUNNY will develop, implement and operate biogas generation devices on a small scale (biogas production of about 5.6m³/day), in a distributed manner and adapted to the substrates and waste produced in the local communities of the countries under study. Bringing such biogas solutions to the communities targeted in SUNNY will be a first. Work on developing biogas technology has been carried out by META as part of the SESA project (Smart Energy Solutions for Africa). Based on the results already observed, the process will be improved, and the technology will be further simplified using materials from the local supply chain. META will develop simplified bioreactors, with a frugal and

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local approach, made with at least 70% of materials sourced locally, allowing to make it relevant to use in the targeted communities. With a smaller scale, improved reliability and lower costs, the solution developed is expected to be relevant to be included in new areas not possible before for economic reasons. The solution will moreover allow an economic activity such as food processing, for instance, thanks to the thermal energy produced, reinforcing the income generation in local value chains.

Process description

The input will go through a reception and manual pretreatment first step, in which the non-organic or high-volume materials will be discarded. This first step will be carried out in a screening and selection area, equipped with a 65-litre reject tank, sized to store approximately 30% of the total input for three consecutive days that would work as a garbage bin. Afterwards, the sorted organic waste (50 kg/day) will be manually transferred with a shovel to a 150-litre waste storage tank made of PVC, which will be able to store the expected input for two-three days. The organic matter is manually loaded to a manual grinder for particle size reduction, making organic matter more digestible. After that, it is transferred to a 300 litre tank (mixer), at this stage, the crushed waste will be mixed with rainwater and liquid fraction of the digestate to reduce the solids concentration to a dry matter of 13.5%, suitable for the anaerobic digestion process.

To reduce the dry matter, it's foreseen the construction of a 200-litre tank with a rainwater storage system consisting of a rooftop installation with a catchment area of 20m2 and a collection efficiency of 80%. It it is estimated that during the rainiest season (e.g. August, with 148 mm of rainfall), at least 2 days of autonomy can be guaranteed with the 200 L tank. The water and the liquid fraction of digestate would be fed manually to the mixer.

After the dilution process - requiring a daily mixture of approximately 55 litres of liquid fraction (from digestate and rainwater) - a total mass of 105 kg/day is obtained with a final concentration of 13.5% dry matter, a value suitable for treatment through anaerobic digestion. For feeding the digester, the installation of a screw pump with a 105-litre/hour capacity is planned, allowing the diluted mixture to be pushed into the digester. This pump will also serve to stir the mixture through recirculation, improving content homogeneity, and enhancing process efficiency.

The anaerobic digester, made of glass-fiber reinforced plastic (GFRP) has been sized considering both the variability in waste characteristics and seasonal fluctuations in their generation. A hydraulic retention time (HRT) of 35 days has been adopted, which - with a daily load of 50 kg - requires a useful volume of approximately 4 m³. However, to

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ensure stable operation in the face of potential load fluctuations, the volume has been oversized to 6 m³. The digester will have a cylindrical shape, with a diameter of 2.4 meters and a total height of 2 meters, of which 0.6 meters will be reserved as a safety margin (freeboard) to prevent overfilling. It is thought to be at ambient temperature as regulating its temperature to 38ºC would increase costs and reduce local materials.
It is estimated that, with the projected daily input of substrate, an approximate volume of 5.6 m³ of biogas can be generated per day. To ensure proper storage and allow for continuous operation, a floating-drum type gas holder has been sized with the capacity to store the biogas generated over 1.5 days, which corresponds to a total volume of 8 m³. The system consists of a cylindrical container open at the top, filled with water, and an inverted GFRP drum that floats on this liquid medium. The drum is designed to move vertically, guided by columns or rails, to maintain stability and prevent tipping during upward or downward movement. The produced biogas is introduced at the bottom of the gas holder, accumulating in the space between the water surface and the inside of the drum. As the gas volume increases, the drum rises due to the buoyant force generated by the contained gas. The outlet pressure of the biogas must fall within a suitable range for cooking purposes, between 10 and 15 mbar. To achieve this service pressure, the PVC drum, which acts as the floating dome, must have a total weight of approximately 510 kg, including its own material weight and, if necessary, an additional ballast system.

The gas drum will have a diameter of 2.3 meters and a maximum vertical travel of 1.5 meters, allowing the estimated volume of biogas to be stored at the desired pressure. The lower container, which holds the water on which the drum floats, must have a diameter of 2.5 meters, providing a radial clearance of 10 cm to allow free vertical movement without friction. As for the height, a tank between 1.7 and 2 meters has been considered, which is sufficient to accommodate the drum's vertical movement (1.5 m) plus an additional safety margin of 0.2 to 0.5m. It is essential to ensure that the water level always covers the lower edge of the drum to maintain airtightness and prevent gas leaks. Additionally, the drum will be equipped with a graduated scale (ruler) to display the approximate volume of biogas stored at any given time.
All system tanks (for reception, pretreatment, mixing, dilution, digestion, and digestate storage) will be equipped with a transparent PVC sight glass. This consists of an external tube connected to the bottom and top of the tank, allowing direct visualization of the content level. The tubes will be graduated to facilitate volume reading and ensure proper control of the feeding and digestion processes.

The produced digestate, estimated at 99 kg/day, will be separated into two phases by sedimentation in a sedimentation tank. Hence, liquid fraction is recirculated to dilute the organic matter, and solid fraction is dried and used as a high-quality fertilizer.

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Anaerobic digestion scheme

Anaerobic digestion or biodigestion is a biological process in which organic matter is degraded by the concerted action of a wide variety of microorganisms (mainly bacteria) in the absence of oxygen or other strong oxidizing agents. The main end products of these reactions are a gas called biogas, which is mainly made up of methane and carbon dioxide which also contains nitrogen, hydrogen, hydrogen sulfide and ammonia, which normally account for less than 1% of the total volume of biogas. On the other hand, a digested effluent is generated, which is a mixture of mineral products (nitrogen, phosphorus, potassium ...) and other compounds that are difficult to break down. This effluent, after undergoing a series of treatments, can be used as an agricultural amendment, since it has a greater fertilizing power than the treated waste. Biogas contains a high percentage of methane (between 50-80%, depending on the substrate and the reactor design), so it is susceptible to use the energy to generate heat and / or electricity through its combustion in engines, in turbines or in boilers, either alone or mixed with another fuel. It is also possible to use it in fuel cells, once the hydrogen sulfide, which may affect the membranes, has been removed. Once purified, it can be introduced into the natural gas transportation network, or it can be used as an automotive fuel. Within SUNNY, biogas production from available by-products will be optimised by META through the use of low-cost materials and the training of local partners. Cultural limitations will be taken into account for the use of certain wastes of animal or human origin. Using organic waste from local infrastructure via low-tech biogas digesters will enable to improve energy access, produces fertilizer, and improves local waste management infrastructures.

Implementation steps

The implementation steps for the installations for generation of biogas are the following: 1. Detection of potential water leaks, done by introducing water, which does not need to be potable, into the circuit, filling the digester and auxiliary tanks, if any. By putting the installation into operation, it is possible to detect at which points water is being lost and act on those points. 2. Tightness test: checking that there are no points where the system loses gas. It is necessary to carry out this action to avoid losing a quantity of gas that must be used for cooking. 3. Once it has been verified that the plant has no liquid or gas losses, it must be emptied of water in order to incorporate the acclimatised inoculum. Organic waste contains a very small amount of anaerobic bacteria. This makes it very difficult to start the biological reaction with these by-products. Acclimatised sludge from another biogas plant will be used, if possible, otherwise animal sludge can be introduced into the reactor and water if necessary. This will provide a higher number of anaerobic bacteria. 4. Once the sludge has been introduced, it will be homogenised inside the reactor, and its temperature will be adjusted between 35-40°C. In this way, the

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degradation of organic matter will begin, and the anaerobic process will begin to take place.

The main process control variables will be the following: i) Organic loading flowrate: Amount of daily organic matter that must enter the digester to maintain bacterial health and the stability of the anaerobic process. Above a daily flow of 4gCOD/L of digester (COD=Chemical Oxygen Demand), there is a danger of inhibition due to organic overload. This flow rate depends on the type of waste that will be introduced into the reactor. ii) pH: The optimal value is 7.5. Below this value, there is a danger of inhibition. It is the easiest measurable value to obtain enough information about the stability of the process. The pH is measured in the digestate as soon as it leaves the digester. iii) Biogas production: The amount of gas obtained can be measured daily with analog gasometers. Both flowmeters and gasometrical devices will be used. The decrease in gas produced is an indicator that something in the aerobic reaction is not working correctly.

5) Project KPIs and reference to use case objectives

Table 24: Project KPIs and reference to use case objectives – Biogas production in Uganda

Technical KPIs			
ID	**Name**	**Description**	**Reference to mentioned use case objectives**
1	CAPEX reduction compared to existing alternative	Target: 15-20%	Materials used are locally supplied and low-tech.
3	Percentage increase in lifetime of products used in the demonstrator locations	Target: 10%	Promote circular-economy principles through eco-design supported by ReFuse.
5	Daily biogas production	11.52m³ / day 5,6 expected	Due to the collection of biowastes constraints, biogas production will probably be downsized.
9	GHG emissions mitigated with SUNNY solutions	Target: 1.5 tCO2eq/year * 200 users	Reduce dependency on fossil fuels and firewood. Avoid GHG emissions from biowastes valorization.
17	Number of people benefiting to an enhanced access to energy	Target: 200	Increase access to affordable and reliable energy for refugees' communal use (school, hospital...)
22	Percentage of local materials used in the construction of the biogas solution	70%	Local value chain and local suppliers to promote an affordable biogas device. Simplicity of materials.
25	Percentage of energy solutions replaced by clean technologies in the demonstration sites	Target: 10%	The technology will make the user less dependent on fossil fuels.

6) Diagram of the use case

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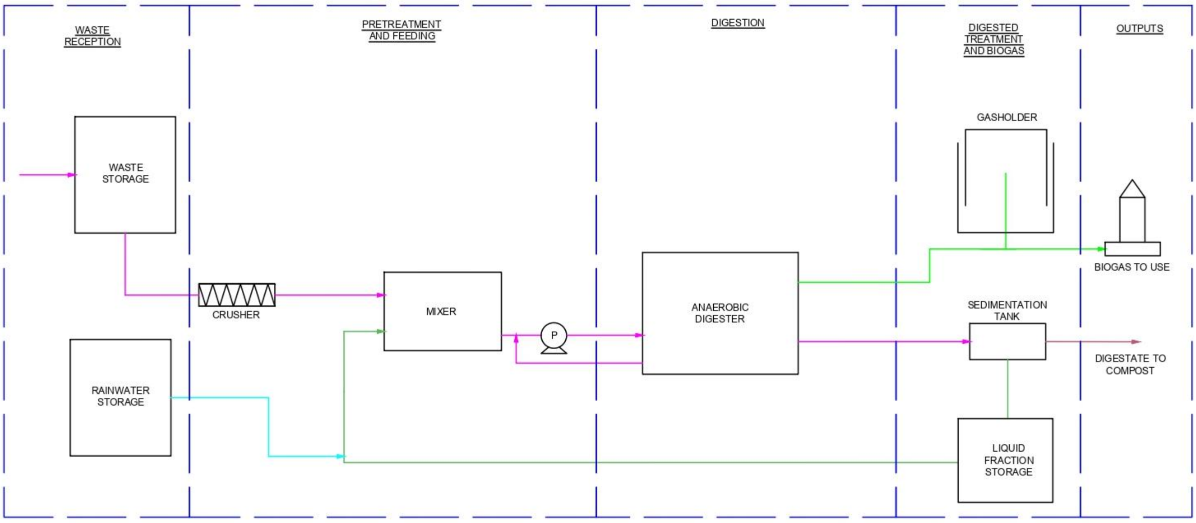

Figure 35: Schematic representation of the use case: Low-tech biogas plant for communal use

d. Uganda: Refrigerated food storage

1) Use case title

"Refrigerated food storage unit with improved remote operation through IoT"

2) Short description

One of the main problems with food in Africa is its conservation, particularly at farmer level. AKO's refrigerated food storage solution leverages innovative technology to extend the shelf life of perishable crops in remote farming communities, combating post-harvest losses and food waste. The system utilizes solar power for energy independence, reducing carbon emissions, and promoting sustainability. Solar panels serve as roofing, generating electricity to power the inverter technology and refrigeration system. Additionally, a 8-12 hours power backup system ensures continuous operation. The solution will also be IoT enabled, giving access to remote monitoring. By creating decentralized community storage units using the pay-as-you-store model, farmers do not need to pay the cost of the entire unit upfront and do not need expertise related to maintenance of the unit. Furthermore, by making the unit solar powered it makes the solution net positive to the environment and a constant source of energy while bridging the energy poverty gap. Refrigerated food storage not only reduces food waste but also preserves food quality, thereby limiting the health problems that can be associated with it.

3) User stories

- As a farmer in the Bidibidi settlement, I want a reliable and continuous food storage solution to reduce post-harvest losses.

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- As a farmer in the Bidibidi settlement, I want to a pay-as-you-store model so I do not have to invest a high amount of money upfront.
- As a farmer in the Bidibidi settlement, I want a food storage solution maintained by trained local technicians to reduce downtimes.

4) Narrative of use case

One of the main problems with food in Africa is its conservation, particularly at farmer level. AKO's refrigerated food storage solution leverages innovative technology to extend the shelf life of perishable crops in remote farming communities, combating post-harvest losses and food waste. The system utilizes solar power for energy independence, reducing carbon emissions, and promoting sustainability. Solar panels serve as roofing, generating electricity to power the inverter technology and refrigeration system. Additionally, a 28-hour power backup system ensures continuous operation. The solution will also be IoT-enabled, giving access to remote monitoring. By creating decentralized community storage units using the pay-as-you-store model, farmers do not need to pay the cost of the entire unit upfront and do not need expertise related to maintenance of the unit. Furthermore, by making the unit solar powered it makes the solution net positive to the environment and a constant source of energy while bridging the energy poverty gap. Refrigerated food storage not only reduces food waste but also preserves food quality, thereby limiting the health problems that can be associated with it.

Existing solar-powered refrigerated food storage systems have several limitations that are addressed by AKO's solution:

- Intermittent Power Generation: Solar energy generation is dependent on sunlight, which is not constant, impacting the consistent operation of the refrigeration system. The solution developed by AKO will make it possible to have a 8-12-hour power backup system ensuring continuous operation. compared with an average of 12h to 24h for mid to large-sized systems.
- High Initial Investment: While there may be long-term savings from reduced energy costs, the initial investment can be a barrier, especially in resource-constrained areas. In SUNNY, by creating a decentralised community storage unit using the pay-as-you-store model, farmers do not need to pay the cost of the entire unit upfront.
- Operation, Maintenance and Expertise: Solar-powered systems, including refrigeration, require regular maintenance and technical expertise on both solar technology and refrigeration systems. The solution developed by AKO will be IoT enabled, giving access to remote monitoring, including temperature control. Local workforce will be trained in the maintenance of the technology to take greater account of the local value chain.

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- Energy Efficiency: While solar panels generate clean energy, the overall energy efficiency of the system (including conversion and cooling processes) can impact its effectiveness in maintaining desired temperature levels. The power capacity of the RFS will be reduced from 8kw to 5kW, to match with the cooling requirements of the storage space to ensure energy-efficient operation.

AKO will focus on testing the effectiveness of its cold storage technology in the context of the water-energy-food nexus, addressing both community and business needs for energy while promoting economic growth in the agricultural sector. The testing plan includes evaluating energy efficiency, performance, reliability, user-friendliness, remote monitoring capabilities, compatibility with various energy sources and data analytics. The goal is to ensure that the technology operates optimally, maintains desired temperature levels for perishable goods, and supports economic development. Stakeholder feedback and data analysis will contribute to refining the technology's performance and impact within the local context.

5) Project KPIs and reference to use case objectives

Table 25: Project KPIs and reference to use case objectives – Refrigerated food storage in Uganda

Project KPIs			
ID	**Name**	**Description**	**Reference to mentioned use case objectives**
1	CAPEX reduction compared to existing alternative	Target: 15%	Avoid high up-front investment costs for farmers. Enable access to cold storage through shared, service-based infrastructure.
2	OPEX reduction compared to existing alternative	Target: >25%	Reduce operating costs through solar-powered operation and centralized maintenance. Improve affordability of refrigerated storage services.
3	Percentage increase in lifetime of products used in the demonstrator locations	Target: >10%	Increase system reliability and durability through professional operation, preventive maintenance, and remote monitoring.
4	Energy efficiency enhancement for the refrigerated food storage (RFS) solution	Target: 20%	Increase energy efficiency of the refrigeration system. Ensure continuous and reliable cold storage operation in off-grid contexts.
5	GHG emissions mitigated with SUNNY solutions	Target: 0.5 tCO2eq/year *150 users	Reduce greenhouse gas emissions by replacing diesel-based or inefficient cooling solutions with solar-powered refrigeration.
6	Number of people benefiting to an enhanced access to energy	Target: 150	Improve access to reliable energy services for agricultural value chains. Support farmer livelihoods and food security.
7	Reduction (%) of food waste thanks to RFS	Target: 25-30%	Reduce post-harvest losses. Improve food security and income stability for farmers.

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6) Diagram of use case

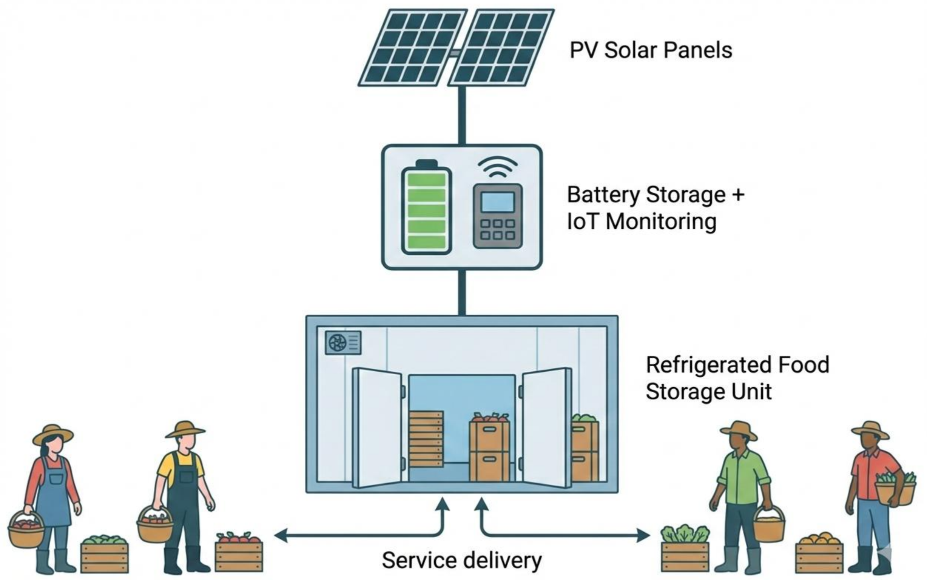

Figure 36: Schematic representation of the use case: Refrigerated food storage unit with improved remote operation through IoT

e. Uganda: Smart solar irrigation system in Uganda

1) Use case title

"Smart solar irrigation system to improve water efficiency and increase yields"

2) Short description

This use case addresses the challenge that farmers in refugee and host communities often have only limited access to reliable energy and water for irrigation. To respond to this, a solar-powered irrigation system is installed to pump and distribute water for agricultural production. The system is monitored remotely so that performance can be tracked continuously, problems can be identified at an early stage, and maintenance needs can be addressed in a timely manner. Operators are responsible for overseeing system performance and coordinating field technicians when maintenance or repairs are required. Overall, the use case demonstrates how solar-powered irrigation can improve water availability, increase agricultural productivity, and reduce irrigation-related costs, thereby contributing to more secure livelihoods and improved food security.

3) User stories

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- As a farmer in a water-scarce area, I want a solution that allows me to adjust irrigation based on weather and soil conditions.
- As a farmer in a water-scarce area, I want to optimize irrigation to increase my yields.

4) Narrative of use case

Smart irrigation systems are an emerging technology for adjusting irrigation based on actual weather and soil condition. It is suitable for use in places where water scarcity and climate are a challenge. Solar powered irrigation systems enable to intensify crop production, improve water efficiency and reduce the associated costs. The technology developed by SOLEK; AQUAnet is used for water management, where farmers receive the quantity of water according to their request. An operator performs these tasks by software on a tablet by remote monitoring.

This technology enables farmers to raise cropping yields, to increase the value to their crops and to encourage business opportunities. The solution is improved with the view to ensure quick maintenance and assistance solutions, to ensure the sustainability of the irrigation system and to improve the control of the water flow.
The following analyses will be carried out: i) Integrated WEF nexus: Analysis of how efficient energy use, water management, and food preservation contribute to overall sustainability and resilience; ii) Data integration and analytics: SUNNY will explore methods for integrating data from different systems to optimize decision-making. Algorithms and models that leverage data from solar irrigation, refrigerated storage, and clean cooking systems will be developed to enhance energy efficiency and resource allocation; iii) Remote Monitoring and Control: SUNNY will study how remote monitoring and control technologies can be utilised to manage and optimize the performance of these systems. It will examine the benefits of real-time data analytics for improving irrigation scheduling, temperature control, and cooking efficiency; iv) Energy synergy and sharing: The project will investigate the potential for energy sharing and synergy among these systems. For instance, surplus solar energy from irrigation could be used for refrigeration or cooking, enhancing system efficiency and reliability; v) Technology Standards and Protocols: SUNNY will investigate the development of standardized communication protocols and interfaces that enable seamless interoperability among these systems. This can lead to easier integration and scalability.

- Business actors: SOLEK (System Owner), Water User Committee (WUC), Farmers / End Users, Makerere University (Research Partner), Mobile Money Providers (MTN/Airtel)

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These actors shape the irrigation business model: SOLEK install and manage the system; WUC governs water distribution and fee collection; farmers are the primary users; Makerere analyzes affordability and water-energy-food nexus data; and mobile operators enable digital payments.

- Operator: SOLEK Technical Team and Water User Committee

Operate and maintain pumps, sensors, and distribution networks; monitor performance; manage schedules; and ensure O&M cost recovery.

- Logical Actors: PV Production Unit (Solar Panels), Storage Unit (Water Tank/Reservoir), IoT Monitoring & Payments Device, Distribution Network (Pipes, Hoses, Valves)

Logical actors form the system infrastructure: solar PV powers the pump; water is stored in tanks; IoT devices measure and report flow and payments; and the distribution network delivers water to the fields.

5) Project KPIs and reference to use case objectives

Table 26: Project KPIs and reference to use case objectives – Solar irrigation in Uganda

Project KPIs			
ID	**Name**	**Description**	**Reference to mentioned use case objectives**
KPI-01	System Deployment & Operational Reliability	Successful installation and commissioning of the solar-powered irrigation system, achieving ≥90% operational uptime during irrigation season.	OBJ-T1, OBJ-T2
KPI-02	Smart Monitoring & Metered Water Delivery	Implementation of IoT-based monitoring ensuring real-time water flow measurement, credit validation, and accurate telemetry reporting.	OBJ-T3

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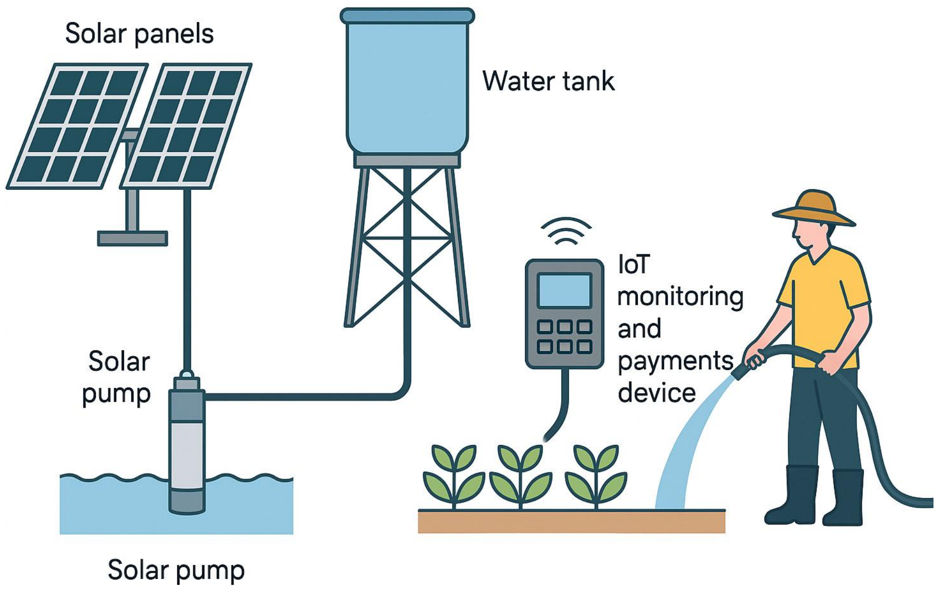
KPI-03	Agricultural Productivity Improvement	Percentage increase in crop yield of participating farmers compared to baseline season.	OBJ-S1
KPI-04	Affordable & Transparent Payment Compliance	Share of registered farmers actively using the system and maintaining timely mobile-money payments under the agreed tariff structure.	OBJ-S2, OBJ-S3
KPI-05	Environmental & Resource Sustainability Impact	Reduction of diesel-based irrigation and improved water-use efficiency through solar-powered and scheduled irrigation.	OBJ-E1, OBJ-E2

6) Diagram of the use case



4. Summary and Outlook

This chapter presented the use cases developed for the SUNNY project. It first outlined the objective of the use-case work and the methodological approach applied in SUNNY.

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It then explained the structure of the use-case template and presented the individual use cases for the different SUNNY technologies in Rwanda and Uganda. Together, the chapter provides a structured overview of the intended application of the technologies in the demonstration contexts, including the actors involved, the core processes, and the expected outcomes.

The use cases will serve as an important reference point for the next phases of the SUNNY project. They provide a structured basis for further refining technological requirements and specifications and for linking these more clearly to user needs, contextual conditions, and implementation pathways. In this way, they will support the continued work in WP3, inform the preparation and implementation of demonstrations in WP4, and contribute to activities in WP5. As the project progresses, the use cases can be further refined based on additional stakeholder engagement, technical development, and implementation experience in the demonstration sites.

5. Literature

Alacreu, Lola, Alberto Zambrano, and Markus Mirz, eds. 2021. *Bridge Use Case Repository: "Action 1- Set up a Use Case Repository"*. European Commission. https://energy.ec.europa.eu/system/files/2021-06/bridge_wg_data_management_use_case_repository_report_2020-2021_0.pdf.

Andres, Beatriz, Faustino Alarcon, Daniel Cubero, and Raul Poler. 2023. 'A Methodology for Project Use Case Definition'. In *IoT and Data Science in Engineering Management*, edited by Fausto Pedro García Márquez, Isaac Segovia Ramírez, Pedro José Bernalte Sánchez, and Alba Muñoz Del Río, vol. 160. Lecture Notes on Data Engineering and Communications Technologies. Springer International Publishing. https://doi.org/10.1007/978-3-031-27915-7_78.

IEC. 2015. *Use Case Methodology - Part 2: Definition of the Templates for Use Cases, Actor List and Requirements List*. 62559–2.

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VII. COMPARISON OF THE SUNNY USE CASES WITH RELATED PROJECTS

This chapter presents the comparison of the SUNNY use cases with related projects as one of the central components of Deliverable D1.3. It first introduces the rationale and objective of this component and then outlines the methods used for the comparison. This is followed by the presentation of the results in two main parts: the comparison of SUNNY use cases with related use cases in European projects, and the overview of related energy projects, including results for Uganda, Rwanda, and relevant documented learnings beyond these two countries.

As such, the chapter contributes to the overall objective of the deliverable by linking the SUNNY use cases to relevant external experience and documented implementation learnings. In this way, it complements the project-internal analysis by providing broader points of reference for the further refinement of use cases, requirements, and implementation pathways within the SUNNY project.

1. Introduction

The definition of SUNNY use cases forms part of a broader effort to ensure that the project's solutions are both contextually grounded and informed by relevant external experience. In line with Task 1.4, the specification of project-specific use cases and requirements is complemented by a comparison with related use cases, experiences, and implementation approaches from other relevant projects and initiatives. This comparative perspective is important for strengthening the quality of the SUNNY use cases.

This chapter therefore places the SUNNY use cases in relation to two complementary bodies of experience. On the one hand, it considers relevant European projects whose activities, objectives, or technological focus are linked to the challenges addressed by SUNNY. This helps to position SUNNY within the wider landscape of current research and innovation efforts and to reflect on how similar approaches have been conceptualized in other project contexts. On the other hand, the chapter considers energy-related projects that have already been implemented in the demonstration locations or their surrounding environments. This perspective is particularly relevant for understanding how previous interventions have engaged with local conditions, which practical challenges and opportunities have emerged, and which lessons may be valuable for SUNNY.

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The objective of this chapter is to compare the SUNNY use cases with related project experience in order to identify relevant points of reference for their further development. More specifically, the chapter aims to situate SUNNY within the landscape of related European projects, to highlight connections between SUNNY and energy-related interventions in the demonstration contexts, and to capture insights that can inform implementation pathways, requirements analysis, and the broader transferability of solutions. In this way, the chapter contributes to ensuring that the SUNNY use cases are informed not only by project-internal analyses, but also by relevant external experience and context-specific learning.

2. Methods

This chapter brings together two complementary strands of analysis. The first strand compares SUNNY use cases with related use cases and activities in relevant European projects. The second strand reviews energy-related projects implemented in the demonstration contexts in order to identify relevant experiences and derive practical learnings for SUNNY. Together, these two strands support the comparison of SUNNY with related project experience at both the broader European level and the local implementation level.

Identification and comparison with related European projects

The comparison with related European projects was conducted in three steps. In a first step, relevant Horizon 2020 and Horizon Europe calls were identified through a targeted review of funding programmes and call topics. The selection was guided by search criteria. Calls were considered relevant if they addressed access to energy or closely related fields of decentralized and renewable energy provision, and if they either focused on EU–AU cooperation or on implementation contexts outside continental Europe that offered meaningful points of comparison for SUNNY. Particular attention was given to calls addressing off-grid solutions, productive use of energy, clean cooking, decentralized energy systems, and integrated water–energy–food approaches, as these are central to the technological and application areas covered by SUNNY.

In a second step, the projects funded under the selected calls were reviewed in order to identify those with particular relevance for SUNNY. This review considered the thematic orientation of the projects, their technological focus, their implementation context, and their overall proximity to the challenges addressed in SUNNY. Projects were included when they showed relevant overlap with SUNNY in terms of technologies, use-case logic, target settings, or broader intervention objectives. Projects with a stronger focus on modelling, policy, or networking were also considered in the general mapping where relevant, but the detailed comparison of use cases focused primarily on projects with

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demonstrative or application-oriented activities.

In a third step, the activities and use-case-relevant elements of the selected projects were reviewed and compared with the SUNNY use cases. The comparison did not aim to establish equivalence between projects, but rather to identify areas of similarity and difference with regard to application fields, technology combinations, implementation logic, and expected functions of the systems. The resulting overview provides a structured basis for situating SUNNY within the wider European project landscape and for identifying points of reference for knowledge transfer.

Overview of related energy projects in the demonstration contexts

The second strand of work consisted of a comprehensive review of relevant energy-related projects in the demonstration contexts and their surrounding implementation environments. This review combined grey literature and scientific literature in order to capture both project documentation and more analytical reflections on implementation experience. Sources included project reports, learning briefs, scientific publications, and available data platforms and networks documenting humanitarian and development-related energy interventions.

For Uganda, the review focused on energy-related projects implemented in the north of the country and therefore included not only Bidibidi, but also other refugee settlements and related intervention areas where relevant for understanding the regional energy environment. For Rwanda, the review included energy-related projects implemented in refugee camps, thereby allowing Mahama to be contextualized within the broader national landscape of refugee energy interventions. This wider scope was chosen in order to capture relevant implementation experience even where no direct intervention in the exact SUNNY demonstration site had taken place.

Following the identification of relevant projects, these were mapped in a structured way and documented in overview tables. The mapping focused on key characteristics such as project title, timeframe, main actors, location, outreach, technology focus, and relevance to the SUNNY demonstration sites. In a subsequent step, learnings explicitly reported in project descriptions, project outputs, and related publications were extracted and documented in separate tables. The objective of this step was to synthesize practical lessons from earlier interventions in a form that could inform the further refinement of SUNNY use cases, implementation pathways, and requirements analysis.

The results of both strands of work are presented in the following sections.

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3. Comparison of SUNNY use cases with related use cases in European projects

This section presents the results of the comparison between SUNNY use cases and related use cases identified in relevant European projects. The results are structured in four parts. First, an overview is provided of the Horizon 2020 and Horizon Europe calls identified as relevant to the SUNNY project. Second, the projects funded under these calls and assessed as relevant to SUNNY are presented. Third, the links between these projects and the individual SUNNY use cases are summarized in a comparative matrix. Fourth, the relevance of the identified projects for SUNNY is discussed in qualitative terms by highlighting key points of overlap as well as major differences. Together, these results position SUNNY within the broader landscape of European research and innovation related to energy access, decentralized renewable energy systems, and productive uses of energy.

Error! Reference source not found. provides an overview of the Horizon 2020 and Horizon Europe calls identified as relevant to the SUNNY project. The table shows that SUNNY is situated within a broader funding landscape in which energy access in Africa, AU–EU cooperation, off-grid renewable energy systems, and water–energy–food nexus approaches have become increasingly important themes. The identified calls also illustrate that relevant points of comparison for SUNNY are not limited to direct technology demonstration but also include broader cooperation frameworks and modelling-oriented initiatives.

Error! Reference source not found. presents the projects identified as relevant to SUNNY within these calls. The table shows a broad range of projects with different thematic foci, including multi-technology renewable energy systems, peer-to-peer smart energy networks, off-grid cooling, renewable energy parks, hydrogen-based solutions, biomass valorisation, and integrated water–energy–food systems. In addition, the overview includes projects that are relevant at a more strategic level, for example through modelling, planning, capacity building, or long-term EU–AU research cooperation.

Error! Reference source not found. translates this wider project landscape into a direct comparison with the SUNNY use cases. The matrix indicates which identified projects include activities related to the six SUNNY use-case areas: solar home systems, hydrogen cooking, bioenergy cooking, bioenergy from waste, solar irrigation, and cold storage. The table shows that the strongest overlap exists for solar home systems, irrigation, cold storage, and integrated renewable energy access approaches. Some projects are linked only to one specific use-case area, while others span several. In particular, ENERGICA and SESA show broad overlap across multiple SUNNY use cases,

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while projects such as SWARM-E, OPTiMG, and LoCEL-H2 show more focused but still relevant connections. At the same time, the matrix also makes clear that direct points of comparison are more limited for hydrogen cooking and for the particular combination of technologies addressed in SUNNY.

Error! Reference source not found. complements the matrix with a qualitative assessment of the relevance of each project for the SUNNY use cases. It shows that the identified projects are not directly equivalent to SUNNY but rather provide partial points of comparison. Some projects are relevant because they demonstrate integrated renewable energy systems in African contexts, while others are particularly relevant for specific domains such as hydrogen, solar home systems, irrigation, refrigeration, biomass-based energy, or replication of energy-access solutions. At the same time, the table highlights important differences. Several projects focus on islands, agricultural value chains, health facilities, modelling, or governance rather than on displacement settings and host-community contexts. This comparison is particularly important because it shows that SUNNY combines several dimensions that are often addressed separately in other projects, namely multiple technology areas, and a strong emphasis on context-sensitive implementation.

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Table 27: Overview of Horizon Europe projects calls related to the SUNNY project

Year	Call	Code
2020	Accelerating the green transition and energy access Partnership with Africa	LC-GD-2-3-2020 (Horizon 2020 - Green Deal Call)
2021	AU-EU Water Energy Food Nexus	HORIZON-CL5-2021-D3-03-01
2022	Demonstration of innovative plug-and play solutions for system management and renewables storage in off-grid applications	HORIZON-CL5-2022-D3-01-05
	AU-EU Energy System Modelling	HORIZON-CL5-2022-D3-02-02
2023 (SUNNY)	**Accelerating the green transition and energy access in Africa**	**HORIZON-CL5-2023-D3-02-16**
	Sustainable, secure and competitive energy supply	**HORIZON-CL5-2023-D3-02**
2024	Africa-EU CO-FUND action	HORIZON-CL5-2024-D3-01-09
2025	Building a Long-Term Africa Union (AU) and European Union (EU) Research and Innovation joint collaboration on Sustainable Renewable Energies	HORIZON-CL5-2025-02-D3-15
2026	Improving climate and weather models for Africa	HORIZON-CL5-2026-07-D1-05
	Europe-Africa Research and Innovation call on Sustainable Energy - 2026	LEAP-SE
2027	Renewable Energy Valleys in Africa to increase energy security and energy access in Africa	HORIZON-CL5-2027-02-D3-10
	African Union – European Union Partnership on Food and Nutrition Security and Sustainable Agriculture (FNSSA)	HORIZON-CL6-2027-02-FARM2FORK-09
	Optimising the water-nutrient-energy nexus for sustainable and climate smart agriculture in Africa (FNSSA)	HORIZON-CL6-2027-02-FARM2FORK-02-two-stage
	Africa-EU CO-FUND action on climate	HORIZON-CL5-2027-01-D1-11

Table 28: Overview of Horizon Europe projects that are related to the SUNNY project

Project Name	Full title	Primary Focus	Project Webpage
ENERGICA	ENERGy access and green transition collaboratively demonstrated in urban and rural areas in AfrICA	Multi-technology renewable energy solutions across African sites	https://energica-h2020.eu/
MAESHA	deMonstration of smArt and flExible solutions for a decarboniSed energy future in Mayotte and other European islAnds	Low-carbon energy and grid flexibility for remote communities in Mayotte and other European islands	https://maesha.eu/
SWARM-E	LEAVE NO ONE BEHIND: BOTTOM-UP ENERGY TRANSFORMATION OF LAST-MILE COMMUNITIES	Peer-to-peer modular smart energy networks	https://swarm-e.eu/
AGRI-COOL	Advancing sustainable AGRIculture through off-grid energy and COOLing solutions in Africa	Off-grid cooling and storage for agricultural supply chains	https://agri-cool.eu/about-the-project/
AfricaEnergyParks	Improving energy access and climate resilience in Africa's fringe communities	Renewable energy parks supporting local economies	https://africaenergyparks.eu/
KijaniBox	Transforming African Organic Waste into Green Energy for Cooling	Waste-to-energy cooling for food preservation	https://www.kijanibox.eu/
OPTiMG	Optimization of integrated Mini-Grids for Water, Energy, and Food	Decentral renewables and storages in WEF-systems and integrated mini grids	https://www.leap-re.eu/optimg/
RePower	Improving Renewables Penetration Through Plug and Play Microgrids	Plug-and-play microgrids for productive rural uses	https://repowerproject.com/
LoCEL-H2	Low-Cost, Circular, plug & play, off grid Energy for Remote Locations including Hydrogen	Solar, battery, and green hydrogen energy systems	https://locelh2.org/
REFFECT AFRICA	Renewable energies for Africa: Effective valorization of agri-food wastes	Biomass gasification for clean energy and biochar	https://www.reffect-africa.eu/
SophiA	SUSTAINABLE OFF-GRID SOLUTIONS FOR PHARMACIES AND HOSPITALS IN AFRICA	Sustainable energy and water for healthcare facilities	https://sophia4africa.eu/

SteamBioAfrica	Innovative Large-Scale Production of Affordable Clean Burning Solid Biofuel and Water in Southern Africa: transforming bush encroachment from a problem into a secure and sustainable energy source	Invasive biomass conversion to clean fuel and water	https://www.steambioafrica.com/
SESA	Smart Energy Solutions for Africa	Replicable energy access solutions and business models across Africa	https://sesa-euafrica.eu/
EPIC Africa	ENERGY PLANNING AND MODELLING THROUGH INTEGRATED ASSESSMENT OF CLIMATE LAND ENERGY WATER NEXUS IN SUB-SAHARAN AFRICA	Comprehensive planning and modelling of water, energy, and food systems integration	https://www.epicafrica.eu/energy-planning-and-modelling-through-integrated-assessment-of-climate/
ONEPlanET	OpeN source nExus modelling tools for Planning sustainable Energy Transition in Africa	Stakeholder capacity building and policy for energy transition	https://www.sei.org/projects/open-source-nexus-modelling-tools-for-planning-sustainable-energy-transition-in-africa-oneplanet/
LEAP-RE	Long-Term Joint EU-AU Research and Innovation Partnership on Renewable Energy	A long-standing collaboration between the EU and AU focuses on advancing research and innovation in renewable energy	https://www.leap-re.eu/
EMERGE	ENERGY SYSTEM MODELLING FOR GREEN DEVELOPMENT OF AFRICA	Advanced energy system models to empower Africa's sustainable development	https://emerge4green-africa.eu/
OpenMod4Africa	Open Modelling Toolbox for development of long-term pathways for the energy system in Africa	Dynamic platform designed for long-term energy system modeling in African countries	https://openmod4africa.eu/the-open-modelling-toolbox-for-africa-powering-a-just-energy-transition
RE-INTEGRATE	RE-thinking of approaches and toolkits for transdisciplinary INTEGRATEd assessment of climate-compatible energy strategies from the African Union through to the European Union	Comprehensive evaluation of energy strategies that align with climate goals	https://orbit.dtu.dk/en/projects/rethinking-approaches-and-tools-for-an-integrated-transdisciplina/

Table 29: Matrix indicating Horizon Europe projects with activities that are related to the SUNNY use cases

SUNNY Use Case	1	2	3	4	5	6
Technology	**Solar Home Systems**	**Hydrogen cooking**	**Bioenergy cooking**	**Bioenergy from waste**	**Solar Irrigation**	**Cold storage**
ENERGICA	x		x	x	x	x
MAESHA	x					
SWARM-E	x	x			x	x
AGRI-COOL						x
AfricaEnergyParks	x			x		
KijaniBox						x
OPTiMG	x				x	x
RePower	x				x	
LoCEL-H2	x	x				
REFFECT AFRICA				x		
SophiA	x					x
SteamBioAfrica				x		
SESA	x		x	x	x	x

Table 30: Description of relevance of Horizon Europe projects for the SUNNY use cases

Project Name	Relevance	Main differences
ENERGICA	Demonstrates integrated renewable energy systems in diverse African contexts, including microgrids and biogas.	Broader technology mix and demonstration scope compared to SUNNY's targeted community projects.
MAESHA	Addresses energy access and grid reliability for isolated communities using PV and hydrogen, aligned with SDG 7.	Island-centric approach focused on grid flexibility, combining local renewable generation with grid-connected hydrogen; unlike SUNNY's refugee focus.
SWARM-E	Implements a peer-to-peer smart grid for solar home systems, enabling dynamic energy exchange and productive uses.	Emphasizes network scaling and peer-to-peer distribution, in contrast to SUNNY's site-specific technology deployments.
AGRI-COOL	Provides containerized, off-grid cooling solutions to reduce food loss and greenhouse gas emissions in Africa.	Focuses on agricultural value chains and food loss reduction, whereas SUNNY emphasizes energy access and livelihoods.
AfricaEnergyParks	Establishes renewable energy parks using microgrids and circular economy approaches for productive energy use.	Community park infrastructure model versus SUNNY's tailored household/community energy systems.
KijaniBox	Converts organic waste into green energy for cooling, targeting food supply chains and small businesses.	Circular economy and waste-to-cooling focus, differing from SUNNY's clean energy and socio-economic solutions.
OPTiMG	Develops smart solar irrigation and integrated mini-grids to improve water efficiency and agricultural yields.	Focuses on productive uses (irrigation, refrigeration), while SUNNY integrates broader community solutions.
RePower	Demonstrates modular, scalable microgrid systems for rural electrification and productive energy applications.	Rural microgrid economy and productive energy applications versus SUNNY's integrated household/community interventions.
LoCEL-H2	Provides renewable, cost-effective, plug-and-play energy and clean fuels, including hydrogen-based solutions.	Specific focus on hydrogen energy solutions, while SUNNY integrates hydrogen among a broader portfolio of renewables.
REFFECT AFRICA	Demonstrates biomass gasification for renewable energy and biochar production, targeting agri-food waste valorization.	Focuses on bioenergy from agricultural waste, whereas SUNNY adopts a multi-technology renewable access approach.

SophiA	Delivers off-grid, carbon-neutral electricity, heating, cooling, and clean water for rural health facilities.	Sector-specific health infrastructure focus, in contrast to SUNNY's broader community empowerment.
SteamBioAfrica	Converts invasive woody biomass into clean burning biofuel and water, supporting ecosystem restoration.	Focused on invasive biomass conversion and rural job creation, while SUNNY emphasizes energy access pipelines.
SESA	Facilitates co-development and replication of energy access innovations, integrating solar, microgrids, and biomass.	Strong replication, co-development, and technology portfolio versus SUNNY's focused pilots and community impact.
EPIC Africa	Builds advanced WEF models for infrastructure planning and governance in Sub-Saharan Africa.	Strategic, data-driven planning and modelling, as opposed to SUNNY's on-the-ground technology deployments.
ONEPlanET	Develops open-source nexus modelling tools for planning sustainable energy transitions in Africa.	Governance and stakeholder empowerment focus, rather than SUNNY's technology deployment and demonstration.
LEAP-RE	Creates a large-scale research network to advance renewable energy collaboration between Africa and Europe.	Research network covering many renewable energy themes, including microgrids, while SUNNY is project-focused.
EMERGE	Provides tools and knowledge for optimizing clean energy production and sustainable resource use in Africa.	Toolbox for scenario simulation and participatory knowledge communities, compared to SUNNY's deployment focus.
OpenMod4Africa	Develops open, scalable models and capacity building for African universities and decision-makers.	Capacity building and open models for academia and policy, while SUNNY focuses on community-level technology.
RE-INTEGRATE	Establishes multilateral sharing of modelling expertise and fit-for-context toolkits for energy planning.	Multilateral modelling expertise sharing, whereas SUNNY is focused on local technology demonstration.

4. Overview of related energy projects

This section presents the results of the review of related energy projects and the learnings derived from them. The results are structured in three parts. First, the section presents relevant projects and learning identified in Uganda, with a focus on the energy environment of Bidibidi and the wider context of Northern Ugandan refugee settlements. Second, it presents relevant projects and learnings identified in Rwanda, situating Mahama within the broader landscape of energy-related interventions in Rwandan refugee camps. Third, it presents selected learnings from relevant projects beyond Uganda and Rwanda that offer additional points of reference for the development of the SUNNY use cases and implementation pathways.

a. Projects in Uganda

This subsection presents the results of the review of relevant energy-related projects in Uganda. The results are structured in two parts. First, an overview is provided of projects related to the energy environment of Bidibidi and the wider Northern Ugandan refugee response context. This overview captures the diversity of interventions that have shaped the local energy landscape and shows how Bidibidi is embedded in a broader regional field of humanitarian and development-oriented energy activities. Second, the subsection presents learnings derived from relevant projects. These results include, on the one hand, an overview of the projects from which learnings were extracted and, on the other hand, more detailed thematic syntheses for selected projects for which particularly comprehensive learning material was available. Together, these results provide both a descriptive mapping of the intervention landscape and a more analytical overview of practical lessons that are relevant for the further development of SUNNY.

Overview of relevant energy projects

The overview table on relevant energy projects in Uganda (Table 31) shows that the energy environment of Bidibidi has been shaped by a wide range of interventions with different technological foci and implementation models. The identified projects include activities related to improved and alternative cooking solutions, off-grid solar energy, solar home systems, market-based energy access, repair and e-waste management, and solar e-cooking. The table also shows that relevant projects were implemented not only in Bidibidi itself, but also in other refugee settlements in Northern Uganda, reflecting the wider regional context in which SUNNY is situated.

A key result of the overview is that the Ugandan project landscape is characterized by a focus on both technology provision and enabling conditions for access. Several projects address not only the distribution of energy technologies, but also financing, retail structures, entrepreneurship, repair services, and user awareness. This is relevant for

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SUNNY because it shows that energy access in and around Bidibidi is shaped by a combination of technologies, actors, and support systems rather than by single interventions in isolation.

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Table 31: Overview of projects related to the energy environment of Bidibidi, Uganda

Project title	Time	Main actor	Location	Outreach	Technology	SUNNY Demonstration site	Reference links
Charcoal briquetting	since 2010	UNHCR	Nakivale refugee settlement	Around 70,000 tons of briquettes produced per year by groups in various settlements; typical household uses 1–2 kg of briquettes daily; Price range from USD 0.18 (household production) to USD 0.55 per kg (private sector production)	Charcoal briquettes: 1 kg of briquettes run a cookstove much longer than 1 kg of firewood: Raw materials are sawdust, wood, maize, cereals, roots, cane sugar, coffee residues, organic waste; Briquettes are locally produced by refugees as well as host community members	No	https://www.unhcr.org/media/access-clean-energy-refugees-uganda-case-studies; https://www.unhcr.org/news/stories/innovation-briquette-making-project-helps-protect-women-ugandan-camp
Local production of cookstoves	10/2018 to 07/2019	UNHCR	Ugandan refugee settlements	93% of refugees in the project region are aware of the benefits of improved cookstoves and find fuel savings as the most compelling advantage; raw material available locally and setup cost is low: Price range of USD 1.40 – USD 4 per cookstove; Community involvement allows for custom made design to fit the local needs	improved cookstoves from local materials: clay-made cookstoves are twice as efficient as traditional open three stone fires and increase safety during cooking: Cookstove fuel efficiency of 20–25% (Tier 2): Firewood or charcoal fuel need cut in half to 0.85 kg/per person per day; Significant health benefits: reduce indoor smoke by 90%, increases safety during cooking in comparison to three stone fires as the risk of burns is reduced by 45%; annual costs for fuel wood can be reduced by USD 50-60, leading to annual costs for the cookstove and the fuel of USD 15-20; User-centered design increased the acceptability	no information	https://www.unhcr.org/media/access-clean-energy-refugees-uganda-case-studies; https://energypedia.info/images/2/23/SAFE_Brochure-2.pdf

Solar lamp lifecycle and market	2016 to 2021 (distribution); since 2021 (Rhino Camp and Imvepi energy kiosks); since July 2022 (Bidibidi and Palorinya)	UNHCR, GIZ	Rhino Camp, Imvepi, Bidibidi and Palorinya	more than 300,000 solar lanterns to new arrivals from 2016 to 2021; Energy kiosk operated by 10 to 15 refugee/host community members and serving 3,500 households; eight energy kiosks were set-up in four settlements selling high-quality solar lanterns and other energy products; energy kiosks also serve as an innovative and integrated electronic waste management point for the repurposing, recycling and adequate disposal of solar products; 60% reported to feel safer using WASH facilities at night;	Solar lamp: 45 minutes more lighting per evening compared to those reliant on candles; Energy kiosks sell solar lamps at an average price of USD 10; No operational costs, phone charging possible with solar lamps ; Energy kiosks as central element in e-waste management, as contact point for warranty claims, repairs and recycling	Yes	https://www.unhcr.org/media/access-clean-energy-refugees-uganda-case-studies; https://energypedia.info/images/e/e0/ESDS_End_User_Finance_Report_Uganda.pdf; https://energypedia.info/wiki/Energy_Solutions_for_Displacement_Settings
Solarization of health facilities	11/2018 – 12/2022	UNHCR, GIZ	six health facilities in Imvepi and Rhino camps	Health care significantly improved and made available to an estimated 60,000 refugees and more than 10,000 host community members; higher upfront costs of 3-3.5 USD/Watt; Cost for electricity from a solar mini-grid generally lower than the national ceiling tariff of 0.3 USD/kWh	MIni-grids of typically 10 kVA or more supply six health facilities in Imvepi and Rhino camps; electricity for light and medical equipment such as refrigerators, microscopes, and baby warmers, as well as for ICT equipment such as mobile phones and landlines	No	https://www.unhcr.org/media/access-clean-energy-refugees-uganda-case-studies; https://globalcompactrefugees.org/sites/default/files/2021-12/HLOM-VirtualSpace-Germany-FactsheetSUN-Energy.pdf
Accessing Markets through Private Sector Enterprises for Refugees Energy (AMPERE)	since 2019	Mercy Corps, RVO	Bidibidi Settlement	Market-based access to solar products benefiting 2,270 refugee households; 56% of solar systems purchased by women; Energy access for small business improving livelihood opportunities; Strengthened off-grid solar market and mobile money sector linkages for PAYGo expansion	Off-grid solar systems, Solar home systems, Solar-powered lanterns, Solar mini-grids, PAYGo (Pay-As-You-Go) technology, Improved cookstoves, Solar-powered energy kiosks, Mobile money platforms, Community mapping technologies (e.g., OpenStreetMap)	Yes	https://www.responseinnovationlab.com/uganda-access-to-clean-energy-in-refugee-settlements; https://www.mercycorps.org/research-resources/affordable-reliable-sustainable-modern-energy

AMPERE: Building Sustainable Markets for Energy Products in Bidibidi Refugee Settlement	07/2019 - 06/2020	Mercy Corps, D-Light, Village Power	Bidibidi Settlement	4,000 products sold to households and enterprises, demonstrating there is a market for OGS products in these communities and an opportunity for energy companies, once adequate supports are in place	Off-Grid-Solar Products (OGS market)	Yes	https://www.humanitarianenergy.org/assets/resources/Improving_Effectiveness_and_Efficiency_in_Humanitarian_Energy.pdf
HOTOSM Energy Saving Retail Mapping	Since 02/2020	Humanitarian OpenStreetMap Team (HOTOSM), Netherlands Enterprise Agency	Bidibidi Settlement	HOT in general: 1,500,000 buildings and 36,000 km of roads digitized using satellite imagery and more than 4000 facilities and services mapped across refugee communities and hosting districts; generated base layer maps that can be used to guide government agencies and organizations in the design and implementation of interventions; 52 sub-counties and 33 refugee zones and engaged more than 550 refugee and host community members; trainings with more than 20 partner organizations and government agencies; datasets are available through OpenStreetMap, and exports via platforms such as the Humanitarian Data Exchange; trainings have been designed for and provided to 23 partner organizations across Uganda and in Tanzania	Retail map, mapping technology: Mapping of energy retailers and sustainable technologies; worked with local refugee communities to collect data from energy-saving solutions retail shops across Bidibidi; assess the distribution and availability of such products and where barriers lay in the existing market	Yes	https://www.hotosm.org/projects/energy-saving-solutions-and-retailers-in-bidibidi-refugee-settlement/; https://www.mercycorps.org/sites/default/files/2020-08/Fact-Sheet_Energy-Saving-Solutions-in-Bidibidi-Settlement.pdf; https://umap.openstreetmap.fr/en/map/energy-saving-solutions-retailers-in-bidibidi-refu_430122#12/3.3909/31.3876
Greening Humanitarian Responses Through Recovery, Repair, And Recycling of Solar Products in Displacement Settings	Since 2022	IOM, Innovation Norway, BRIGHT Products	Bidibidi Settlement	5,300,000 NOK (about EUR 554,600); reached over 110,920 community members with e-waste awareness campaigns, and facilitated the collection and repair of solar lanterns; generated $625.60 in revenue for the community; facilitated the collection of 1,559 solar lanterns and the repair of 513;	solar lanterns and off-grid solar products	Yes	https://www.iom.int/news/ugandas-bidibidi-refugee-settlement-benefit-iom-and-innovation-norways-electronic-waste-management-project; https://www.mercycorps.org/research-resources/sustainable-

				By February 2024, approximately 358 community members had paid for the repair of various e-waste items			community-led-e-waste-management#:~:text=In%202022%2C%20Mercy%20Corps%2C%20in,products%20the%20primary%20energy%20source.
Battery laboratory (BatLab)	Since 2022	IOM, Innovation Norway, BRIGHT Products	Bidibidi Settlement	Households (both host and refugee), Youth, Informal repair technicians and artisans, small businesses and enterprises, e-waste informal collectors, spare parts suppliers: •30 direct jobs created (both refugees and host community), enhancing social cohesion. •5 repair and collection hubs operational across Bidibidi (3 physical hubs + 2 mobile tricycles) •110,920 people reached with awareness campaign •Over 5,900 e-waste items collected • So far, 150 second-life battery packs have been built through repurposing these end-of-life lithium batteries •User data collected and shared with the private sector to improve solar products design. •Sustainable procurement guidelines developed • Developed a Toolkit for E-waste Management in Displacement Settings	Battery laboratory (end-of-life L-ion cells testing, repurposing, and assembly), electronics repair	Yes	https://uganda.iom.int/stories/ioms-electronic-waste-initiative-continues-ease-access-repair-solar-lanterns-bidibidi-refugee-and-host-communities; https://bright-products.com/articles/repair-program-bidibidi-ewaste
Transforming Humanitarian Energy Access (THEA)	09/2024 - 12/2026	Mercy Corps, FCDO, Carbon Trust, Ashden, GPA	Uganda, Ethiopia, and Bangladesh	identifying promising, inclusive energy delivery models; facilitate their replication and scaling, ultimately enhancing energy access for displacement-affected communities; focus on three different country contexts: Uganda, Ethiopia, and Bangladesh; identify inclusive, replicable and scalable business models along a spectrum of market readiness	Diverse technologies: codify existing market-based energy interventions to extrapolate guidelines for other actors to inform future programming, as well scaling up and replicating existing work	no clear information	https://www.mercycorps.org/what-we-do/transforming-humanitarian-energy-access; https://www.humanitarianenergy.org/thematic-working-areas/programmes/thea-programme/

Solar-Electric Cooking Partnership for Displacement Contexts (SOLCO)	2023 - 2027	Last Mile Climate, Ikea Foundation, UNEP Copenhagen Climate Centre	intially Uganda to extend to eight African countries	Transition of more than 250,000 households to solar-electric cooking by 2027; Leverage minimum of $100 million in financing to scale solar-electric cooking solutions; environmental sustainability and stimulate economic development through creation of green jobs across the solar-electric value chain	Solar e-cooking	no clear information	https://unepccc.org/uganda-leads-the-way-on-electric-cooking/; https://www.humanitarianenergy.org/news/latest/solar-electric-cooking-partnership-solco-pledge-for-the-global-refugee-forum-2023
Empowering Clean Cooking Transitions in Bidibidi Refugee Settlement: A SOLCO–NREP Partnership Milestone	24&25/06/2025	NREP, SOLCO	Bidibidi Settlement	World Refugee Day Celebrations in Zone 5; theme "Solidarity with Refugees."; leaders and members of refugee and, host communities, and other key stakeholders such as government, non-government organizations, and donor agencies; various cultural performances and inclusive dialogues on financial inclusion, community led innovation and collaborative partnerships to advance long-term development in refugee settings; private-sector innovators, NGOs and community members	Solar e-cooking	Yes	https://solcopartnership.org/; https://nrep.ug/empowering-clean-cooking-transitions-in-bidibidi-refugee-settlement-a-solco-nrep-partnership-milestone/

Learning derived from relevant energy projects

The overview table on documented learnings (Table 32) shows that relevant lessons were identified across a range of projects in Northern Ugandan refugee settlements. These projects cover areas such as market-based access to energy products, energy retail, e-waste management, and broader innovation on sustainable energy access. Overall, the table indicates that the available learnings relate not only to technology, but also to community engagement, financing, service delivery, and institutional arrangements.

Across the documented learnings, several recurring issues emerge. These include the importance of community engagement and contextual adaptation, the role of financing and affordability, and the need for stronger support systems such as repair services, distribution networks, and awareness creation. The results therefore suggest that sustainable energy access depends not only on the availability of technologies, but also on the wider ecosystem that enables their adoption and long-term use.

The more detailed learning tables add further insight for selected projects. The table on e-waste management (Table 33) highlights the importance of local repair services, cooperative approaches, training, and business support, while also showing that affordability, access to spare parts, and limited awareness remain key barriers. The table on retail mapping in Bidibidi (Table 34) shows that solar products are present, but that fuel-efficient cooking solutions and after-sales services are less developed. It also points to the importance of market analysis for identifying service gaps and planning future interventions.

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Table 32: Overview of learning documented for projects with Northern Ugandan refugee settlements as an implementation site

Project title	Key learnings	Links
AMPERE: Building Sustainable Markets for Energy Products in Bidibidi Refugee Settlement	• Effective Community engagement throughout design and implementation of project • High level of sales demonstrating market-based approaches can work in refugee settlements with appropriate supports • Work with donors and energy companies to develop longer term, phased projects which support sustained operations in the region • including the wider community, not only focused on the refugee settlements	https://www.humanitarianenergy.org/assets/resources/Improving_Effectiveness_and_Efficiency_in_Humanitarian_Energy.pdf
Accessing Markets through Private Sector Enterprises for Refugees Energy (AMPERE)	• Use pilot projects to collect and analyze data on ways to make energy access both sustainable and market-driven in refugee environments. • Conduct geospatial mapping of energy solution retailers (e.g., in collaboration with organizations like the Humanitarian OpenStreetMap Team) to identify where energy-saving products are available and sold within the community. • Leverage mapping insights to address "last-mile" distribution challenges by strategically locating distribution and service agents for optimal reach.	https://www.responseinnovationlab.com/uganda-access-to-clean-energy-in-refugee-settlements
BatLab: E-waste circularity in Bidibidi Refugee Settlement	• co-design approach involved all project partners, refugee and host community members, and local authorities, and ensured solutions were tailored to local needs • Community participation through the IOM Community Response App provided real-time feedback, guiding private sector R&D and enabling continuous refinement of solutions based on end-user experience • leverage the cooperative's governance to source more flexible financial mechanisms • access to flexible financing mechanisms for the cooperative remains a challenge,	https://www.humanitarianenergy.org/assets/resources/Improving_Effectiveness_and_Efficiency_in_Humanitarian_Energy.pdf; https://www.mercycorps.org/sites/default/files/2025-10/ewaste-management-learning-brief.pdf

	and early efforts to bridge this gap can help cooperatives to grow with greater confidence and stability	
Green Innovations Catalogue 2019 -2020	• Sustainable energy access requires market-driven solutions: Pure aid distribution is not enough; combining pay-as-you-go models, private sector involvement, and local cooperatives scales impact. • Community engagement is critical: Solutions succeed when tailored to local needs, cultural norms, and economic conditions, fostering ownership and adoption. • Digital and financial tools improve accessibility: Platforms for savings, mobile payments, and awareness campaigns help low-income users afford and adopt clean energy. • Partnerships amplify impact: Collaboration between humanitarian organizations, private companies, and local actors enhances reach, trust, and sustainability. • Ongoing challenges remain: High transport/logistics costs, behavioral barriers, infrastructure gaps, and market distortions need continual attention.	https://static1.squarespace.com/static/5d7fba1a7dc0f278f09832df/t/5f31bf2a52a6ce3afd7cb015/1597095729676/Green+Innovations+Catalogue+-+Small.pdf
Empowering Clean Cooking Transitions in Bidibidi Refugee Settlement: A SOLCO–NREP Partnership Milestone	• High upfront costs of clean cooking appliances • need for targeted financing, subsidies, and integration with energy access initiatives • participation of financing institutions and the display of diverse technologies highlighted a growing ecosystem of support and innovation for energy transitions in refugee contexts.	https://nrep.ug/empowering-clean-cooking-transitions-in-bidibidi-refugee-settlement-a-solco-nrep-partnership-milestone/

Greening Humanitarian Responses Through Recovery, Repair, And Recycling of Solar Products in Displacement Settings	• Consider developing a self-sustaining financial model that leverages sufficient e-waste volumes to achieve economies of scale. • Explore ways to understand and integrate the local e-waste ecosystem into circular economy solutions. • Test flexible management models that can be adapted to different locations and contexts. • Consider establishing a cooperative business model for inclusive and effective e-waste management. • Use market assessment analysis to guide cooperative pricing structures. • Explore financial sustainability through the introduction of fee-based repair services. • Consider setting up e-waste satellite hubs to expand reach and efficiency. • Map formal and informal e-waste actors to identify potential partnerships and collaborations. • Explore revenue generation opportunities through specialized services, such as a Battery Laboratory (BatLab).	https://www.mercycorps.org/research-resources/sustainable-community-led-e-waste-management#:~:text=In%202022%2C%20Mercy%20Corps%2C%20in,products%20the%20primary%20energy%20source;
E-Waste Management Learning Brief	• Community-led cooperatives improve ownership, inclusivity, and sustainability. • Market analysis & awareness are essential for paid repair service adoption. • Financial sustainability is possible via fee-based services, but requires training and flexible pricing. • Mobile and satellite repair hubs increase accessibility. • Informal e-waste actors can be integrated through training and partnerships. • Battery repurposing (BatLab) offers new revenue streams but needs technical capacity and market support. • Scaling recommendations: strengthen financing, formalize informal actors, expand partnerships, and intensify community awareness.	https://www.mercycorps.org/sites/default/files/2025-10/ewaste-management-learning-brief.pdf

HOTOSM Energy Saving Retail Mapping	• Steady increase in businesses selling energy-saving solutions in Bidibidi, peaking in 2019 with 10 new shops. • Shops are established for various missions, including profit and social impact (e.g., skill training by Raising Gabdho Foundation). • Solar solutions are the most popular energy-saving products, followed by briquettes, cooking bags, water filters, and cookstoves. • Progressive adoption of energy-saving products, with more shops now supported by NGOs, government, and loans. • Nearly half of surveyed retailers cite high upfront costs as the main barrier to wider adoption. • Lack of consumer awareness about available products is also a significant challenge.	https://www.hotosm.org/en/projects/energy-saving-solutions-and-retailers-in-bidibidi-refugee-settlement/; https://www.mercycorps.org/sites/default/files/2020-08/Fact-Sheet_Energy-Saving-Solutions-in-Bidibidi-Settlement.pdf; https://umap.openstreetmap.fr/en/map/energy-saving-solutions-retailers-in-bidibidi-refu_430122#12/3.3909/31.3876

Table 33: Comprehensive overview of learnings of E-Waste Management Learning Brief

Key Area	Key Learnings & Recommendations
Cooperative Business Model	• Community-owned cooperatives foster local ownership and inclusivity. • Partnering with experienced institutions improves governance and compliance. • Limited initial capital constrains inventory and scaling. • Use concessional finance, map informal technicians, provide ongoing capacity building and networking.
Market Assessment & Pricing	• Consumers are willing to pay, but awareness is low. • Spare parts scarcity increases repair costs • Tailored awareness campaigns, track customer preferences, link to spare parts suppliers to reduce costs.
Fee-based Repair Services	• Revenue is possible but demand drops when discounts end. • Households prioritize essential needs over full-cost repairs. • Behavior change communication, discounts/flexible payments, broaden services, strengthen finance and inventory systems.
Satellite Hubs & Mobile Services	• Fixed hubs and mobile tricycle repair services improve accessibility. • Safety, durability, and context-appropriate design are crucial. • Hybrid models are cost-effective, continuous communication increases uptake.
Mapping Informal & Formal Actors	• Informal technicians are key but often under-resourced. • Partnerships with solar/energy companies diversify services. • Formalize and train informal actors, use tiered partnerships and certification to expand capacity.

Battery Laboratory (BatLab)	• Repurposing lithium batteries introduces new revenue streams. • Certification and market acceptance are critical. • Strategic partnerships and training, market assessment for pricing, awareness campaigns and retail linkages for consumer trust.

Table 34: Comprehensive overview of HOTOSM Energy Saving Retail Mapping

Key Area	Insights / Findings
Energy Product Availability	• Market for solar lamps, bulbs, cookstoves, and briquettes is growing. • Solar products dominate; cookstoves and fuel-efficient solutions are less available. • Solar products mostly imported; cookstoves locally produced.
Retail Ecosystem	• Sold by private businesses, NGOs, cooperatives, and social enterprises. • Private businesses are the largest share. • Few retailers offer after-sale services or repairs.
Affordability & Awareness	• High purchase costs limit access for refugee households. • Lack of knowledge about benefits reduces demand. • Low confidence in new technologies slows adoption.
Maintenance & Support	• Repair services for solar and other products are scarce in the settlement. • Items often need to be sent outside Bidibidi for repair, increasing costs and downtime.
Data-Driven Planning	• Mapping and market analysis help identify gaps and intervention points. • Supports awareness campaigns and adoption of energy-saving products. • Enables sustainable, long-term access to clean energy.

b. Projects in Rwanda

This subsection presents the results of the review of relevant energy-related projects in Rwanda. The results are structured in two parts. First, an overview is provided of projects relevant to the energy environment of Mahama and the wider Rwandan refugee response context. Second, the subsection presents learnings derived from relevant projects implemented in Rwandan refugee camps.

Overview of relevant energy projects

The overview table (Table 35) shows that the energy environment of Mahama is shaped by a range of interventions focused mainly on clean cooking and electricity access. The identified projects include improved cookstoves, LPG-based cooking, solar lanterns, solar streetlights, solar home systems, solar mini-grids, and renewable energy solutions linked to livelihoods and productive uses. The table also shows that relevant experience exists not only from Mahama, but also from other refugee camps in Rwanda, placing Mahama within a broader national context of refugee energy interventions.

A key result of the overview is that the Rwandan project landscape combines direct energy provision with market-based and system-supporting approaches. Some projects focused on distributing specific technologies, while others addressed market development, productive uses of energy, community-based maintenance, or financing mechanisms. This shows that energy access in the Rwandan refugee context is shaped by a mix of technological, financial, and institutional approaches.

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Table 35: Overview of projects related to the energy environment of Mahama, Rwanda

Project title	Time	Main actor	Location	Outreach	Technology	SUNNY Demonstration site	Reference links
The Save80 Stove	since 10/2013	UNHCR & Atmosfair	Kigeme, Nakivale	around 4,000 fuel-efficient stoves distributed to refugees, total of 11,000 planned; reduce the emission of approximately 30,000 tons of CO_2 per year in refugee settings in Rwanda	Improved cook stove (ICS): Save80 stove; designed to reduce the amount of firewood used for cooking, according to laboratory tests the Save80 stove requires 80 per cent less wood than traditional cooking methods	no information	https://www.unhcr.org/media/carbon-financing; https://www.unhcr.org/media/global-strategy-safe-access-fuel-and-energy-safe
Become the light project	2017 - 02/2018	UNHCR	Mahama	20,000 families and two major sports grounds	solar lanterns, solar street lights and two solar mini-grid systems	Yes	https://www.unhcr.org/news/stories/ioc-launches-campaign-bring-light-refugee-camps#:~:text=%E2%80%9CSport%20restores%20childhood.,Korea%2C%20in%20February%20next%20year.
Pilot project gasifier pellet stove	2017 - 2018	UNHCR, IKEA Foundation, Inyenyeri	Kigeme	initial pilot focused on serving approximately 300 families in the Kigeme refugee camp, plans to eventually expand the service to the entire camp population and potentially other camps in Rwanda, ended in 2018 due to high costs associated with the high-quality technology	gasifier stove using pellets, with an efficiency of 45%, corresponding to tier 4 in the access to energy ranking scheme; used pellets made from compressed biomass, which are more homogeneous and efficient than raw wood or charcoal	No	https://cleancooking.org/wp-content/uploads/2021/07/552-1.pdf; https://www.unhcr.org/innovation/a-solution-that-gives-refugees-a-choice/

Humanitarian Engineering and Energy for Displacement (HEED)	2017 - 2021	Coventry University	Rwanda: Ghiembe, Nyabiheke and Kigeme; Nepal: IDPs living in Khalte	£1.1 million; Congolese refugees in Rwanda and IDPs in Nepal	Solar streetlights, Standalone Solar System , PV-battery micro-grid, Stove Use Monitors (SUM), Sensor monitor mobile solar lanterns, Individual Appliance Monitors (IAMS), Footfall monitoring	No	http://heed-refugee.coventry.ac.uk; https://heed-data-portal.coventry.ac.uk/
Renewable Energy for Refugees (RE4R)	04/2017 - 02/2022	Practical Action	Rwanda: Kigeme, Nyabiheke and Gihembe refugee camps; Jordan: Irbid	€8.6 million; Rwanda: 66,000 people/ Jordan: 17,000 people; installed 815 solar streetlights and created 200 dignified jobs for refugees and host community members	Rwanda: Biomass cooking technologies, Solar home systems, Solar systems for small enterprises, Camp-wide solar street lighting, Solar mini-grid for institutions and community facilities; Jordan: Solar water heating systems and energy efficiency upgrades, (Skills training and capacity building), Onsite PV and energy efficiency upgrades for public schools	No	https://practicalaction.org/our-work/projects/re4r/; https://www.unhcr.org/renewableenergy4refugees/; https://globalcompactrefugees.org/good-practices/renewable-energy-refugees-re4r; https://www.humanitarianenergy.org/assets/resources/RE4R_Household_Electriciy_SHS_June_2021_vFin.pdf
Solar streetlights with community ownership (RE4R)	Since 2017	UNHCR, IKEA Foundation, SOLEKTRA Rwanda, Practical Action	Kigeme, Gihembe, Nyabiheke	185 additional solar streetlights installed: 60 in Kigeme, 62 in Gihembe, 63 in Nyabiheke	Solar streetlights: 10–20 year lifespan + seven years warranty; Single light cost of €1.159 and double light cost of €1.595	No	https://www.unhcr.org/sites/default/files/legacy-pdf/632481844.pdf; https://solektra.rw/works/solar-street-lights-installation-in-refugee-camps/#:~:text=Solar%20Street%20lights%20were%20installed,to%20socio%2DEconomic%20investment%20opportunities
Solar Home Systems through a marketbased approach (RE4R)	Since 2018	UNHCR, Practical Action	Kigeme, Nyabiheke, Gihembe	4,279 households (58% of the targeted populations) purchased SHS through a market-based approach; 70 refugees trained by suppliers and hired as sales agents and	Solar Home Systems (SHS): SHS cost (50W) of 5.05 $/month and 3.05 /month with subsidy | SHS cost (20W) of 2.74 $/month; 6–8h hours electricity per day for lighting, mobile	No	https://www.unhcr.org/sites/default/files/legacy-pdf/632481844.pdf; https://research-information.bris.ac.uk/ws/portalfiles/portal/282165224/Paper_3_Final_Accepted

				technicians in the camp	phone charging and small electronics such as radios		_Version.pdf
Improved cookstoves with pellets through a market-based approach (RE4R)	2019 – 2021	UNHCR, Inyenyeri, Energy 4 Impact, SNV	Kigeme	6,951 households purchased improved cookstoves through a market-based approach; 75 refugees trained and hired as sales agents, technicians and construction workers in the camp; 50% camp-wide access to cleaner cooking after the intervention	Improved cooking stoves: Cookstoves with 32.7% efficiency and one year warranty, Stove cost of $30 / $12–13 with subsidy; Pellets made from sawdust and forest residues	No	https://www.unhcr.org/sites/default/files/legacy-pdf/632481844.pdf; https://data.unhcr.org/en/documents/download/107462; https://data.unhcr.org/en/documents/download/107462
Access to clean cooking energy solutions in refugee camps in Rwanda	Since 01/2019	Ministry in charge of Emergency Management (MINEMA) & UNHCR Rwanda	Mahama, Mubombwa, Nkamira	10,500 gas stoves	mix of briquette and pellet fuel solutions in the smaller camp populations and LPG in the largest refugee camp (Mahama)	Yes	https://www.unhcr.org/sites/default/files/legacy-pdf/632481844.pdf; https://globalcompactrefugees.org/good-practices/alternative-cooking-fuel
Distribution of LPG cooking fuel	Since 01/2019	UNHCR, Energy 4 impact	Mahama, Mugombwa	100% coverage in Mahama and Mugombwa camps (18,500 households); >200,000 LPG cylinder fillings/year donated by UNHCR	LPG gas cylinders and cookers: Stove costs of $18-20 with one burner and $27-45 with two burners; $2 montly LPG refilling cost per person	Yes	https://globalcompactrefugees.org/good-practices/alternative-cooking-fuel; https://mecs.org.uk/wp-content/uploads/2021/10/Policy-and-market-review-for-modern-energy-cooking-in-Rwanda.pdf

Renewable Energy for Refugees - Phase II (RE4RII)	08/2022 - 04/2027	Practical Action, Sida	Kigeme, Nyabiheke, Mahama, Mugombwa, Kiziba	£6 million; Over 8000 refugee households	Solar Home Systems, clean cooking, solar streetlights, & PUE for livelihoods	Yes	https://practicalaction.org/our-work/projects/renewable-energy-for-refugees-a-second-phase-of-impact/; https://umc.rw/2024/01/31/renewable-energy-for-refugees-re4r-2/
Result based Financing for Refugees (RBF4R)	under implementation (06/2025)	Practical Action, GIZ, EnDev	Mahama, Nyabiheke, Kigeme, Kiziba, Mugombwa	6,700 vulnerable HHs; Supporting 50 female refugee entrepreneurs with gaining business and financial skills to establish or enhance their enterprises	higher-tier cookstoves; productive use of renewable energy (PURE) Appliances (standalone Solar refrigerators) and Solar Home systems (100-200 W) appliances	Yes	https://practicalaction.org/news-stories/local-news/how-were-making-clean-cooking-work-for-africa/; https://www.jobinrwanda.com/sites/default/files/job_description_files/revisedrequest-proposal-supply-productive-use-renewable-energy-appliances-standalone-solar.pdf
Refugee Environmental Protection Fund (REP Fund)	In procurement process (06/2025)	UNHCR	Kigeme camp as pilot project in Rwanda	tens of millions more trees and hundreds of thousands of refugees and their hosts to access clean cooking solutions; over 10+ years; initial capitalization target for fund pilot project is USD $30 million in grants, which is expected to unlock USD +200m in carbon financing	reforestation and clean cooking	No	https://www.unhcr.org/what-we-do/build-better-futures/climate-change-and-displacement/strengthening-climate-adaptation-0; https://globalcompactrefugees.org/pledges-contributions/multi-stakeholder-pledges-2023/multi-stakeholder-pledge-refugee-environmental#:~:text=The%20REP%20Fund%20is%20the,environmental%20degradation%20in%20these%20contexts

Rwanda: Learning derived from relevant energy projects

The overview of documented learnings (Table 36) shows that relevant lessons are available from projects on clean cooking, solar streetlighting, and solar home systems in Rwandan refugee camps. Across these projects, a recurring finding is that there is strong demand for improved energy solutions, especially where they bring visible benefits such as greater safety, health improvements, time savings, or convenience. At the same time, affordability remains a major barrier, particularly where technologies involve higher upfront or recurring costs.

Another important result is that market-based approaches can be valuable but require supportive conditions. The documented learnings indicate that such approaches are more effective when combined with measures such as subsidies, flexible payment options, demand creation, and stronger local supply systems. The learnings also highlight the importance of maintenance, repair, and local technical support. Reliable after-sales service, access to spare parts, and the involvement of camp residents in operation and maintenance are repeatedly identified as important for long-term use.

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Table 36: Overview of learning documented for projects with Rwandan refugee camps as an implementation site

Project title	Key learnings	Links
Pilot project gasifier pellet stove	• Strong demand and waiting lists demonstrated preference for Tier 4/5 clean cooking solutions • High-tier stoves achieved measurable impacts: 83% reduction in respiratory symptoms, 96% improved fuel-collection safety, five times faster cooking • Market-based delivery treated refugees as consumers, increasing ownership and informed choice • Unrestricted cash-based assistance was essential to enable fuel purchasing and market function • Public–private partnerships supported innovation and scalable implementation • Recurrent fuel costs were the primary barrier to sustained use despite high satisfaction • Long-term affordability likely requires subsidies and/or integration with income-generating activities • Integrated interventions delivered co-benefits across protection, health, environment, and livelihoods • Local fuel value chains created employment and ownership but required significant capital and logistical support	https://www.unhcr.org/sites/default/files/legacy-pdf/632481844.pdf#:~:text=In%202017%2C%20a%20pilot%20project%20in%20partnership,high%20quality%20solution%20at%20tier%20level%204.
Solar streetlights with community ownership (RE4R)	• High initial costs often need subsidies, especially for international SSL procurement. • Battery replacement is necessary during SSL use; local spare parts are essential for efficient maintenance. • Involving camp residents in maintenance, repair, site selection, and operation improves affordability and system ownership. • Regular cleaning and upkeep — especially in dry, sandy areas — are required, and trained residents can help ensure SSL function.	https://www.unhcr.org/sites/default/files/legacy-pdf/632481844.pdf

Solar Home Systems through a marketbased approach (RE4R)	• Factors such as power output, system size, local access, spare parts availability, and financing play a major role in the adoption of SHS. • While higher product quality encourages uptake, it also increases costs; SHS solutions should align with household requirements. • The likelihood of purchase is heavily influenced by household income, highlighting the importance of supporting productive energy uses. • Measures like subsidies, extended repayment periods, and opportunities for income generation can make SHS more affordable. • Involving refugees in roles such as sales, technical support, and e-waste management supports job creation and improves implementation.	https://www.unhcr.org/sites/default/files/legacy-pdf/632481844.pdf
Improved cookstoves with pellets through a market-based approach (RE4R)	• Cookstove types vary by ease of use, cultural fit, cost, sourcing, financing, and distribution. • The country needs suppliers with adequate production capacity and quality for stoves and pellets. • Improved cookstoves provide health and environmental benefits, but affordability drives adoption. • Sustaining the solution requires a reliable, long-term supply of pellet materials. • Financial support may help local suppliers enhance capacity, affordability, and product quality.	https://www.unhcr.org/sites/default/files/legacy-pdf/632481844.pdf
Distribution of LPG cooking fuel	• Subsidies help cover high initial costs for gas cylinders, cookers, and related logistics. • Financial planning should include budgeting for the organization of LPG supply. • Imported equipment and LPG prices are influenced by market fluctuations and government regulations. • Awareness campaigns educate refugees on safe and efficient LPG usage. • Engaging camp residents in distribution builds skills, generates employment, and promotes self-reliance.	https://globalcompactrefugees.org/good-practices/alternative-cooking-fuel

Social impact assessment by the International Center for Research on Women (ICRW) in Rwanda	• Interventions should prioritize long-term impact and scaling over pilot projects. • Cooking programs must consider user preferences and leverage local capacity and willingness to pay, reducing reliance on donor support. • In areas with low refugee income and new fuel markets, sustained funding is needed to build markets and encourage private sector involvement. • Investing in infrastructure and demand generation can lower costs of alternative solutions, supporting a gradual move away from subsidies and enhancing sustainability. • Integrating interventions with existing local markets and supply chains improves distribution and effectiveness. • Considering the wider local economy, not just refugees, increases intervention sustainability.	https://www.chathamhouse.org/sites/default/files/publications/2019-01-22-PatelGross2.pdf
The diffusion of Solar Home Systems in Rwandan refugee camps	• SHS can significantly improve household lighting, safety, phone charging, and children's study, demonstrating clear relative advantage over existing solutions. • Adoption is constrained by system capacity, weather sensitivity, portability concerns, and affordability, with many households unable to pay market rates. • PAYG payment models and maintenance processes need to be user-friendly, and local technician support is critical for sustaining adoption. • Direct engagement through trained sales agents is more effective than relying on opinion leaders or mass communication alone. • Future interventions should increase system capacity, offer flexible payment schedules, strengthen after-sales support, and provide safeguards for low-income households.	https://research-information.bris.ac.uk/ws/portalfiles/portal/282165224/Paper_3_Final_Accepted_Version.pdf

c. Relevant documented generalized learnings for projects in displacement context

This subsection presents selected learnings from relevant projects and publications beyond Uganda and Rwanda. The purpose is to complement the country-specific findings with additional experience from other displacement and off-grid contexts and to identify cross-cutting insights relevant for SUNNY.

The table shows several recurring themes. A first key result is the importance of aligning energy solutions with user needs and local conditions. This includes selecting appropriate technologies, considering existing practices, and supporting uptake through awareness raising and context-sensitive implementation. A second important result is that sustainable energy access depends not only on the technology itself, but also on enabling conditions such as distribution systems, maintenance and repair services, technical support, and strong partnerships. A third recurring finding concerns affordability and financing. The reviewed projects highlight that flexible payment models, subsidies, and other targeted financing approaches are often necessary to enable adoption, especially in low-income and displacement settings.

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Table 37: Relevant documented generalized learnings for projects in displacement context

Project title	Key learnings	Links
Mapping Successful Cookstove Distribution Models: Eight Success Factors to Reach the Last Mile	• Identify and select suitable stove models. • Develop innovative strategic partnerships. • Prepare effectively for market entry within target communities. • Provide comprehensive bundled product solutions. • Ensure the sales team is highly trained and motivated. • Minimize financial obstacles for customers. • Leverage peer networks and word-of-mouth marketing. • Foster sustained long-term demand in the market.	https://beamexchange.org/media/filer_public/e5/0d/e50d9a26-f413-4878-9160-1c48dcb1de4e/mapping cookstoves_distribution.pdf
Facilitating market-based access to clean cooking fuels in refugee camps	• Market-based clean cooking enables refugees to procure fuels themselves, potentially with cash assistance. • Biomass pellets are currently the only viable market-based fuel: affordable, clean, renewable, and locally produced. • Pellets are cost-competitive, with daily household expenses of ~0.2–0.3 USD, similar to or lower than charcoal. • Fast, smoke-free cooking improves usability and uptake in refugee camps. • Pellets could cover up to 32% of Rwanda's clean cooking target, and serve as a backup option where LPG distributions exist. • In the medium to long term, shifting from LPG in-kind distributions to cash-based pellet purchases is feasible. • For camps with cash-for-energy (CfE) assistance, pellets provide an affordable and cleaner alternative to charcoal.	https://data.unhcr.org/en/documents/download/107462

Cooking in Displacement Settings Engaging the Private Sector in Non-wood-based Fuel Supply	• Reliance on biomass fuels: Refugees in displacement settings mostly use firewood or charcoal, which is unsustainable, unsafe, and unhealthy. • Private sector potential: Camps represent a concentrated market, offering opportunities for private companies to supply non-wood fuels like LPG. • Market-based solutions work: The Kakuma, Kenya case showed that a concession model could provide fuel affordably while attracting commercial actors. • Refugees as active consumers: Interventions should account for willingness to pay, existing fuel habits, and local market dynamics. • Partnerships are essential: Collaboration between humanitarian agencies, private firms, and local authorities ensures feasibility and sustainability. • Long-term support needed: Sustained funding and policy backing help create markets that can eventually operate without subsidies. • Inclusive market design: Involving host communities alongside refugees strengthens market viability and social cohesion.	https://www.chathamhouse.org/sites/default/files/publications/2019-01-22-PatelGross2.pdf

Powering progress: market creation strategies for solar e-cooking technologies in off-grid and displaced communities	• Prioritize clean cooking solutions: Solar e-cooking reduces emissions, improves health, and enhances safety for displaced populations, especially women and children. • Address cost barriers: Use innovative financing models (pay-as-you-go, microfinance, carbon credits) to make clean cooking affordable in camp or off-grid settings. • Support both supply and demand: Build local distribution networks, service providers, and technical capacity while raising awareness among residents about benefits and proper use. • Integrate policies and partnerships: Coordinate across energy, humanitarian, and climate actors to align resources, strategies, and scaling opportunities. • Tailor solutions to context: Adapt technologies to local cooking habits, fuel availability, and cultural preferences for higher adoption rates. • Maximize co-benefits: Beyond energy access, promote economic activities, education, gender equity, and environmental protection in displacement settings.	https://unepccc.org/wp-content/uploads/2024/05/powering-progress-market-creation-strategies-for-solar-e-cooking-in-off-grid-and-displaced-communities.pdf
Protection-Sensitive Access to Lighting	• Lighting improves safety, especially for women and children, by enabling secure movement and facility use. • Engaging refugees, host communities, and women throughout project stages boosts ownership and sustainability. • Choose delivery methods suited to context: in-kind for emergencies, cash for flexibility, market-based to support local economies. • Planning for maintenance, including training technicians and supplying parts, ensures lights keep working. • Address environmental and safety issues with renewables, efficient devices, safe e-waste disposal, and electrical hazard prevention. • Monitor access, usage, and outcomes to refine programs and measure impact.	https://www.unhcr.org/sites/default/files/legacy-pdf/63fcd2fe4.pdf

Result-based financing	• Design results-based financing with explicit inclusion goals. • Identify and analyze marginalized groups, including the poorest, refugees, women, and girls. • Tie payments to outcomes benefiting "Leave No One Behind" groups, using strong verification. • Support implementers to help them reach excluded populations. • Use dual incentives: reward companies for inclusive action and customers for adopting solutions. • Monitor progress, adapt as needed, and use targeted subsidies alongside results-based financing if necessary.	https://endev.info/wp-content/uploads/2024/10/241022_RBF_LNOB.pdf
Refugee Environmental Protection Fund (REP Fund)	• Sustainable financing: Carbon credit revenues fund ongoing environmental protection and clean energy for refugees and hosts. • Integrated goals: Reforestation and clean energy together cut deforestation, boost health, and restore ecosystems. • Community engagement: Involving locals ensures culturally relevant and accepted solutions. • Green jobs: Employment in nurseries, reforestation, stoves, and carbon markets supports women, youth, and marginalized groups. • Verification: Certification standards uphold credibility and accountability. • Equitable sharing: Prioritizing benefits for refugees and hosts keeps interventions impactful. • Scalability: Adaptable project designs enable broader implementation and learning.	https://www.unhcr.org/what-we-do/build-better-futures/climate-change-and-displacement/strengthening-climate-adaptation-0; https://www.unhcr.org/media/refugee-environmental-protection-fund-annual-report-2024

VIII. SUMMARY AND OUTLOOK

This deliverable documents the work carried out under Task 1.3 and Task 1.4 of the SUNNY project. It brings together several complementary components: an overview of the SUNNY technologies and innovations, the specification of energy needs, the definition of environmental requirements, the development of project-specific use cases, and the comparison of these use cases with related projects and documented project learnings. Taken together, these components provide a structured analytical basis for understanding the technologies addressed in SUNNY, the needs and conditions of their intended application contexts, the sustainability-related requirements relevant for their development, and the practical pathways through which they can be implemented in the demonstration sites.

The results presented in this deliverable will be taken up in the next phases of the project. They provide an important basis for the further refinement and adaptation of SUNNY technologies in WP3, support the preparation and implementation of demonstrations in WP4, and contribute to considerations related to transferability, replication, and broader impact in WP5. In this way, the work documented in Deliverable D1.3 forms a bridge between the analytical work carried out in WP1 and the subsequent technical and implementation-oriented phases of the SUNNY project.

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IX. ANNEX – USE CASE TEMPLATES

1. Guide to reading the SUNNY use case template

a) Purpose of this guide

The SUNNY use case specifications are based on the IEC 62559-2 use case methodology, but they are adapted to the realities of the SUNNY project. In particular, the SUNNY template goes beyond a purely technical reading of use cases by adding socio-economic, ecological, and business-related dimensions. This guide explains how to read the resulting use case specifications and how to interpret their main elements.

b) How the SUNNY use case template differs from the standard framework

The SUNNY project uses IEC 62559-2 as a guiding framework but adapts it to the characteristics of energy access in refugee and host-community contexts. The standard methodology and related repositories are primarily geared towards European contexts and do not sufficiently capture the environmental, socio-economic, and business issues that are central to SUNNY. For this reason, the SUNNY template adds socio-economic, ecological, and business objectives, user stories, ecological KPIs, additional categories of use case conditions, and non-technical requirements.

As a result, SUNNY use cases should not be read as purely technical system descriptions. They are better understood as structured implementation documents. Each use case explains not only what the technology does, but also why it is relevant, which actors are involved, under which conditions it can function, how success will be assessed, and which requirements must be fulfilled for implementation in the demonstration context.

c) Recommended reading order for the SUNNY use cases

Identification, scope, and objectives
The first step is to read the identification, scope, and objectives. This section clarifies what the use case is about, which technology and context it refers to, and which technical, socio-economic, ecological, and business objectives it is expected to achieve. It provides the basic framing for the rest of the document.

Narrative of the use case
The second step is to read the narrative of the use case. This includes the short

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description, the user story, and the complete description. For most readers, this is the most accessible entry point because it explains the use case in plain language and from the perspective of its intended users.

KPIs

The third step is to review the KPIs. In the SUNNY template, these include both project KPIs and ecological KPIs. This section shows how the success of the use case will be assessed and which objectives are considered most important.

Use case conditions

The fourth step is to examine the use case conditions. In SUNNY, these are grouped into technical, environmental, socio-economic, and business conditions. They explain the assumptions and prerequisites that must be in place for the use case to work. This section is particularly important because it shows that implementation depends on more than technical functionality alone.

Actors

The fifth step is to review the actors. The template distinguishes between business actors, operators, and logical actors. Reading this section helps clarify who is involved, who operates the system, and which technical entities are part of the use case.

Scenario overview

The sixth step is to read the overview of scenarios. This section breaks the use case into operational parts and shows, for each scenario, the primary actor, the triggering event, and the pre- and post-conditions. For understanding how the use case works in practice, this is one of the most important sections.

Step-by-step analysis

The seventh step is to read the step-by-step analysis. This section expands each scenario into individual events, activities, actors, information exchanges, and linked requirements. It is more detailed and technical than the narrative, but it is especially useful for readers who want to understand implementation logic in depth.

Information exchanged and requirements

The eighth step is to review the sections on information exchanged and requirements. These clarify what information must move between actors or systems and which specific conditions have to be fulfilled for the use case to operate successfully.

References and definitions

The final step is to consult the references and the section on common terms and

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definitions. These support interpretation, clarify terminology, and link the use case to relevant standards, frameworks, and background documents.

d) Key terms for reading the SUNNY use case specifications

Use case: A use case can be understood as a structured description of how a system creates value for one or more actors. In the SUNNY deliverable, use cases are presented as one of the main ways of specifying how individual technologies are intended to function in the demonstration sites.

Scenario: In the SUNNY use case template, a use case is composed of several scenarios. Each scenario describes a distinct part of the overall process and is structured around a primary actor, a triggering event, a pre-condition, and a post-condition. In other words, a scenario is a specific operational sequence within the wider use case.

Scope and objectives: The scope defines the boundaries of the use case. It clarifies what is covered and what is not covered. The objectives explain what the use case is intended to achieve. In the SUNNY template, objectives are grouped into technical, socio-economic, ecological, and business objectives.

Narrative: The narrative of the use case explains the use case in prose form. It usually includes a short description, one or more user stories, and a complete description. The purpose of this section is to make the use case understandable before the reader moves to more detailed operational and technical sections.

User story: A user story expresses the intended value of the use case from the perspective of the end user. In the SUNNY template, user stories help connect the technology description to concrete needs, such as affordability, access, convenience, or environmental improvement.

KPIs: KPIs, or key performance indicators, are the indicators used to assess whether the use case meets its objectives. In SUNNY, these include both project KPIs and ecological KPIs. They therefore reflect not only technical performance, but also environmental and implementation-related priorities.
Use case conditions

Use case conditions describe the circumstances under which the use case can function. The SUNNY template distinguishes between assumptions and prerequisites and further separates them into technical, environmental, socio-economic, and business conditions. This means that a use case is understood as depending on a wider implementation

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environment, not only on the technology itself.

Actors: A business actor is a physical or legal person with their own interests or goals in the use case. An operator is a business actor who operates a system. A logical actor is a technical entity that participates in the execution of the use case and can be mapped to a physical component. This distinction is important because SUNNY use cases combine social, organizational, and technical perspectives.

Triggering event, pre-condition, and post-condition: A triggering event is the event that starts a scenario. A pre-condition is the condition that must already be fulfilled before the scenario can begin. A post-condition is the state that should exist once the scenario has been completed. These three elements together make the scenario structure easier to follow.

Information exchanged and requirements: Information exchanged refers to the information, data, messages, or records that move between actors or technical elements during the execution of the use case. Requirements are the specific conditions or capabilities that must be met for the scenario or the wider use case to function as intended. In the SUNNY template, the step-by-step analysis explicitly links activities, information exchanges, and requirement IDs.

e) How to use the SUNNY use case specifications in practice

For a first reading, the most useful sections are the scope and objectives, the narrative, the KPIs, and the scenario overview. Together, these sections provide a concise understanding of what the technology is meant to do, why it matters, and how the overall process is structured.

For a more implementation-oriented reading, the use case conditions, actors, step-by-step analysis, information exchanged, and requirements become particularly important. These sections help identify operational dependencies, responsibilities, data flows, and concrete conditions that must be addressed during technology refinement, testing, and demonstration.

The most important point to keep in mind is that SUNNY use cases are multi-dimensional. They are based on the IEC 62559-2 methodology, but they have been adapted so that technical, social, environmental, and business considerations can be read together within one structured document.

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2. Rwanda: Solar home systems

1. Description of the use case

1.1 Name of the use-case

Use case identification		
ID	***Area/Domain/Zone(s)***	***Name of the use case***
UC1	Area: Energy Systems Domains: DER, Customers Zones: Process, Field	Rwanda: Multi-Household Solar System for Electricity Access in Off-Grid Communities

1.2 Version management

Version management				
Version No.	***Date***	***Name of author(s)***	***Changes***	***Approval status***
0.1	27/10/2025	Nora Stognief - TUB	Draft	
0.2	11/10/2025	SOLEKTRA RWANDA LTD	Draft	
0.3	17/11/2025	Nora Stognief - TUB	Draft	
0.4	10/12/2025	Nora Stognief - TUB	Draft	
0.5	16/12/2025	Nora Stognief - TUB	Draft	

1.3 Scope and objective of use case

Scope and objectives of the use case	
Scope	This use case is limited to the study of sharing of Solar Home System between multiple households in a displacement context in Rwanda.
Technical Objective(s)	• Integrate and test an IoT-enabled PCB developed by LUT within SOLEK's SHS hardware. • Validate interoperability between IoT data systems, the PAYG backend, and mobile-money platforms. • Demonstrate modular upgrade capacity from 76 Wh to 150 Wh and assess shared-use configurations among households. • Ensure product compliance with **IEC 62257-9-5** and **VeraSol** certification standards for reliability and safety.
Socio-Economic Objective(s)	• Increase access to affordable and reliable energy for refugee and host households. • Test shared-use PAYG models to lower per-user energy costs. • Generate local employment through training of technicians. • Strengthen financial inclusion via integration of mobile-money payments. • Contribute to digital inclusion by familiarizing rural users with connected technologies (IoT, PAYG).
Ecological Objective(s)	• Reduce reliance on kerosene and diesel generators, cutting household CO_2 emissions by approximately 0.5 tons/year per unit and improving air quality. • Promote circular-economy principles through eco-design. • Extend equipment lifespan and minimize electronic waste through real-time monitoring and preventive maintenance.

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Business Objective(s)	• Develop a commercially viable PAYG SHS product with integrated IoT data for credit risk management. • Prepare for product certification and market entry via VeraSol / Lighting Global pathways. • Create a scalable SHS service model for humanitarian and rural electrification programs across East Africa. • Attract impact investors by demonstrating data-driven performance and social impact metrics.
Related business case(s)	• Integration of IoT-enabled SHS within Rwanda's national off-grid strategy (RURA / MININFRA). • Expansion opportunities through partnerships with humanitarian programs (UNHCR, GIZ, World Bank EEP). • Alignment with SOLEK's broader business model linking energy access, digital services, and PAYG financing across East Africa.

1.4 Narrative of use case

Narrative of use case
Short description
The modular Solar Home System (SHS) concept is designed to enhance energy access and affordability for refugee and host communities in Rwanda. The improved SHS transitions from the earlier H2G and H3G versions (76 Wh) to a higher-capacity 150 Wh modular system. This enables connection of small appliances and shared use among several households. The design integrates LUT's new IoT-enabled PCB, allowing remote monitoring, performance analytics, and fault detection. The improved solution extends the scope of an individual SHS to serve five households. This enables investment costs to be shared, resulting in a reduction of 75% in investment costs per household for equal loads. Moreover, SUNNY will implement innovative financing models, such as pay-as-you-go systems, microloans, possibility to have different tariffs, subsidies, and cross-subsidies to make SHS even more accessible for communities with limited financial resources. The SHS solution is informed by socio-economic and affordability surveys, currently being conducted across Mahama refugee camp and host communities. These surveys aim to identify energy behaviors, willingness to pay, and affordability thresholds. Eco-design and sustainability KPI development ensure that the SHS model aligns with circular economy principles.
User story
As a resident of Mahama refugee camp, I want a solar home system to get access to electricity. As a resident of Mahama refugee camp, I want to switch to renewable electricity to improve the air quality in and around my family's home. As a resident of Mahama refugee camp, I want a low-cost solar home system so that I can afford it. As a resident of Mahama refugee camp, I want to share the cost of a solar home system with my neighbors so that I can afford it.
Complete description
The SHS are an improvement on an existing system and have already been installed in 5 refugee camps by SOLEKTRA. Solar home systems have made significant strides in providing clean and reliable energy to households in off-grid and rural areas. SHS typically consist of photovoltaic (PV) panels, a battery storage unit, and various electronic components to distribute the generated energy. An important limitation to their developments is capacity: Current designs are limited to serving individual households and do not allow for system extensions to satisfy growing energy needs. SUNNY will provide a modular solution through which the storage capacity is increased from 76 Wh (current state of the art) to 150 Wh. The improved solution extends the scope of an individual SHS to serve up to five households. Thus, it bridges the gap between SHS and minigrids, which are often too costly and require extensive organizational efforts. The resulting synergies allow for a connection of households with basic loads, which currently is uneconomic and simultaneously expands the maximal loads a SHS can provide to an individual household, beyond what is currently possible. Maintenance and Support: Irregular intervention by maintenance technicians leads to longer downtimes and shorter system lifespans. To remedy this, IoT (Internet of Things) technology will be integrated to remotely monitor system performance, diagnose issues, and provide timely maintenance. The use of IoT functionality will go beyond monitoring through the control of different load levels at different times (e.g., shared utilization of basic loads and alternating access to higher loads). Knowledge transfer to technicians and users will also contribute to this challenge. Recent improvements in SHS includes: i) Efficiency: Advances in PV technology have improved the efficiency of solar panels, allowing them to capture more sunlight and convert it into electricity. ii) Battery Storage: Lithium-ion and other advanced battery technologies have increased energy storage capacity and lifespan, ensuring uninterrupted power supply even during cloudy days or nighttime. iii) Energy Management: Smart controllers enable efficient energy distribution, optimizing power usage and extending the lifespan of batteries. iv) Appliance Compatibility: Modern solar home systems are designed to power a range of appliances, from LED lights and mobile chargers to fans and small televisions.

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Business Actors: **SOLEK (System Owner), Local Technicians, Local Community/Household Users, Mobile Money Providers (MTN/Airtel), LUT (IoT Data Management Partner)** These actors define and sustain the SHS business model: SOLEK designs and operates the systems; LUT provides IoT data management; local technicians ensure after-sales service; users pay for energy through mobile money; and telecom partners process transactions. Operator: **SOLEK Backend Team / PAYG Operator** Operates the PAYG platform, activates and monitors devices, processes user data, and coordinates maintenance responses. Logical Actor: **PV Production Unit (Solar Panels), Storage Unit (Battery), IoT System (PCB + Modem), Distribution Line** Together these logical actors form the SHS hardware ecosystem: panels generate energy, batteries store it, the IoT system monitors and reports performance, and the distribution line connects multiple households in a shared system model.

1.5 Key performance indicators

1.5.1 Project KPIs

Project KPIs			
ID	***Name***	***Description***	***Reference to mentioned use case objectives***
1	CAPEX reduction compared to existing alternative	Target: 75%/household	Increase access to affordable and reliable energy for refugee and host households.
2	OPEX reduction compared to existing alternative	Target: 60-70%/household	Increase access to affordable and reliable energy for refugee and host households. Test shared-use PAYG models to lower per-user energy costs.
3	Percentage increase in lifetime of products used in the demonstrator locations	Target: 40%	Promote circular-economy principles through eco-design supported by HUDARA. Extend equipment lifespan and minimize electronic waste through real-time monitoring and preventive maintenance.
4	Storage capacity enhancement of the SHS	Target: From 76 to 150 Wh	Demonstrate modular upgrade capacity from 76 Wh to 150 Wh and assess shared-use configurations among households.
9	GHG emissions mitigated with SUNNY solutions	Target: 0.5 tCO2eq/year *500 users	Reduce reliance on kerosene and diesel generators, cutting household CO_2 emissions by approximately 0.5 tons/year per unit.
17	Number of people benefiting from an enhanced access to energy	Target: 500	Increase access to affordable and reliable energy for refugee and host households.
23	Reduction of respiratory diseases due to solar lighting, and cleaner cooking fuels	Target: 50%	Reduce reliance on kerosene and diesel generators, cutting household CO_2 emissions by approximately 0.5 tons/year per unit and improving air quality.
25	Percentage of energy solutions replaced by clean technologies in the demonstration sites	Target: 10%	Reduce reliance on kerosene and diesel generators, cutting household CO_2 emissions by approximately 0.5 tons/year per unit.

1.5.2 Ecological KPIs from REFUSE's Ecodesign Toolkit

Ecological KPIs

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ID	Name	Weight	Scoring
Theme 1: Nature-Based Design, Environmental Footprint			*67%*
1.1	Local material sourcing	0%	0.00
1.2	Use of natural/low-impact materials	25%	1.00
1.3	Toxicity potential	0%	0.00
1.4	Local water risk sensitivity	0%	0.00
1.5	Nature-based or low-tech integration	6%	0.00
1.6	Climate change mitigation potential	25%	0.75
1.7	Climate change adaptation support	25%	0.75
1.8	Footprint of material sourcing	13%	0.13
1.9	Circularity of material sourcing	6%	0.06
Theme 2: Durability and Repairability			*73%*
2.1	Design lifetime	11%	0.43
2.2	Ease of disassembly	25%	0.50
2.3	Tools required for maintenance and repair	25%	0.50
2.4	Spare parts availability	19%	0.19
2.5	Spare parts cost	25%	1.00
2.6	Repair documentation	19%	0.38
2.7	Modularity	19%	0.56
2.8	Remote support	25%	1.00
2.9	Upgradeability	25%	0.75
2.10	Resilience to environmental conditions	25%	1.00
Theme 3: Recyclability & End of Life Management			*61%*
3.1	Recyclability	17%	0.50
3.2	Reusability, second life potential	17%	0.50
3.3	Hazardous materials share	13%	0.25
3.4	Ease of material separation	17%	0.33
3.5	Local disposal/recycling chain	4%	0.04
3.6	Takeback schemes at End of Life (EOL)	8%	0.25
3.7	Materials, components identification	8%	0.08

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3.8	EOL documentation	17%	0.50
Theme 4: Service Orientation			*79%*
4.1	Service model	11%	0.21
4.2	Maintenance contract	14%	0.57
4.3	Buy-back schemes	11%	0.21
4.4	Pay-per-use and leasing models	14%	0.57
4.5	Warranty duration	14%	0.43
4.6	Components replacement services	14%	0.43
4.7	Remote monitoring	14%	0.43
4.8	Service impact on lifetime	7%	0.29

1.6 Use case conditions

1.6.1 Technical use case conditions

Technical use case conditions
Assumptions
- Refugee and host communities already have basic access to mobile money services (MTN MoMo, Airtel Money) to support PAYG transactions. - GSM/4G connectivity exists in pilot areas to allow continuous IoT data communication between SHS units and the LUT monitoring platform. - Existing off-grid regulations from RURA and MININFRA support SHS deployment and data-sharing agreements. - Users will accept shared SHS systems among nearby households as part of affordability and energy-access improvement strategies. - Community leadership and camp management will facilitate user registration, access permissions, and household clustering. - The IoT PCB design developed by LUT will be compatible with SOLEK's SHS hardware without major modification. - Climate and weather conditions will not significantly affect the SHS performance (sufficient solar irradiation >5 kWh/m²/day).
Prerequisites
- Survey completion by LUT and SOLEK to define user needs, affordability, and willingness-to-pay data. - Technical integration and testing of LUT's IoT-enabled PCB before field deployment. - Activation of SIM cards and connectivity setup for IoT telemetry. - Training of local technicians through SOLEK Academy to install, monitor, and maintain SHS units. - Approval and coordination with Terra Energy (WP4 Lead), camp authorities, and RURA for SHS installation sites. - Procurement of certified SHS components (panels, batteries, PCB, lamps, cables) cleared through Rwanda Revenue Authority customs. - Community sensitization meetings to prepare end-users for PAYG payments and shared-ownership management.

1.6.2 Environmental use case conditions

Environmental use case conditions
Assumptions
-
Prerequisites

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-

1.6.3 Socio-economic use case conditions

Socio-economic use case conditions
Assumptions
- Target households have access to mobile phones and mobile-money accounts (MTN MoMo, Airtel Money). - Average monthly household income supports PAYG payments of 2000–5000 RWF. - Community leaders and camp managers facilitate user registration and allow installations. - Digital literacy training provided during onboarding enables users to manage mobile payments independently. - Shared-use SHS configurations are socially accepted within refugee settings. - Local technicians remain available for on-site support.
Prerequisites
- Completion of affordability and behavior survey by LUT–SOLEK to finalize tariff design. - Integration of mobile-money APIs with SOLEK backend and IoT platform. - Community sensitization sessions conducted with local authorities and humanitarian partners (UNHCR/MINEMA). - Technical training for at least three local technicians per site. - Procurement of certified SHS components compliant with VeraSol or Lighting Global standards. - Formal authorization from camp administration for installations.

1.6.4 Business use case conditions

Business use case conditions
Assumptions
- Target users (refugee and host households) have consistent income flows from small trades, remittances, or humanitarian cash transfers that can support monthly PAYG payments. - Mobile money agents are active in the pilot zones, ensuring reliable payment collection and credit top-ups. - Government and regulatory agencies (RURA, MININFRA) support private-sector PAYG business models within refugee and rural electrification programs. - The shared-system model (multiple households per SHS) is socially accepted and does not face ownership conflicts. - Device lifespan (≥5 years) and low maintenance costs allow for repayment within 24–36 months, ensuring financial sustainability. - Import taxes and duties on solar products remain exempt or minimal, preserving affordability for end users. - Carbon credit markets and impact-financing mechanisms will remain available for monetizing environmental benefits of SHS deployment.
Prerequisites
- Set up advisory and replication boards - Develop an adapted financial and pricing strategy - Collect empirical data to validate business assumptions - Completion of affordability and willingness-to-pay survey (LUT–SOLEK) to set tariff levels. - Activation of IoT PAYG platform and integration with mobile-money APIs for automated disconnections/reconnections. - Availability of credit line or working-capital facility to finance the initial SHS inventory. - Recruitment and training of local sales and after-sales agents through SOLEK Academy. - Approval from camp authorities and humanitarian partners (UNHCR, MINEMA) for household installations and data collection. Preparation of customer service and maintenance workflow, including spare-parts logistics and warranty tracking.

1.7 Further information to the use case for classification/mapping

Classification information

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Relation to other use cases
Level of depth
Generic
Prioritization
Obligatory
Generic, regional or national relation
Regional
Nature of the use case
Technical, socio-economic, and business UC
Further keywords for classification
Distributed Energy Resource (DER), Solar Home Systems, Storage, Modularity, Internet of Things, Cost-sharing, Mobile Payment Systems, Remote control

1.8 General remarks

General remarks

2 Diagrams of use case

Diagram(s) of use case

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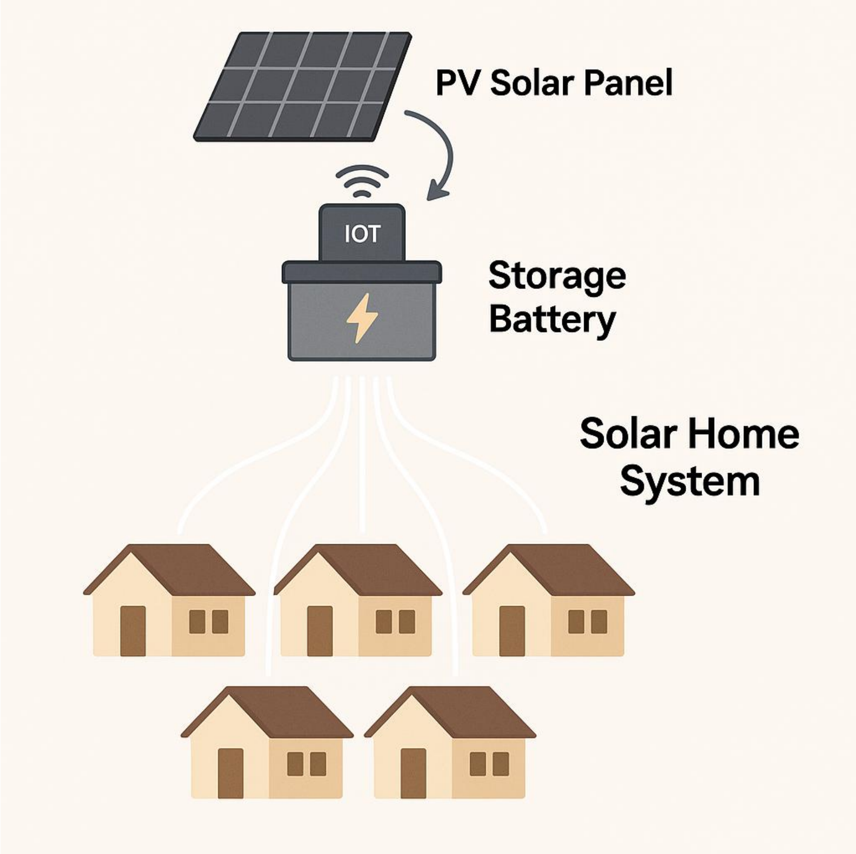

3 Technical details

3.1 Actors

Actors			
Grouping		**Group Description**	
Business Actor		Physical or legal person that has his own interests, defined as “Business Goals”	
Operator		Business Actor that operates a system	
Logical Actor		Technical entity that takes part in the execution of a use case. A logical actor can be mapped to a physical component	
Actor name	**Actor type**	**Actor description**	**Further information specific to this use case**
Business Actor			
SOLEK (System Owner / Energy Service Provider)	Business Actor	Designs and operates the SHS Operates the PAYG software backend, manages user accounts, billing cycles, and remote activation or deactivation of SHS units.	Coordinates all operational aspects of SHS management, including data uploads, alerts, and reporting to consortium partners.
Community Leader	Business Actor	Recognized authority or organization responsible for coordination, representation, and oversight of communities, camps, or institutions, supporting service delivery and development initiatives.	Supports coordination, approvals, and stakeholder engagement for solar home system installations within camps or institutions; facilitates identification of beneficiaries, ensures compliance with operational and protection standards, and assists in monitoring system use and sustainability.
Household User	Business Actor	Individual household benefiting from a Solar Home System to access reliable, affordable, and clean electricity for basic domestic needs.	End users of solar home systems for lighting, phone charging, and household appliances, contributing to

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			improved living conditions, energy access, and reduced reliance on traditional energy sources.
Local Technician (SOLEK Field Technician)	Business Actor	Responsible for maintenance and support Conduct on-site installation, maintenance, and customer training.	Trained through SOLEK Academy; ensure >95 % uptime and capture maintenance logs for LUT IoT platform.
Mobile Money Service (MTN / Airtel)	Business Actor	Processes and validates user mobile-money payments through an API connected to the SOLEK backend.	Ensures real-time payment confirmation for energy credits and generates automated receipts.
Operator			
SOLEK Backend Operator	Operator	Operates the PAYG software backend, manages user accounts, billing cycles, and remote activation or deactivation of each unit.	Coordinates all operational aspects of SHS management, including data uploads, alerts, and reporting to consortium partners.
SOLEK PAYG Operations Team	Operator	Responsible for deployment, management, and support of Pay-As-You-Go (PAYG) Solar Home Systems.	Ensures reliable operation of PAYG solar systems through field operations, customer service, and digital payment management.
Logical Actor			
PV Production Unit (Solar Panels)	Logical Actor	Converts solar radiation into electrical energy.	Mounted on shared arrays near households; provides DC input for battery charging.
Storage Unit (Battery)	Logical Actor	Stores electrical energy for evening and night use.	Includes built-in IoT sensors for state-of-charge (SoC) and temperature monitoring.
IoT System (PCB + Modem)	Logical Actor	Controls, monitors, and communicates system performance and payment data.	Developed by LUT; integrated in each SHS; transmits data via GSM/4G to LUT/SOLEK IoT platform and SOLEK backend.
Charge Controller / Inverter Module	Logical Actor	Regulates power flow between panels, batteries, and connected loads.	Protects components and ensures optimal energy conversion.
Distribution Line / Shared Network	Logical Actor	Distributes power from the SHS to one or more connected households.	Enables the shared-usage model to lower costs per user.
Mobile Money Gateway API	Logical Actor	Interface for payment validation and synchronization with PAYG system.	Connects MTN/Airtel servers with SOLEK backend; supports auto-credit updates.
Monitoring Dashboard (LUT IoT Platform)	Logical Actor	Displays live operational data, usage patterns, and alerts.	Used by consortium members for analytics, KPI tracking, and sustainability reporting.

3.2 References

References

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No.	Reference type	Reference	Status	Impact on use case	Originator/organization	Link
1	Technical Standard / Certification Framework	*VeraSol Quality Standards for Solar Home Systems and Components* (2023)	Active	Establishes global certification and testing protocols for SHS; required for donor and government procurement. Guides design specifications and verification process for SOLEK's upgraded 150 Wh modular SHS.	VeraSol / Lighting Global	https://verasol.org/standards
2	Technical Research Reference	*IoT-Enabled PAYGo Solar Systems: Enhancing Reliability and Affordability through Smart Control Boards* (World Bank ESMAP, 2021)	Published	Confirms that integrating IoT and remote monitoring at PCB level improves payment recovery, maintenance, and system uptime. Supports SOLEK–LUT approach to embedded IoT design.	World Bank / ESMAP	https://www.esmap.org/
3	Academic / Design Study	*Development of a Low-Cost IoT-Based Solar Home System for Remote Monitoring* (IEEE Access, Vol. 9, 2021)	Published	Demonstrates effectiveness of IoT-based PCB control units in optimizing	IEEE / University of Nairobi	https://ieeexplore.ieee.org/

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				SHS performance and user experience.		
4	Technical Standard	*IEC 62257-9-5: Recommendations for Small Renewable Energy Systems* (Edition 4.0, 2022)	Active	Provides safety, interoperability, and testing criteria for SHS; referenced for compliance with international norms.	International Electrotechnical Commission (IEC)	https://webstore.iec.ch/
5	Policy / Regulatory Framework	*Rwanda Standards Board – RS S H S / 2020: Minimum Requirements for Solar Home Systems*	Active	National requirement ensuring alignment with Lighting Global / VeraSol quality standards.	Rwanda Standards Board (RSB)	https://www.rsb.gov.rw/
6	Consortium Reference	*SUNNY Project WP4 – Technical Specification for IoT-Integrated PCB Development* (LUT & SOLEK, 2024)	Internal	Defines hardware and firmware interface between LUT-developed PCB and SOLEK SHS hardware; forms baseline for field testing and certification preparation.	LUT / SOLEK Consortium	Internal project documentation
7	Financial / Market Guidance	*Off-Grid Solar Market Trends Report 2024*	Published	Stresses importance of IoT data for credit risk management and	GOGLA / World Bank / Lighting Global	https://www.gogla.org/

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				pay-as-you-go scalability. Supports SOLEK's integration of smart monitoring and modular energy sharing.		

4 Step by step analysis of use case

4.1 Overview of scenarios

Scenario conditions						
No.	***Scenario name***	***Scenario description***	***Primary actor***	***Triggering event***	***Pre-condition***	***Post-condition***
1	Household onboarding & installation	Register household cluster, install SHS , activate IoT PCB and SIM, brief users.	SOLEK Field Technician	Site confirmed and users selected	Equipment available; access approved by local authorities; PAYG account created	SHS commissioned; users trained; device visible on LUT dashboard
2	PAYG top-up & credit validation	User pays via mobile money; backend updates credit; device authorization refreshed.	Household User	Mobile money payment received	Mobile network available; user KYC complete; PAYG backend operational	Credit applied; usage limit extended; user notified
3	Energy delivery & shared access	Authorized device powers household(s); optional low-voltage sharing to nearby homes.	IoT-enabled SHS	Credit validity window active	Wiring completed; safety checks passed; tariff active	Loads powered; consumption recorded; SoC tracked
4	Remote monitoring & alerting	Telemetry (voltage, current, SoC, events) sent to LUT; anomalies create alerts/tickets.	LUT IoT Platform	Telemetry threshold crossed or periodic heartbeat	IoT link active; device provisioned	Alerts issued; ticket opened in SOLEK system if needed
5	Field maintenance & repair	Technician dispatches, diagnoses hardware/firmware, replaces parts, closes ticket.	SOLEK Field Technician	Fault ticket created	Spare parts available; site	System restored; KPIs return to normal

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					access granted	
6	Tariff & affordability review	Usage and payment data analyzed to refine pricing and sharing model.	SOLEK Backend Ops	Monthly analytics cycle	Adequate dataset collected; surveys completed	Tariff recommendation logged; policy update scheduled

4.2 Steps – Scenarios

Scenario								
Scenario name1		***Household Onboarding & Installation***						
Step No.	***Event***	***Name of process/activity***	***Description of process/activity***	***Service***	***Information producer (actor)***	***Information receiver (actor)***	***Information exchanged (IDs)***	***Requirements, R-IDs***
1	Site survey approved	Household identification	Identify target households and verify access through local leaders and camp authorities.	CREATE	SOLEK Technician / Community Leader		User list (Inf01)	R-01 : Authorization from local authorities required
2	Equipment delivered	Installation of SHS	Mount solar panels, battery, activate the device and link the device with our system.	EXECUTE	SOLEK Technician		Device ID, IMEI, GPS (Inf02)	R-02 : Trained technician required
3	System activation	PAYG account creation	Create user profile in SOLEK backend and LUT IoT platform.	CREATE	SOLEK Backend Operator		User Account ID (Inf03)	R-03 : System must sync with LUT server
4	Training session	User education	Provide training on usage, mobile payments, and basic safety.	EXECUTE	SOLEK Technician		Training record (Inf04)	R-04 : User must complete orientation
Scenario name2		***PAYG top-up & credit validation***						

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Step No.	***Event***	***Name of process/activity***	***Description of process/activity***	***Service***	***Information producer (actor)***	***Information receiver (actor)***	***Information exchanged (IDs)***	***Requirements, R-IDs***
1	User initiates payment	Mobile money transaction	Customer pays energy credit through MTN MoMo or Airtel Money.	GET	Household User		Payment confirmation (Inf05)	R-05 : Mobile network available
2	Gateway notifies backend	Credit validation	PAYG backend validates payment and updates user account.	UPDATE	Mobile Money API		Credit update (Inf06)	R-06 : Backend synchronization
3	System authorized	Device unlock	IoT PCB receives unlock command allowing energy flow.	CHANGE	SOLEK Backend		Unlock signal (Inf07)	R-07 : Secure GSM connection
4	Power delivered	Electricity supply	User receives power; IoT PCB logs usage and battery status.	CREATE	IoT PCB		Usage log (Inf08)	R-08 : Data must reach LUT platform
5	Monitoring event	Telemetry analysis	LUT platform analyzes data and alerts SOLEK if anomaly detected.	CREATE	LUT IoT Platform		Performance data (Inf09)	R-09 : Alert within 24 h of fault
Scenario name 3		***Energy delivery & shared access***						
Step No.	***Event***	***Name of process/activity***	***Description of process/activity***	***Service***	***Information producer (actor)***	***Information receiver (actor)***	***Information exchanged (IDs)***	***Requirements, R-IDs***
1	Access window active	Shared access authorization	PAYG backend confirms valid credit and shared-access rules for clustered households.	GET	SOLEK Backend	Shared Access Controller / IoT PCB	Access authorization (Inf10)	R-10: Valid credit & shared rules configured

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2	Energy request	Load request handling	Connected household(s) request power; controller checks available capacity and priorities.	GET	Household User(s)	IoT PCB / Shared Controller	Energy request (Inf11)	R-11: Active IoT controller
3	Power distributed	Load sharing control	Solar system distributes energy among households based on defined limits and priorities.	CHANGE	IoT PCB	Connected Loads / Households	Distribution status (Inf12)	R-12: Load control enabled
4	Consumption recorded	Shared usage logging	System records individual and total consumption across shared users.	CREATE	IoT PCB	LUT IoT Platform	Shared usage log (Inf13)	R-13: Data transmission available
5	Status updated	System state reporting	Battery SoC and system health data sent for monitoring and optimization.	CREATE	LUT IoT Platform	SOLEK Operations Team	System status data (Inf14)	R-14: Monitoring platform active
Scenario name 4		***Remote monitoring & alerting***						
Step No.	***Event***	***Name of process/activity***	***Description of process/activity***	***Service***	***Information producer (actor)***	***Information receiver (actor)***	***Information exchanged (IDs)***	***Requirements, R-IDs***
tep No.	***Event***	***Name of process / activity***	***Description of process / activity***	***Service***	***Information producer (actor)***	***Information receiver (actor)***	***Information exchanged (IDs)***	***Requirements, R-IDs***
1	Telemetry generated	Data collection	IoT PCB collects system telemetry including voltage,	CREATE	IoT PCB	LUT IoT Platform	Telemetry data (Inf15)	R-15: IoT device operational

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			current, battery SoC, and usage events.					
2	Data received	Telemetry ingestion	LUT platform receives, validates, and stores incoming telemetry data.	CREATE	LUT IoT Platform	Monitoring Database	Telemetry record (Inf16)	R-16: Stable data connection
3	Threshold breached	Anomaly detection	Monitoring engine evaluates telemetry against thresholds and detects faults or abnormal behavior.	GET	LUT IoT Platform	Alert Engine	Anomaly flag (Inf17)	R-17: Defined thresholds available
4	Alert issued	Alert notification	System generates alert and notifies SOLEK operations team for action.	CREATE	LUT IoT Platform	SOLEK Operations Team	Alert notification (Inf18)	R-18: Alert within SLA
5	Response initiated	Incident handling	Operations team reviews alert and initiates troubleshooting or field intervention if required.	UPDATE	SOLEK Operations Team	Ticketing / Maintenance System	Incident ticket (Inf19)	R-19: Support process active
Scenario name 5		***Field maintenance & repair***						
Step No.	***Event***	***Name of process/activity***	***Description of process/activity***	***Service***	***Information producer (actor)***	***Information receiver (actor)***	***Information exchanged (IDs)***	***Requirements, R-IDs***
1	Fault detected	Alert generation	IoT system detects low voltage or error	GET	IoT PCB		Error code (Inf20)	R-20 : Fault detection automatic

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			and sends alert.					
2	Ticket created	Maintenance workflow	Backend creates ticket and assigns field technician.	CREATE	SOLEK Backend		Ticket ID (Inf21)	R-21 : Response within 48 h
3	On-site repair	Troubleshooting	Technician visits household, replaces part or updates firmware.	EXECUTE	SOLEK Technician		Repair report (Inf22)	R-22 : Use certified spares
4	Closure	Verification and closure	System tested and ticket closed in database.	CLOSE	SOLEK Backend		Ticket closure (Inf23)	R-23 : Update LUT database

Scenario name ***6***	***Tariff & affordability review***							
Step No.	***Event***	***Name of process/activity***	***Description of process/activity***	***Service***	***Information producer (actor)***	***Information receiver (actor)***	***Information exchanged (IDs)***	***Requirements, R-IDs***
1	Review triggered	Tariff review initiation	Periodic review or performance trigger initiates tariff and affordability assessment.	GET	SOLEK Operations Team	Tariff Management System	Review request (Inf24)	R-24: Review schedule or trigger defined
2	Data analyzed	Usage & payment analysis	System analyzes consumption, payment behavior, and system costs across users or clusters.	GET	Tariff Management System	Analytics Engine	Analysis dataset (Inf25)	R-25: Historical data available

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3	Tariff adjusted	Tariff configuration update	Tariff rates, limits, or payment options are adjusted to improve affordability and sustainability.	CHANGE	Tariff Management System	PAYG Backend / IoT Controller	Updated tariff rules (Inf26)	R-26: Approval obtained
4	Users informed	Tariff communication	Users and stakeholders are notified of updated tariffs or payment terms.	CREATE	PAYG Backend	Household Users / Community Leaders	Tariff notice (Inf27)	R-27: Communication channel available
5	Impact monitored	Affordability monitoring	Post-change usage and payment patterns are monitored to assess affordability impact.	CREATE	Analytics Engine	SOLEK Operations Team	Impact report (Inf28)	R-28: Monitoring period defined

5 Information exchanged

Information exchanged			
Information exchange, ID	***Name of information***	***Description of information exchanged***	***Requirement, R-IDs***
Inf01	User list		R-01
Inf02	Device ID, IMEI, GPS		R-02
Inf03	User Account ID		R-03
Inf04	Training record		R-04
Inf05	Payment confirmation		R-05
Inf06	Credit update		R-06
Inf07	Unlock signal		R-07
Inf08	Usage log		R-08
Inf09	Performance data		R-09
Inf10	Error code		R-10
Inf11	Ticket ID		R-11
Inf12	Repair report		R-12
Inf13	Ticket closure		R-13

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6 Requirements

Requirements		
Categories ID	**Category name for requirements**	**Category description**
Requirement R-ID	**Requirement name**	**Requirement description**
R-01	Authorization from local authorities required	
R-02	Trained technician required	
R-03	System must sync with LUT server	
R-04	User must complete orientation	
R-05	Mobile network available	
R-06	Backend synchronization	
R-07	Secure GSM connection	
R-08	Data must reach LUT platform	
R-09	Alert within 24 h of fault	
R-10	Fault detection automatic	
R-11	Response within 48 h	
R-12	Use certified spares	
R-13	Update LUT database	

7 Common terms and definitions

Common terms and definitions	
Term	**Definition**
Solar Home System (SHS)	A standalone photovoltaic system designed to provide basic electricity services (lighting, phone charging, and small appliances) to off-grid households.
PAYG (Pay-As-You-Go)	A financing and payment model allowing users to purchase energy services in small increments using mobile money.
IoT (Internet of Things)	A network of connected devices that collect and exchange data; in this project, IoT modules in SHS units transmit operational and payment information to the cloud.
PCB (Printed Circuit Board)	The electronic control board inside the SHS responsible for monitoring power flow, managing PAYG logic, and communicating with the IoT platform.
State of Charge (SoC)	The current battery capacity expressed as a percentage of total capacity, used to assess energy availability.
Telemetry	Remote data sent from IoT-enabled SHS devices to monitoring platforms for performance tracking and fault detection.
LUT IoT Platform	The centralized monitoring and analytics system developed by LUT University to collect SHS data and visualize performance.
Mobile Money Gateway	The digital financial interface (MTN MoMo, Airtel Money) enabling user payments and automatic synchronization with the PAYG backend.

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SOLEK Backend System	The management platform used by SOLEK to oversee SHS installations, payments, and maintenance activities.
Terra Energy (WP4 Lead)	The work-package lead partner coordinating SHS field demonstrations and reporting in Rwanda.
Shared-Use Model	A system configuration where several neighboring households share one SHS to reduce per-user cost and improve affordability.
VeraSol Certification	An internationally recognized quality-assurance process ensuring SHS products meet performance and safety standards for donor and market acceptance.

8 Custom information (optional)

Custom information (optional)		
Key	***Value***	***Refers to section***

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3. Rwanda: Hydrogen cooking solution

1. Description of the use case

1.1 Name of the use-case

Use case identification		
ID	**Area/Domain/Zone(s)**	**Name of the use case**
UC2	Area: Energy systems Domains: Generation, DER, Customers Zones: Field, Process, station, operation	Rwanda: Valorise locally produced hydrogen for clean cooking through tailored hydrogen cookstoves and Develop low-cost, frugal storage solutions. (Develop hydrogen cooking solutions with retrofitting of existing stoves and development of low-cost storage solutions)

1.2 Version management

Version management				
Version No.	**Date**	**Name of author(s)**	**Changes**	**Approval status**
0.1	27/10/2025	Nora Stognief - TUB	Draft	
0.2	19/01/2025	Charles Fransman - SLDR	Draft	

1.3 Scope and objective of use case

Scope and objectives of the use case	
Scope	This use case is limited to the study of low-pressure hydrogen solutions for clean cooking in refugee communities in Rwanda.
Technical Objective(s)	- Improve existing system's safety, efficiency, robustness and affordability - Refinement and adaptation of the clean cooking and hydrogen storage technology to the local context - Retrofit existing LPG stoves into hydrogen compatible cookstoves - Design new cookstoves to be compatible with hydrogen, biogas, and/or LPG - Ensure safety and reliability of hydrogen storage and cooking solution
Socio-Economic Objective(s)	- Reduce health hazards and time needed to collect solid fuel (wood and charcoal) for cooking, thus increasing time spent by women and children on productive tasks and leisure activities. - Provide a solution that respects cooking preferences in diverse cultural contexts - Increase social acceptance by retrofitting existing and accepted cookstoves - Adapt and improve the hydrogen technology by co-creation - Reduce up-front cost for end-users through retrofitting cookstoves and integrating frugal storage solutions - Develop innovative financing mechanisms
Ecological Objective(s)	- Reduce CO2, CO and PM emissions - Define a local value chain to improve circularity and sustainability - Reduce dependency on fossil and solid fuels - Increase robustness and lifetime of the hydrogen appliances
Business Objective(s)	- Accelerate the spread and uptake of clean cooking solutions - Reduce hydrogen storage costs through a new low-tech storage solution using tire inner tubes - Reduce operating costs to close to zero by the end of the project

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Related business case(s)	- Central hydrogen production and distribution to households with individual hydrogen cookstoves, using a mobile hydrogen storage solution - Hydrogen production linked to a central community kitchen for surrounding households, using a fixed hydrogen storage solution

1.4 Narrative of use case

Narrative of use case
Short description
Most of the traditional cooking solutions rely on liquefied petroleum gas (LPG), wood and charcoal, which leads to high CO2 emissions and a major health hazard. Solar hydrogen clean cooking combines the benefits of existing alternatives (solar cookers, biogas) and LPG, with the added benefits of local off-grid production capacities and low-cost energy storage solution, enabling to accelerate the spread and uptake of clean cooking technologies. The starting point is a stand-alone, low-maintenance and safe hydrogen panel producing hydrogen out of sunlight and water collected from airborn humidity . The hydrogen gas is temporarily stored at low pressures in proximity to the production site. This gas can be burned in tailored hydrogen cookstoves using specific hydrogen diffusion burners. Gas transport from the production location to end-user can be achieved via a microgrid system (underground tubing) or with mobile gas bags. This unique technology will be further refined and adapted to the local African context through a combination of design considerations for a low-tech low-pressure cookstoves, storage and transport solutions. Local distribution will be performed from a small hydrogen production station by filling tire tubes or gas bags, while leaving room for new contextual insights and product modifications by local stakeholders. A flexible-volume, mobile hydrogen storage solution combined with local fuel production and innovative payment models such as leasing and PAYG will enable households to reliably secure the basic need of having Fuel For A Day. meet end-user acceptance, the design of the hydrogen technology and appliances will be adapted and improved by co-creation. This participatory user-centric design process will result in a user-friendly, robust, low-tech and low-cost application of the hydrogen technology transferring solar energy to the cookpot.
User story
As a resident of Mahama refugee camp, I want to switch to a clean cooking fuel to improve the **air quality** in and around my family's home. As a resident of Mahama refugee camp, I want to switch to a renewable**, low-cost** fuel so that I no longer have to buy expensive LPG. As a resident of Mahama refugee camp, I want a clean cooking stove that functions like **the one I am used to** so that I do not have to change my habits and can keep following my cultural requirements and traditions. As a resident of Mahama refugee camp, I want an efficient and **fast cooking** stove to limit the time spent cooking meals every day As a resident of Mahama refugee camp, I want to switch to a locally produced clean cooking fuel to **limit the time spent** collecting firewood, or time spent to go and buy charcoal or LPG As a resident of Mahama refugee camp, I want to be able to buy **variable volumes of hydrogen** gas depending on daily need and purchasing capacity, to be able to also cook on the days with minimal income and always having **Fuel For A Day** As a resident of Mahama refugee camp, I want to **share a cookstove** with other households or use a community kitchen to lower the or avoid the cost of buying (at once or spread over a longer period) a hydrogen cookstove myself As a resident of Mahama refugee camp, I want to use a clean cooking system so that I can help **combat deforestation, global warming** and climate change
Complete description
Most of the traditional cooking solutions in Sub-Sahara Africa rely on liquefied petroleum gas (LPG), charcoal and wood, which leads to high CO2 emissions and a major health hazard. Solar hydrogen combines the benefits of existing alternatives (solar cookers, biogas) and LPG, with the added benefits of local off-grid production capacities and low-cost energy storage solution, enabling to accelerate the spread and uptake of clean cooking technologies. The main problems associated with the introduction of innovative cooking systems are i) Social acceptance of the solution by end-users. To remedy this problem, SUNNY will implement two types of cookstoves: existing LPG stoves will be refitted in hydrogen compatible stoves, and new cookstoves will be designed to be usable with hydrogen, biogas, and LPG. In this way, end-users will not have to change their habits completely, targeting positive feedback from users of over 80% for single gas cookstoves; ii) High upfront costs. In SUNNY, refitting existing cookstoves aims at reducing upfront costs for end-users by 80%. In addition, a new low-tech storage solution using tire inner tubes will be researched and developed with the aim to reduce the storage costs by 90%. Moreover, innovative financing mechanisms such as leasing schemes, pay-as-you-go models or microcredits will be developed to overcome the problem of high upfront costs. Furthermore, in the case of refugee camps , the significant operating costs, such as distribution of LPG in refugee camps in Rwanda, are borne by humanitarian organisations such as the UNHCR. With the hydrogen solution, the operating costs are expected to be close to zero at the end of the project.

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Hydrogen solar panels are a patented technology developed by SOLHYD that absorbs water out of the air during the night and produces hydrogen by harnessing solar energy during the day. The starting point is a stand-alone, low-maintenance and safe hydrogen panel producing hydrogen out of sunlight and airborne humidity. The hydrogen gas is temporarily stored at low pressures in proximity to the production site. This gas can be burned in tailored hydrogen cookstoves using specific hydrogen diffusion burners. Gas transport from production location to end-user can be achieved via a microgrid system (underground tubing) or with mobile gas bags. A solar hydrogen panel can be adapted to a specific climate by tuning the water vapor collection (most critical in dry climate) and the solar hydrogen splitting functions (most critical in less solar regions). This unique technology will be further refined and adapted to the local African context through a combination of design considerations for a low-tech low-pressure cookstoves, storage and transport solutions. Local distribution will be performed from a small hydrogen production station by filling tire tubes or gas bags, while leaving room for new contextual insights and product modifications by local stakeholders. Within SUNNY, this design of the existing multi-burner cookstoves will be modified for low-tech single and multi-fuel stoves providing the robust safety inherently required in hydrogen systems. However, the gas flow and burner mechanism of a propane stove cannot be used with hydrogen gas. Hence, research and experiments will be conducted to determine the modified design that best assures safety and reliability in the burning of hydrogen gas within a domestic environment. The safe handling and burning of hydrogen gas are paramount considerations in the hydrogen cooking design: the burner muffles the sound produced by ignition and creates an even flame spread. Additionally, flame arresters and blowback devices are installed on the gas storage side for guaranteed safety. The technical upgrades of the hydrogen panels performed during the project will be the following: i) incorporation of sensors in the panels for remote monitoring (from Europe) of the performance of the hydrogen panels; ii) practical evaluation of an original idea for short distance low pressure hydrogen transportation combining a small hydrogen production park, filling station of inner tubes of tires of trucks and tractors, and connections to hydrogen cookstoves; iii) Admixing of solar hydrogen with other fuels like biogas; iv) Design of a multifuel cookstoves running either on hydrogen, biogas or mixtures, depending on availability and preferences, especially because in refugee camps cultural contexts are diverse. To gain acceptance of a new technology, the cooking preferences need to be respected and cookstoves need to be flexible to suit all kinds of cooking habits. The number of burners (one pot cooking or multiple), the cooking times and temperatures are important, especially since the delivery of fuel (hydrogen or biogas) is limited by the volume available and the maximum pressure off the system. To meet end-user acceptance, the design of the hydrogen technology will be adapted and improved by co-creation. This participatory user-centric design process will result in a user-friendly, robust, low-tech and low-cost application of the hydrogen technology transferring solar energy to the cookpot. The improvement of the technology will be combined with establishing collaboration with local stakeholders, and with demonstration and training at the MALLS.

For the hydrogen cooking solution preliminary tests will verify the safety aspects. This step will be dedicated to the finalization of the Hazard and Operability (HAZOP) study and the Standard Operating Procedure (SOP) for the household case and the solar hydrogen hub case. The HAZOP assessment will assist in formulating step-by-step emergency procedures in the case of accidental hydrogen release and detection, while the SOP is dedicated to the description of the safe operation and transfer of hydrogen from the solar hydrogen panel to the gas bag and through the piping system for the two cases. The HAZOP and SOP will be jointly constructed and shared with the respective living lab partners.

Site preparation, commissioning and testing of the household installation will be done at the demonstration site, according to the designed SOP. Technical validation of the clean cookstove will be done against the baseline tests performed in the EU. These validation tests include the assessment of hydrogen flow rate from the solar hydrogen panel, pressure testing of the gas bag, and NOx measurement of the cook stove flame. A full 100 h extended performance test will be done to assess hydrogen generation rate, re-usability of the hydrogen gas bag and the inner tubes of truck tires, and cooker thermal efficiency. Testing of the sensor incorporated in the hydrogen panels for monitoring hydrogen production and warning of failures will be performed at demonstration site. In addition, hydrogen storage in tubes of big tires will be tested though the assessment of maximum pressure, leakages, mode of quick connection to hydrogen filling station and cookstove, ease of transportation by rolling and ease of filling and emptying operations.

1.5 Key performance indicators

1.5.1 Technical KPIs

Technical KPIs			
ID	**Name**	**Description**	**Reference to mentioned use case objectives**
1	CAPEX reduction compared to existing alternative	Target: 80%	Technical and socio-economic objectives
2	OPEX reduction compared to existing alternative	Target: 80%	Technical, socio-economic and business objectives
3	Percentage increase in lifetime of products used in the demonstrator locations	Target: 20%	Technical and ecological objectives
7	Improved energy efficiency of the hydrogen panels	Target: 400L of H2 per day at 13% efficiency	Technical objectives

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9	GHG emissions mitigated with SUNNY solutions	Target: 1 tCO2eq/year *400 users	Technical, socio-economic, ecological, business objective
17	Number of people benefiting to an enhanced access to energy	Target: 400	Socio-economic and business objective
23	Reduction of respiratory diseases due to solar lighting, and cleaner cooking fuels	Target: 50%	Socio-economic objective
25	Percentage of energy solutions replaced by clean technologies in the demonstration sites	Target: 10%	Business objective

1.5.2 Ecological KPIs from REFUSE's Ecodesign Toolkit

Ecological KPIs			
ID	***Name***	***Weight***	***Scoring***
Theme 1: Nature-Based Design, Environmental Footprint			*59%*
1.1	Local material sourcing	13%	0.00
1.2	Use of natural/low-impact materials	10%	0.10
1.3	Toxicity potential	10%	0.40
1.4	Local water risk sensitivity	13%	0.53
1.5	Nature-based or low-tech integration	10%	0.30
1.6	Climate change mitigation potential	13%	0.53
1.7	Climate change adaptation support	10%	0.30
1.8	Footprint of material sourcing	10%	0.20
1.9	Circularity of material sourcing	10%	0.00
Theme 2: Durability and Repairability			*67%*
2.1	Design lifetime	14%	0.28
2.2	Ease of disassembly	10%	0.40
2.3	Tools required for maintenance and repair	10%	0.30
2.4	Spare parts availability	10%	0.10
2.5	Spare parts cost	10%	0.20
2.6	Repair documentation	7%	0.13
2.7	Modularity	10%	0.40
2.8	Remote support	10%	0.30
2.9	Upgradeability	10%	0.30
2.10	Resilience to environmental conditions	7%	0.20
Theme 3: Recyclability & End of Life Management			*58%*

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3.1	Recyclability	13%	0.38
3.2	Reusability, second life potential	13%	0.25
3.3	Hazardous materials share	8%	0.17
3.4	Ease of material separation	13%	0.38
3.5	Local disposal/recycling chain	13%	0.13
3.6	Takeback schemes at End of Life (EOL)	17%	0.67
3.7	Materials, components identification	13%	0.00
3.8	EOL documentation	13%	0.38
Theme 4: Service Orientation			*68%*
4.1	Service model	17%	0.67
4.2	Maintenance contract	17%	0.50
4.3	Buy-back schemes	17%	0.33
4.4	Pay-per-use and leasing models	0%	0.00
4.5	Warranty duration	17%	0.67
4.6	Components replacement services	6%	0.06
4.7	Remote monitoring	17%	0.50
4.8	Service impact on lifetime	11%	0.00

1.6 Use case conditions

1.6.1 Technical use case conditions

Technical use case conditions
Assumptions
- The solar hydrogen solution can meet strict safety requirements - Patented hydrogen solar panels can be refined and adapted to the local African context - Lack of sufficient and qualitative data is a decisive limitation in the field of Humanitarian Energy - LPG cooking stoves are commonly used in the Mahama refugee camp?
Prerequisites
- Conduct preliminary tests to verify the safety aspects - Adapt solar hydrogen panel to local climate - Modify design for low-tech single-fuel and multi-fuel burner stoves - Conduct research and experiments to determine the modified design that best assures safety and reliability of the use of hydrogen within the targeted environment

1.6.2 Environmental use case conditions

Environmental use case conditions
Assumptions
-
Prerequisites

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-

1.6.3 Socio-economic use case conditions

Socio-economic use case conditions
Assumptions
- Factors like traditional cooking methods, gender roles, and religious practices play an important role in the design of energy interventions - Assessing preferences, perceptions, and understanding influencers to decisions is crucial to design context-embedded energy delivery models that can successfully sustain in the local setting - Inadequate participation of underrepresented groups, inadequate infrastructure, and weak linkages among actors can hinder the effectiveness and inclusivity of local value chains - Improving the reliability and affordability of renewable energy solutions has the potential to improve its local acceptance
Prerequisites
- Gain comprehensive and in-depth knowledge of the local context, including technical infrastructures, environmental conditions, , value chain, social resources, and societal habits - Approach target groups and assess their preferences, perceptions and barriers to adoption - Identify elements for building a local value chain considering both hard and soft infrastructure

1.6.4 Business use case conditions

Business use case conditions
Assumptions
- Business models must consider local, national, and international regulations, as well as the existing market analysis
Prerequisites
- Set up advisory and replication boards - Understand local value chain and capacity building potential - Develop an adapted financial and pricing strategy - Collect empirical data to validate business assumptions

1.7 Further information to the use case for classification/mapping

Classification information
Relation to other use cases
Level of depth
Generic
Prioritization
Obligatory
Generic, regional or national relation
Regional
Nature of the use case
Technical, socio-economic, and business UC
Further keywords for classification
Distributed Energy Resource (DER), Solar hydrogen, Cookstoves, Retrofitting, Hydrogen Storage

1.8 General remarks

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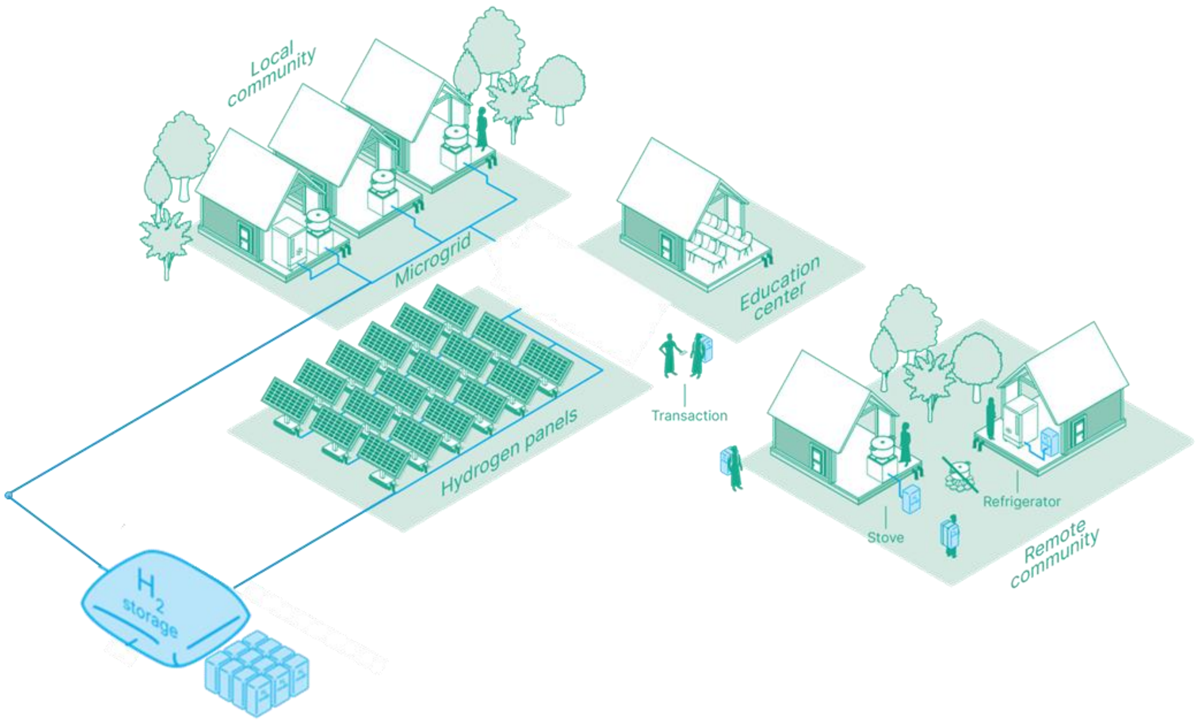
General remarks

2 Diagrams of use case

Diagram(s) of use case


3 Technical details

3.1 Actors

Actors			
Grouping		**Group Description**	
Business Actor		Physical or legal person that has his own interests, defined as "Business Goals"	
Operator		Business Actor that operates a system	
Logical Actor		Technical entity that takes part in the execution of a use case. A logical actor can be mapped to a physical component	
Actor name	**Actor type**	**Actor description**	**Further information specific to this use case**
Business Actor			
System Owner	Business Actor	Being Solhyd and/or Solhydair. Solhyd owing the hydrogen production systems, and Solhydair owing the hydrogen storage units and hydrogen stoves. Operates the hydrogen panels, storage solutions and distribution system	Coordinates operations, data collection and reporting
Local System Operator	Business Actor	Responsible for maintenance and support, acting as a local partner	
Local Partner	Business Actor	Local partner supporting non-technical parts of the project, helping communicating and collaborating with local communities	
Local Community	Business Actor	Local community in need of clean cooking solutions. End-users using the hydrogen clean cooking systems on household level or as users of a central community kitchens	

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System owner after handover	Business Actor	Local system operator, possibly in collaboration with local partner managing the system after certification and handing over the system at the end of the SUNNY project	
Operator			
Local System Operator	Operator	Operator of the hydrogen production, storage systems and hydrogen filling station (if part of the use case), acting as a local partner	
Logical Actor			
Hydrogen panel	Logical Actor	Solar hydrogen production system	Central hydrogen production site composed of several connected hydrogen production panels
Mobile Storage Unit	Logical Actor	Low-tech mobile storage solution using tire inner tubes or gas bags	Mobile hydrogen storage solution used to transport hydrogen from production location to hydrogen cookstove location
Fixed storage unit	Logical actor	Large buffer storage, if required by the use case?	Depending on the use case, a fixed storage solution can be added to the system
Refilling system	Logical actor	Mobile gas bags or tire tubes are filled directly from the hydrogen production system, or from an intermediate fixed storage solution (depending on the use case and site restrictions)	Smart and safe refilling system
Hydrogen cookstove	Logical actor	Single or multi-fuel stove burning hydrogen including a Flame arrestor, preventing eventual flame flashback into the hydrogen gas storage bag or the hydrogen production system	Efficient, safe, robust and user-friendly hydrogen cookstove

3.2 References

References						
No.	**Reference type**	**Reference**	**Status**	**Impact on use case**	**Originator/organization**	**Link**
1	Cookstove standard	PAS 4444: Hydrogen appliances standards	Active	Guidance for the design, construction, safety, installation, operation, and servicing of hydrogen-fired appliances, including cookstoves	Developed under the Hy4Heat programme	https://knowledge.bsigroup.com/products/hydrogen-fired-gas-appliances-guide-1
2	Global air quality guidelines	WHO global air quality guidelines	Active	Giving Guidance to air quality limits	WHO	https://www.who.int/publications/i/item/9789240034228
3	Defining clean cooking and clean fuels	Defining clean fuels and technologies	Active	Defining clean cooking and how to be categorised as clean cooking	WHO	https://www.who.int/tools/clean-household-energy-solutions-toolkit/module-7-defining-clean

4 Step by step analysis of use case

4.1 Overview of scenarios

Scenario conditions

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No.	Scenario name	Scenario description	Primary actor	Triggering event	Pre-condition	Post-condition
1	***Hydrogen clean cooking ecosystem with decentralised clean cooking***	Commission the hydrogen production system and perform all safety checks and SOP for start-up. Operating the central hydrogen production and storage systems, and linking this to hydrogen gas bag distribution and household hydrogen cookstoves.	System owner, together with Local Partner and Local System Operator	Site confirmed, End-user engagement, household onboarding, Local System Operator training and collaboration	Equipment available; access approved by local authorities; Training of Local System Operator	Clean cooking at household level
2	***Hydrogen clean cooking ecosystem with centralised clean cooking via gasbags***	Commission the hydrogen production system and perform all safety checks and SOP for start-up. Operating the central hydrogen production and storage systems, and linking this to hydrogen gas bag distribution and communal kitchens with hydrogen cookstoves	System owner, together with Local Partner and Local System Operator	Site confirmed, End-user engagement, household onboarding, Local System Operator training and collaboration	Equipment available; access approved by local authorities; Training of Local System Operator	Clean cooking at household level at communal hydrogen kitchen
3	***Hydrogen clean cooking ecosystem with centralised clean cooking via microgrid***	Commission the hydrogen production system and perform all safety checks and SOP for start-up. Operating the central hydrogen production and storage systems, and linking this to communal kitchens with hydrogen cookstoves via microgrid gas distribution	System owner, together with Local Partner and Local System Operator	Site confirmed, End-user engagement, household onboarding, Local System Operator training and collaboration	Equipment available; access approved by local authorities; Training of Local System Operator	Clean cooking at household level at communal hydrogen kitchen
4	***Maintenance and troubleshooting***	IoT- integration in hydrogen production systems. Periodic control of hydrogen (mobile and/or fixed) storage and cooking system with hydrogen cookstoves. Problem identification, remediation or reparation during operations	Local System Operator, supported by System owner	Timely check-up. Troubleshooting. Reporting of operational faults	Internet or 4G connectivity, IoT functioning, Trained Local System Operator to perform routine check-ups and troubleshooting, and feedback system	Continuously operating system with online data monitoring
	Business model and technology evaluation	Evaluate user experience, operator feedback to gain insights into optimal business model and possible next steps in technological improvement.	System owner, With Local Partner	/	Operating a fully integrated hydrogen clean cooking system within defined use cases	Guidelines for further implementation and improvement of clean cooking technology

4.2 Steps – Scenarios

Scenario	
Scenario name	***Hydrogen clean cooking ecosystem with decentralised clean cooking***

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Step No.	Event	Name of process/activity	Description of process/activity	Service	Information producer (actor)	Information receiver (actor)	Information exchanged (IDs)	Requirements, R-IDs
1	Site selection and household onboarding	Identify location/site fit for safe hydrogen production, storage and distribution. Identify and onboard households of the local community for clean cooking implementation	Identify target households and verify site qualification and access through local leaders and camp authorities. Identify households willing to engage in clean cooking with Local Partner	Execute	System owner, Local Partner	Local community	Inf01: Site information. User information	R-01: Authorization from local authorities and support from Local Partner required
2	The hydrogen panels collected water from air moisture during the night	Water collection	Water from air is collected in the hydrogen panels when air is ventilated through the cores of the panels at night	EXCECUTE	Hydrogen panel	System Owner. Local system operator	@solhyd: is water capture being monitored?	
3	Solar irradiation is used to split water into hydrogen and oxygen during the day	Water electrolysis	Water is split using solar energy during the day	EXECUTE	Hydrogen panel	System Owner. Local system operator	Inf02: Solar irradiation and hydrogen production @Solhyd, will the panels be able to monitor total hydrogen output?	R-02: IoT, data monitoring and cloud sharing
4	Hydrogen stored in Mobile or Fixed storage unit	Storage under slight overpressure directly in mobile storage unit or in a fixed storage unit acting as a buffer.	Hydrogen is produced under slight overpressure, this overpressure compresses the hydrogen directly in a Mobile storage unit or Fixed storage unit	EXECUTE	Hydrogen Panel.	System Owner. Local system operator	Inf03: Filling cycles and total volume of hydrogen produced	R-03: IoT and trained Local System Operator
5	Refill mobile storage unit (gas bag or tire tube) from buffer storage using a refilling system or directly from	Gas transfer to tire tube or gas bag, via Refilling system. This step is only necessary if a fixed storage unit is added to the ecosystem.	From the fixed storage unit under slight overpressure, transport bags or tire tubes can be filled using a smart filling system,	EXECUTE	Storage unit and refilling system. Local System Operator	System Owner. Local system operator	Inf04: Refuelling cycles Inf07: Transactional data.	R-04: trained Local System Operator collecting data R-07: local partner of local system operator recording

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	production system		and a Pay-As-You-Go system					transactional data. R-16: smart filling system
6	Transportation of portable bags to households	Transport of Fuel	Mobile storage units can be transported home and used for clean cooking on a household-based hydrogen cookstove	Execute	Local Community	Local system operator	Inf05: Distance travelled	R-05: Trained Local System Operator or Local Partner collecting data
7	Connection with hydrogen cookstove	Connection to hydrogen Cookstove	Before cooking the Mobile storage unit (gas bag/Tire tube) needs to be connected to the cooking stove via safe connection system	EXECUTE	Local Community	Hydrogen stove	Gas bag safely connected	R-04: Trained Local System Operator or Local Partner. R-15: safe connection system
8	Operation of clean cooking system	Consumption of Fuel and clean cooking	The end-user of the local community can operate the cookstove and use the hydrogen gas for clean cooking	Execute	Local Community	Hydrogen stove	Inf06: Number of meals cooked and cooking time	R-06: End-user identification and collaboration R-14: operational hydrogen cookstove
9	System Handover	Handing over the system to local system operator, possibly together with Local partner	At the end of the project the hydrogen systems are being transferred to a local system operator to further serve the community	Execute	System Owner and Local system operator	Hydrogen panels, hydrogen storage units, hydrogen cookstoves	Inf14: Assessment of local operator skills and control of the system (certification).	R-17: Certified Local System Operator or Local Partner.

Scenario name		***Hydrogen clean cooking ecosystem with centralized clean cooking via gasbags***						
Step No.	***Event***	***Name of process/activity***	***Description of process/activity***	***Service***	***Information producer (actor)***	***Information receiver (actor)***	***Information exchanged (IDs)***	***Requirements, R-IDs***
1	Site selection and household onboarding	Identify location/site fit for safe hydrogen production, storage and distribution. Identify and onboard households of the local	Identify target households and verify site qualification and access through local leaders and camp authorities. Identify households	Execute	System owner, Local Partner	Local community	Inf01: Site information. User information	R-01: Authorization from local authorities and support from Local Partner required

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		community for clean cooking implementation	willing to engage in clean cooking with Local Partner					
2	Hydrogen communal kitchen start-up	Integrated hydrogen ecosystem, Hydrogen panels, storage units and central hydrogen kitchen with hydrogen cookstoves	Commissioning and testing of the integrated hydrogen ecosystem, including production, storage and central hydrogen kitchen	Execute	System Owner, Local System Operator	System Owner, Local Communit y	System integration	/
3	The hydrogen panels collected water from air moisture during the night	Water collection	Water from air is collected in the hydrogen panels when air is ventilated through the cores of the panels at night	EXCECUT E	Hydrogen panel	System Owner. Local system operator	@solhyd: is water capture being monitored?	
4	Solar irradiation is used to split water into hydrogen and oxygen during the day	Water electrolysis	Water is split using solar energy during the day	EXECUTE	Hydrogen panel	System Owner. Local system operator	Inf02: Solar irradiation and hydrogen production @Solhyd, will the panels be able to monitor total hydrogen output?	R-02: IoT, data monitoring and cloud sharing
5	Hydrogen stored in Mobile or Fixed storage unit	Storage under slight overpressure directly in mobile storage unit or in a fixed storage unit acting as a buffer.	Hydrogen is produced under slight overpressure, this overpressure compresses the hydrogen directly in a Mobile storage unit or Fixed storage unit	EXECUTE	Hydrogen Panel.	System Owner. Local system operator	Inf04: Refueling cycles Inf07: Transactiona l data.	R-04: trained Local System Operator collecting data R-07: local partner of local system operator recording transactional data. R-16: smart filling system
5	Refill mobile storage unit (gas bag or tire tube) from buffer storage using a refilling system or directly from production system	Gas transfer to tire tube or gas bag, via Refilling system	From the storage tank under slight overpressure, transport bags or tire tubes can be filled using a smart filling system, and a Pay-As-You-Go system	EXECUTE	Storage unit and refilling system. Local System Operator	System Owner. Local system operator	Inf04: Refueling cycles Inf07: Transactiona l data.	R-04: trained Local System Operator collecting data R-07: local partner of local system operator recording transactional data.

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								R-16: smart filling system
6	Transportation of Mobile storage units (gas bag or tire tube) to central communal kitchen	Transport of fuel	Mobile storage units can be transported to central communal kitchen and used for clean cooking on hydrogen cookstoves	Execute	Local Community	Local system operator	Inf05: Distance traveled	R-05: Trained Local System Operator or Local Partner collecting data
7	Connection with hydrogen cookstove	Connection to hydrogen Cookstove	Before cooking the Mobile storage unit (gas bag) needs to be connected to the cooking stove of the communal kitchen via safe connection system	EXECUTE	Local Community	Hydrogen stove	Gas bag safely connected	R-04: Trained Local System Operator or Local Partner. R-15: safe connection system
8	Operation of clean cooking system	Consumption of Fuel	The end-user can operate the hydrogen cookstove as part of a communal kitchen and use the hydrogen gas for clean cooking	Execute	Local Community	Hydrogen stove	Inf06: Number of meals cooked and cooking time	R-06: End-user identification and collaboration R-14: operational hydrogen cookstove
9	System Handover	Handing over the system to local system operator, possibly together with Local partner	At the end of the project the hydrogen systems are being transferred to a local system operator to further serve the community	Execute	System Owner and Local system operator	Hydrogen panels, hydrogen storage units, hydrogen cookstoves	Inf14: Assessment of local operator skills and control of the system (certification).	R-17: Certified Local System Operator or Local Partner.
Scenario name		***Hydrogen clean cooking ecosystem with centralised clean cooking via microgrid***						
Step No.	***Event***	***Name of process/activity***	***Description of process/activity***	***Service***	***Information producer (actor)***	***Information receiver (actor)***	***Information exchanged (IDs)***	***Requirements, R-IDs***
1	Site selection and household onboarding	Identify location/site fit for safe hydrogen production, storage and distribution. Identify and onboard households of the local community for	Identify target households and verify site qualification and access through local leaders and camp authorities. Identify households willing to engage in	Execute	System owner, Local Partner	Local community	Inf01: Site information. User information	R-01: Authorization from local authorities and support from Local Partner required

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		clean cooking implementation	clean cooking with Local Partner					
2	Hydrogen communal kitchen start-up	Integrated hydrogen ecosystem, Hydrogen panels, storage units and central hydrogen kitchen with hydrogen cookstoves	Commissioning and testing of the integrated hydrogen ecosystem, including production, storage and central hydrogen kitchen	Execute	System Owner, Local System Operator	System Owner, Local Communit y	System integration	/
3	The hydrogen panels collected water from air moisture during the night	Water collection	Water from air is collected in the hydrogen panels when air is ventilated through the cores of the panels at night	EXCECUT E	Hydrogen panel	System Owner. Local system operator	@solhyd: is water capture being monitored?	
4	Solar irradiation is used to split water into hydrogen and oxygen during the day	Water electrolysis	Water is split using solar energy during the day	EXECUTE	Hydrogen panel	System Owner. Local system operator	Inf02: Solar irradiation and hydrogen production @Solhyd, will the panels be able to monitor total hydrogen output?	R-02: IoT, data monitoring and cloud sharing
5	Hydrogen stored in Mobile or Fixed storage unit	Storage under slight overpressure	Hydrogen is produced under slight overpressure, this overpressure compresses the hydrogen directly in Fixed storage unit	EXECUTE	Hydrogen Panel.	System Owner. Local system operator	Inf04: Refueling cycles Inf07: Transactiona l data.	R-04: trained Local System Operator collecting data R-07: local partner of local system operator recording transactional data. R-16: smart filling system
5	Hydrogen distribution via microgrid	Gas distribution used fixed microgrid tubing system	From the Fixed storage unit under slight overpressure gas is transferred to the hydrogen cookstoves of the central hydrogen kitchen	EXECUTE	Fixed storage unit	System Owner. Local system operator	Inf12: Gas volume consumed daily or per user, via microgrid	R-12: Trained Local System Operator collecting data or via IoT

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6	Operation of clean cooking system	Consumption	The end-user can operate the cookstove of the central communal hydrogen kitchen for clean cooking, using PAYG (Pay-As-You-Go) mechanism	Execute	Local Communit y	Hydrogen stove	Inf13: Number of users using the communal kitchen, Data on PAYG transactions	R-13: End-user identification, Local System Operator for central kitchen and PAYG (or IoT) R-14: operational hydrogen cookstove
9	System Handover	Handing over the system to local system operator, possibly together with Local partner	At the end of the project the hydrogen systems are being transferred to a local system operator to further serve the community	Execute	System Owner and Local system operator	Hydrogen panels, hydrogen storage units, hydrogen cookstoves	Inf14: Assessment of local operator skills and control of the system (certification).	R-17: Certified Local System Operator or Local Partner.

Scenario name		Maintenance and troubleshooting						
Ste p No.	**Event**	**Name of process/activit y**	**Description of process/activit y**	**Service**	**Informatio n producer (actor)**	**Informatio n receiver (actor)**	**Informatio n exchanged (IDs)**	**Requirements , R-IDs**
1a	*Technical problem detected*	*Fault detection by Local community*	*End-user detects problem with cooking installation*	EXECUT E	*Local community*	*local system operator and System Owner*	*Inf 09: Local Community (End-used) fault detection and description*	*R-09*: End-user identification and collaboration
1b	*Technical problem detected*	*Fault detection by local system operator*	Local System Operator *detects problem with hydrogen production or storage system*	EXECUT E	*local system operator*	*System Owner*	*Inf10: Local System Operator fault detection and description*	*R-10*: Trained Local System Operator detecting faults
2	*Communicatio n* Local System Operator	*Fault reporting*	*Communicatin g problem to* Local System Operator, *in case of end-user fault detection (1a)*	EXECUT E	*local system operator*	*System Owner*		
3	*Troubleshootin g and repair*	*Remediation or reparation*	*On-site troubleshooting, problem identification, remediation or reparation*	EXECUT E	*local system operator*	*Local Communit y and system Owner*	*Inf 11: Remediatio n or reparation efficiency*	*R-11*: trained Local System Operator solving faults

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5 Information exchanged

Information exchanged			
Information exchange, ID	***Name of information***	***Description of information exchanged***	***Requirement, R-IDs***
Inf01	Site and user information	Identify target households and verify access through local leaders and camp authorities. Identify households willing to engage in clean cooking	R-01
Inf02	Irradiation and hydrogen production data	Data on solar irradiation on the hydrogen panels and hydrogen produced	R-02
Inf03	Hydrogen storage	Filling cycles	R-03
Inf04	Refuelling	Number of hydrogen refuelling events (or mobile storage units filled)	R-04 and R-16
Inf05	Travel distance	Destination and distance travelled	R-05
Inf06	Clean cooking	Number of meals cooked and cooking time	R-06 and R-14
Inf07	Transactional data	Transactional data linked to hydrogen distribution	R-07
Inf08	Community Kitchen utilisation	Data on utilisation of central or communal hydrogen kitchen	R-08
Inf09	Fault detection	End-user detects problem with cooking installation	R-09
Inf10	Fault detection	Local system operator detects problem with hydrogen production or storage system	R-10
Inf11	Data on remediation or remediation	Remediation or reparation strategy efficiency	R-11
Inf12	Hydrogen consumption	Gas volume consumed daily or per user, via microgrid	R-12
Inf13	User and PAYG data central kitchen	Number of users using the communal kitchen, Data on PAYG transactions	R-13
Inf14	Certified Local system operator	Assessment of local operator skills and control of the system (certification).	R-17

6 Requirements

Requirements		
Categories ID	***Category name for requirements***	***Category description***
Requirement R-ID	***Requirement name***	***Requirement description***
R-01	Authorization from local authorities and support from partner required	
R-02	IoT, data monitoring and cloud sharing	
R-03	IoT and trained local operator	
R-04	Trained operator collecting data	

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R-05	Trained operator collecting data	
R-06	End-user identification and collaboration	
R-07	trained operator collecting data	
R-08	End-user identification and collaboration	
R-09	End-user identification and collaboration	
R-10	Trained operator detecting faults	
R-11	Trained operator solving faults	
R-12	Hydrogen consumption	
R-13	PAYG data central kitchen	

7 Common terms and definitions

Common terms and definitions	
Term	***Definition***
PAYG (Pay-As-You-Go)	A financing and payment model allowing users to purchase energy services in small increments using mobile money.
Clean Cooking	The use of clean, modern household energy and appliances that significantly reduce harmful household air pollution and protect health
Hydrogen storage solution	Any system, technology, or method designed to safely contain, manage, and deliver hydrogen for later use in energy applications such as cooking

8 Custom information (optional)

Custom information (optional)		
Key	***Value***	***Refers to section***

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4. Uganda: Biogas production from waste

1. Description of the use case
1.1 Name of the use-case

Use case identification		
ID	Area/Domain/Zone(s)	Name of the use case
UC3	Area: Energy systems Domains: DER, Customers Zones: Field, Process	Uganda: Low-tech biogas plant for communal use.

1.2 Version management

Version management				
Version No.	Date	Name of author(s)	Changes	Approval status
0.1	10/11/2025	Nora Stognief - TUB	Draft	
0.2	10/02/2026	Metanogenia SL	Draft	

1.3 Scope and objective of use case

Scope and objectives of the use case	
Scope	This use case is limited to the study of biogas production from waste in refugee communities in Uganda.
Technical Objective(s)	- Optimise biogas production from available by-products using low-cost materials and the training of local partners - Improve existing process - Simplify existing technology using materials from the local supply chain. - Improve reliability - Improve local waste management infrastructures - Produce fertilizer - Refinement and adaptation of the technology to the local African context
Socio-Economic Objective(s)	- Improve energy access - Improve food security - Provide a solution that respects cultural limitations - Generate local employment through training technicians. - Reduce population risks of looking for wood.
Ecological Objective(s)	- Reduce dependency on fossil fuels and firewood cutting CO_2 emissions by approximately 1.5 tCO_2eq/year *200 users. - Improve local waste management infrastructures - Define a local value chain to improve circularity and sustainability - Promote circular-economy principles through eco-design - Improve healthier environments by valorising biowastes that are commonly dumped or burned.
Business Objective(s)	- Reduce costs - Reinforce the income generation in local value chains - Provide thermal energy for economic activities such as food processing
Related business case(s)	- Improved energy access - Improved food security

1.4 Narrative of use case

Narrative of use case

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Short description
META aims to develop, implement, and operate small-scale biogas systems adapted to the local realities of African communities, using organic waste generated within local infrastructure. The overall goal is to improve access to energy, strengthen local waste management systems, and produce organic fertilizer in a sustainable, affordable, and culturally acceptable way. Although biogas is a highly relevant solution, most existing biogas technologies are not well adapted to local needs. They are often expensive, prefabricated on a global scale, poorly integrated into local value chains, and sometimes lack cultural acceptability. SUNNY addresses this gap by proposing a frugal, decentralized, and locally adapted approach, bringing biogas solutions to communities where such systems have not previously been feasible. The project will develop small-scale biodigesters made with at least 70% locally sourced materials, designed to be robust, easy to operate, and affordable. The systems will be adapted to the types of organic waste available in each community and will rely on simple processes rather than complex or costly technologies. The approach involves collecting and manually sorting organic waste, preparing it for anaerobic digestion, and converting it into biogas and digestate through a natural biological process (anaerobic digestion). The biogas will mainly be used for cooking and thermal applications, enabling users to reduce reliance on traditional fuels and supporting income-generating activities, such as food processing. The digestate will be reused as a high-quality organic fertilizer, closing the local nutrient cycle.
User story
As a resident of Bidibidi refugee camp, I want to use clean fuels to save money and reduce my dependence on fossil fuels. As a resident of Bidibidi refugee camp, I want an energy solution that uses cheap materials so that I can afford it. As a resident of Bidibidi refugee camp, I want an energy solution that uses locally sourced materials so that energy is always available. As a resident of Bidibidi refugee camp, I want the local waste management infrastructures to be improved to reduce health hazards. As a resident of Bidibidi refugee camp, I want to spend my time on other duties than risking my life looking for firewood.
Complete description
Using organic waste from local infrastructure via low-tech biogas digesters improves energy access, produces fertilizer, and improves local waste management infrastructures. Even though highly relevant, most of the biogas generation devices are not adapted to the African local needs, cultural acceptability, purchasing power and value chain. Some solutions are emerging such as The Waste Transformers involved in the Green Deal project ENERGICA which is still under development and is more relevant to an urban context with a lot of waste, and the biodigesters developed by Flexi Biogas Solutions, one of the market leaders in biodigesters in East Africa, but they are limited in their consideration of the local value chain, because of their prefabrication on a global scale. SUNNY will develop, implement and operate biogas generation devices on a small scale (biogas production of about 5.6m³/day), in a distributed manner and adapted to the substrates and waste produced in the local communities of the countries under study. Bringing such biogas solutions to the communities targeted in SUNNY will be a first. Work on developing biogas technology has been carried out by META as part of the SESA project (Smart Energy Solutions for Africa). Based on the results already observed, the process will be improved, and the technology will be further simplified using materials from the local supply chain. META will develop simplified bioreactors, with a frugal and local approach, made with at least 70% of materials sourced locally, allowing to make it relevant to use in the targeted communities. With a smaller scale, improved reliability and lower costs, the solution developed is expected to be relevant to be included in new areas not possible before for economic reasons. The solution will moreover allow an economic activity such as food processing, for instance, thanks to the thermal energy produced, reinforcing the income generation in local value chains. **Process decscription** The input will go through a reception and manual pretreatment first step, in which the non-organic or high-volume materials will be discarded. This first step will be carried out in a screening and selection area, equipped with a 65-litre **reject tank**, sized to store approximately 30% of the total input for three consecutive days that would work as a garbage bin. Afterwards, the sorted organic waste (50 kg/day) will be manually transferred with a shovel to a 150-litre **waste storage tank** made of PVC, which will be able to store the expected input for two-three days. The organic matter is manually loaded to a manual grinder for particle size reduction, making organic matter more digestible. After that, it is transferred to a 300 litre tank (**mixer**), at this stage, the crushed waste will be mixed with rainwater and liquid fraction of the digestate to reduce the solids concentration to a dry matter of 13.5%, suitable for the anaerobic digestion process. To reduce the dry matter, it's foreseen the construction of a 200-litre tank with a **rainwater storage system** consisting of a rooftop installation with a catchment area of 20m2 and a collection efficiency of 80%. It it is estimated that during the rainiest season (e.g. August, with 148 mm of rainfall), at least 2 days of autonomy can be guaranteed with the 200 L tank. The water and the liquid fraction of digestate would be fed manually to the mixer. After the dilution process - requiring a daily mixture of approximately 55 litres of liquid fraction (from digestate and rainwater) - a total mass of 105 kg/day is obtained with a final concentration of 13.5% dry matter, a value suitable for treatment through anaerobic digestion. For feeding

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the digester, the installation of a screw pump with a 105-litre/hour capacity is planned, allowing the diluted mixture to be pushed into the digester. This pump will also serve to stir the mixture through recirculation, improving content homogeneity, and enhancing process efficiency. The **anaerobic digester**, made of glass-fiber reinforced plastic (GFRP) has been sized considering both the variability in waste characteristics and seasonal fluctuations in their generation. A hydraulic retention time (HRT) of 35 days has been adopted, which - with a daily load of 50 kg - requires a useful volume of approximately 4 m³. However, to ensure stable operation in the face of potential load fluctuations, the volume has been oversized to 6 m³. The digester will have a cylindrical shape, with a diameter of 2.4 meters and a total height of 2 meters, of which 0.6 meters will be reserved as a safety margin (freeboard) to prevent overfilling. It is thought to be at ambient temperature as regulating its temperature to 38ºC would increase costs and reduce local materials.

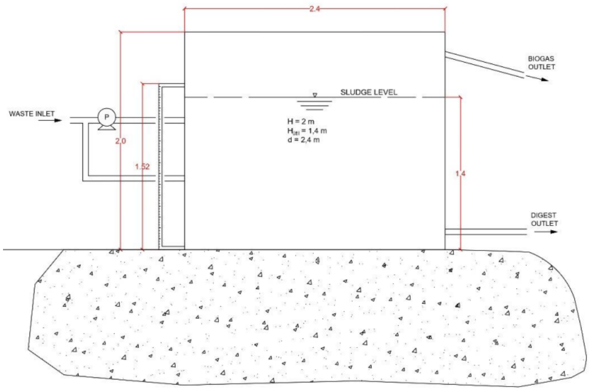

Figure 1. Anaerobic digester scheme

It is estimated that, with the projected daily input of substrate, an approximate volume of 5.6 m³ of biogas can be generated per day. To ensure proper storage and allow for continuous operation, a **floating-drum type gas holder** has been sized with the capacity to store the biogas generated over 1.5 days, which corresponds to a total volume of 8 m³. The system consists of a cylindrical container open at the top, filled with water, and an inverted GFRP drum that floats on this liquid medium. The drum is designed to move vertically, guided by columns or rails, to maintain stability and prevent tipping during upward or downward movement. The produced biogas is introduced at the bottom of the gas holder, accumulating in the space between the water surface and the inside of the drum. As the gas volume increases, the drum rises due to the buoyant force generated by the contained gas. The outlet pressure of the biogas must fall within a suitable range for cooking purposes, between 10 and 15 mbar. To achieve this service pressure, the PVC drum, which acts as the floating dome, must have

a total weight of approximately 510 kg, including its own material weight and, if necessary, an additional <u>ballast system</u>.

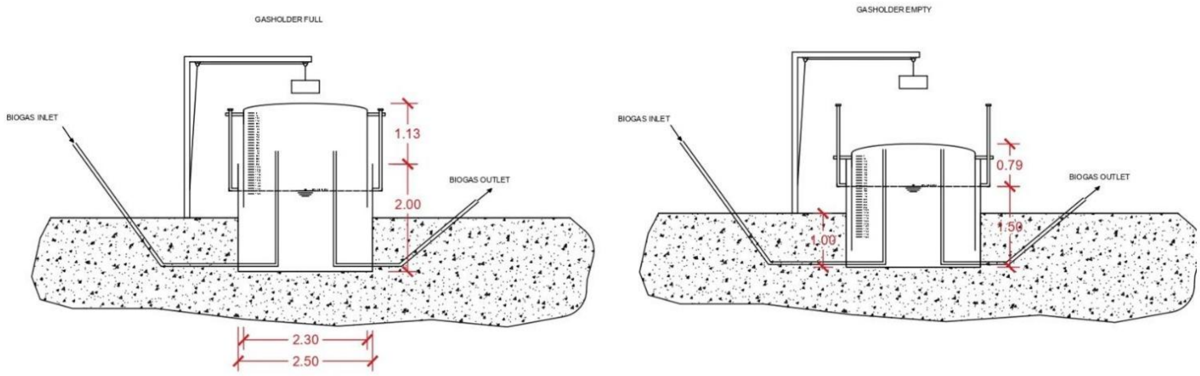

Figure 2. Gasholder scheme.

The gas drum will have a diameter of 2.3 meters and a maximum vertical travel of 1.5 meters, allowing the estimated volume of biogas to be stored at the desired pressure. The lower container, which holds the water on which the drum floats, must have a diameter of 2.5 meters, providing a radial clearance of 10 cm to allow free vertical movement without friction. As for the height, a tank between 1.7 and 2 meters has been considered, which is sufficient to accommodate the drum's vertical movement (1.5 m) plus an additional safety margin of 0.2 to 0.5m. It is essential to ensure that the water level always covers the lower edge of the drum to maintain airtightness and prevent gas leaks. Additionally, the drum will be equipped with a graduated scale (ruler) to display the approximate volume of biogas stored at any given time.
All system tanks (for reception, pretreatment, mixing, dilution, digestion, and digestate storage) will be equipped with a transparent PVC sight glass. This consists of an external tube connected to the bottom and top of the tank, allowing direct visualization of the content level. The tubes will be graduated to facilitate volume reading and ensure proper control of the feeding and digestion processes.

The produced digestate, estimated at 99 kg/day, will be separated into two phases by sedimentation in a **sedimentation tank.** Hence, liquid fraction is recirculated to dilute the organic matter, and solid fraction is dried and used as a high-quality fertilizer.

<u>Anaerobic digestion scheme</u>

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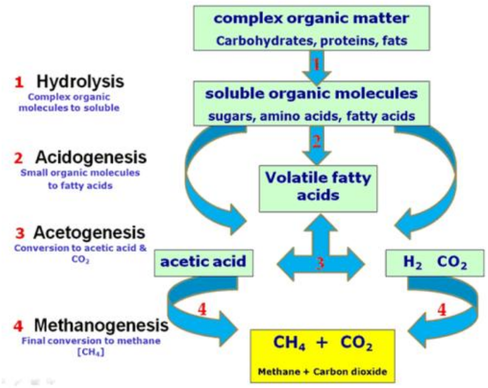

Anaerobic digestion or biodigestion is a biological process in which organic matter is degraded by the concerted action of a wide variety of microorganisms (mainly bacteria) in the absence of oxygen or other strong oxidizing agents. The main end products of these reactions are a gas called biogas, which is mainly made up of methane and carbon dioxide which also contains nitrogen, hydrogen, hydrogen sulfide and ammonia, which normally account for less than 1% of the total volume of biogas. On the other hand, a digested effluent is generated, which is a mixture of mineral products (nitrogen, phosphorus, potassium ...) and other compounds that are difficult to break down. This effluent, after undergoing a series of treatments, can be used as an agricultural amendment, since it has a greater fertilizing power than the treated waste. Biogas contains a high percentage of methane (between 50-80%, depending on the substrate and the reactor design), so it is susceptible to use the energy to generate heat and / or electricity through its combustion in engines, in turbines or in boilers, either alone or mixed with another fuel. It is also possible to use it in fuel cells, once the hydrogen sulfide, which may affect the membranes, has been removed. Once purified, it can be introduced into the natural gas transportation network, or it can be used as an automotive fuel. Within SUNNY, biogas production from available by-products will be optimised by META through the use of low-cost materials and the training of local partners. Cultural limitations will be taken into account for the use of certain wastes of animal or human origin. Using organic waste from local infrastructure via low-tech biogas digesters will enable to improve energy access, produces fertilizer, and improves local waste management infrastructures.

Implementation steps

The implementation steps for the installations for generation of biogas are the following: 1. Detection of potential water leaks, done by introducing water, which does not need to be potable, into the circuit, filling the digester and auxiliary tanks, if any. By putting the installation into operation, it is possible to detect at which points water is being lost and act on those points. 2. Tightness test: checking that there are no points where the system loses gas. It is necessary to carry out this action to avoid losing a quantity of gas that must be used for cooking. 3. Once it has been verified that the plant has no liquid or gas losses, it must be emptied of water in order to incorporate the acclimatised inoculum. Organic waste contains a very small amount of anaerobic bacteria. This makes it very difficult to start the biological reaction with these by-products. Acclimatised sludge from another biogas plant will be used, if possible, otherwise animal sludge can be introduced into the reactor and water if necessary. This will provide a higher number of anaerobic bacteria. 4. Once the sludge has been introduced, it will be homogenised inside the reactor, and its temperature will be adjusted between 35-40°C. In this way, the degradation of organic matter will begin, and the anaerobic process will begin to take place.

The main process control variables will be the following: i) Organic loading flowrate: Amount of daily organic matter that must enter the digester to maintain bacterial health and the stability of the anaerobic process. Above a daily flow of 4gCOD/L of digester (COD=Chemical Oxygen Demand), there is a danger of inhibition due to organic overload. This flow rate depends on the type of waste that will be introduced into the reactor. ii) pH: The optimal value is 7.5. Below this value, there is a danger of inhibition. It is the easiest measurable value to obtain enough information about the stability of the process. The pH is measured in the digestate as soon as it leaves the digester. iii) Biogas production: The amount of gas obtained can be measured daily with analog gasometers. Both flowmeters and gasometrical devices will be used. The decrease in gas produced is an indicator that something in the aerobic reaction is not working correctly.

1.5 Key performance indicators

1.5.1 Technical KPIs

Technical KPIs			
ID	***Name***	***Description***	***Reference to mentioned use case objectives***

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1	CAPEX reduction compared to existing alternative	Target: 15-20%	Materials used are locally supplied and low-tech.
3	Percentage increase in lifetime of products used in the demonstrator locations	Target: 10%	Promote circular-economy principles through eco-design supported by ReFuse.
5	Daily biogas production	11.52m³ / day 5,6 expected	Due to the collection of biowastes constraints, biogas production will probably be downsized.
9	GHG emissions mitigated with SUNNY solutions	Target: 1.5 tCO2eq/year * 200 users	Reduce dependency on fossil fuels and firewood. Avoid GHG emissions from biowastes valorization.
17	Number of people benefiting to an enhanced access to energy	Target: 200	Increase access to affordable and reliable energy for refugees' communal use (school, hospital…)
22	Percentage of local materials used in the construction of the biogas solution	70%	Local value chain and local suppliers to promote an affordable biogas device. Simplicity of materials.
25	Percentage of energy solutions replaced by clean technologies in the demonstration sites	Target: 10%	The technology will make the user less dependent on fossil fuels.

1.5.2 Ecological KPIs from REFUSE's Ecodesign Toolkit

Ecological KPIs			
ID	***Name Reference to mentioned use case objectives***	***Weight***	***Scoring***
Theme 1: Nature-Based Design, Environmental Footprint			*83%*
1.1	Local material sourcing	15%	0.59
1.2	Use of natural/low-impact materials	7%	0.07
1.3	Toxicity potential	4%	0.04
1.4	Local water risk sensitivity	11%	0.33
1.5	Nature-based or low-tech integration	7%	0.30
1.6	Climate change mitigation potential	15%	0.59
1.7	Climate change adaptation support	15%	0.59
1.8	Footprint of material sourcing	15%	0.59
1.9	Circularity of material sourcing	11%	0.22
Theme 2: Durability and Repairability			*67%*
2.1	Design lifetime	13%	0.38
2.2	Ease of disassembly	15%	0.44
2.3	Tools required for maintenance and repair	15%	0.59
2.4	Spare parts availability	15%	0.00

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2.5	Spare parts cost	11%	0.00
2.6	Repair documentation	11%	0.44
2.7	Modularity	15%	0.59
2.8	Remote support	4%	0.07
2.9	Upgradeability	4%	0.15
2.10	Resilience to environmental conditions	15%	0.44
Theme 3: Recyclability & End of Life Management			*44%*
3.1	Recyclability	16%	0.00
3.2	Reusability, second life potential	16%	0.64
3.3	Hazardous materials share	4%	0.12
3.4	Ease of material separation	16%	0.64
3.5	Local disposal/recycling chain	16%	0.00
3.6	Takeback schemes at End of Life (EOL)	8%	0.00
3.7	Materials, components identification	12%	0.36
3.8	EOL documentation	12%	0.00
Theme 4: Service Orientation			*66%*
4.1	Service model	17%	0.50
4.2	Maintenance contract	17%	0.67
4.3	Buy-back schemes	8%	0.17
4.4	Pay-per-use and leasing models	13%	0.50
4.5	Warranty duration	8%	0.25
4.6	Components replacement services	13%	0.13
4.7	Remote monitoring	8%	0.08
4.8	Service impact on lifetime	17%	0.33

1.6 Use case conditions

1.6.1 Technical use case conditions

Technical use case conditions
Assumptions
- Organic waste can be utilized for biogas production via anaerobic digestion - Biogas production from available by-products can be optimised using low-cost materials - Using organic waste from local infrastructure via low-tech biogas digesters can improve energy access, produce fertilizer, and improve local waste management infrastructures. - Lack of sufficient and qualitative and quantitative data is a decisive limitation in the field of Humanitarian Energy

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Prerequisites
- Identify implementation site - Conduct preliminary tests to verify safety aspects - Collect information on the properties of organic waste available in the camp - Understand the way organic waste is handled and how would it be collected for the biogas device. - Identify local suppliers and obtain low-cost materials

1.6.2 Environmental use case conditions

Environmental use case conditions
Assumptions
-
Prerequisites
-

1.6.3 Socio-economic use case conditions

Socio-economic use case conditions
Assumptions
- Factors like traditional cooking methods, gender roles, and religious practices play an important role in the design of energy interventions - Even though highly relevant, most of the biogas generation devices are not adapted to the African local needs, cultural acceptability, purchasing power and value chain. - Assessing preferences, perceptions, and understanding influencers to decisions is crucial to design context-embedded energy delivery models that can successfully sustain in the local setting - Inadequate participation of underrepresented groups, inadequate infrastructure, and weak linkages among actors can hinder the effectiveness and inclusivity of local value chains - Improving the reliability and affordability of renewable energy solutions requires improvements in terms of local acceptance - The use and handling of gases can pose a problem as it is being considered a hazardous element by the population.
Prerequisites
- Gain comprehensive and in-depth knowledge of the local context, including technical infrastructures, environmental conditions, social resources, and societal habits - Approach target groups and assess their preferences and perceptions - Identify elements for building a local value chain considering both hard and soft infrastructure - Build on the training of local people in the safe use of the technology.

1.6.4 Business use case conditions

Business use case conditions
Assumptions
- Business models must consider local, national, and international regulations, as well as the existing market analysis
Prerequisites
- Set up advisory and replication boards - Develop an adapted financial and pricing strategy - Collect empirical data to validate business assumptions

1.7 Further information to the use case for classification/mapping

Classification information
Relation to the other use cases

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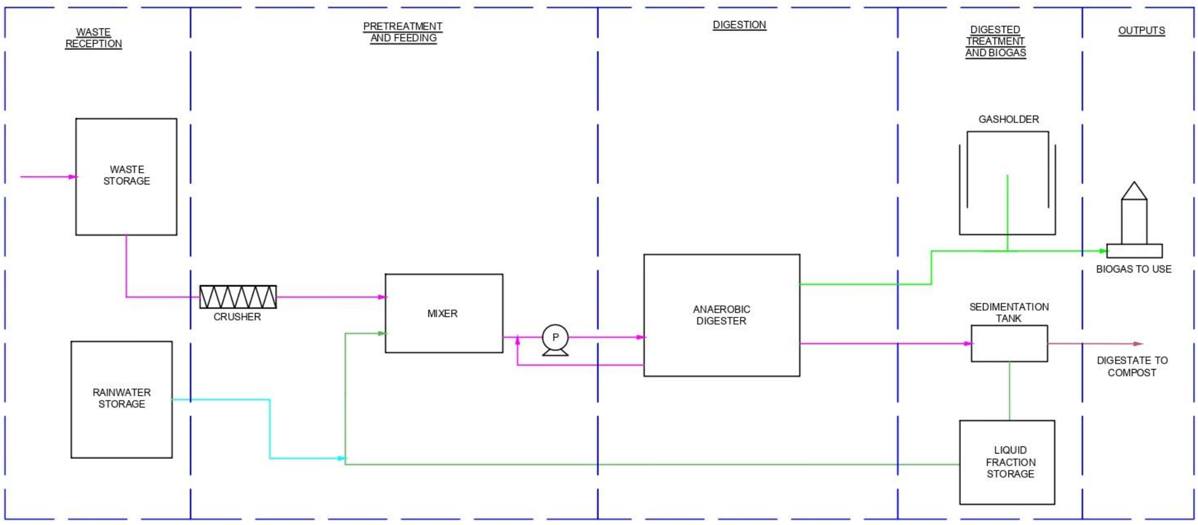
Level of depth
Generic
Prioritization
Obligatory
Generic, regional or national relation
Regional
Nature of the use case
Technical, socio-economic, and business UC
Further keywords for classification
Distributed Energy Resource (DER), Biogas, Organic waste, Biodigestion

1.7 General remarks

General remarks
Willingnes to pay is crucial for technology design

2 Diagrams of use case

Diagram(s) of use case



3 Technical details

3.1 Actors

Actors	
Grouping	**_Group Description_**
Business Actor	Physical or legal person that has his own interests, defined as "Business Goals"
Operator	Business Actor that operates a system
Logical Actor	Technical entity that takes part in the execution of a use case. A logical actor can be mapped to a physical component
Business Actor	

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Actor name	***Actor type***	***Actor description***	***Further information specific to this use case***
		Business Actor	
System Technology Provider **METANOGENIA**	Business Actor	Designs and engineers the distributed biogas system; supplies critical components (e.g., pumps) and provides training and commissioning support.	Does not operate or own the system. Provides know-how transfer, documentation, and start-up assistance.
System Owner / Operator **FUTURE START-UP/SPV**	Business Actor	Owns the biogas asset and is responsible for commercial operation and service delivery to the school/municipality.	Likely responsible for safety compliance, maintenance contracts, and gas supply agreements. Business model: pay-per-use gas.
School (Facility Host & Energy User)	Business Actor	Hosts the installation and consumes the produced biogas for cooking activities.	Provides organic waste feedstock and daily access to the system. Pays for gas consumption.
Municipality	Business Actor	Supports local deployment and may provide additional organic waste streams or co-funding.	May facilitate permits, logistics, or coordination with public services.
Local Construction	Business Actor	Constructs civil works and installs the digester and associated infrastructure.	Trained by the technology provider; responsible for on-site assembly.
Local Materials/Components Suppliers	Business Actor	Supplies locally sourced tanks, piping, fittings, and construction materials.	Reduces cost and simplifies maintenance through local availability.
European Component Supplier (Pumps)	Business Actor	Provides specialized mechanical components not available locally.	Equipment shipped from Europe and integrated during construction.
		Operator	
Local O&M Personnel (School/Municipality Staff)	Operator	Performs daily feeding of organic waste, basic inspections, and routine operation of the digester.	Receives training during commissioning; no advanced technical skills required.
Maintenance Technician (Local)	Operator	Conducts preventive and corrective maintenance of mechanical components and gas lines.	Handles repairs, cleaning, seal checks, and safety verifications.
Kitchen Staff / End Users	Operator	Uses the biogas for cooking activities.	
Technology Provider Support Team	Operator	Provides second-level technical support and troubleshooting during commissioning or exceptional failures.	Remote or occasional on-site assistance only; not responsible for daily operation.
		Logical Actor	
Anaerobic Digester Unit	Logical Actor	Biological reactor that converts organic waste into biogas through anaerobic digestion.	Core energy production component. Sized for small distributed applications.
Feedstock Input System	Logical Actor	Interface for loading organic waste into the digester.	Manual or semi-manual loading by local staff.

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Gas Storage Dome / Gas Holder	Logical Actor	Temporarily stores produced biogas and stabilizes supply pressure.	Low-pressure flexible or fixed dome integrated with digester.
Gas Piping Network	Logical Actor	Transfers biogas from storage to end-use points.	Includes basic valves and safety shut-offs.
Safety Valve System (Overpressure Relief)	Logical Actor	Releases excess gas to prevent unsafe pressure levels.	Passive/automatic protection; no digital control.
Mixing/Pumping System	Logical Actor	Ensures proper mixing and movement of slurry inside the digester.	Pumps supplied from Europe.
Biogas Stove/Burner System	Logical Actor	Converts biogas into usable thermal energy for cooking.	Installed in school kitchen facilities.
Digestate Outlet	Logical Actor	Removes treated slurry after digestion for disposal or reuse.	Can be used as fertilizer if regulations allow.

3.2 References

References						
No.	***Reference type***	***Reference***	***Status***	***Impact on use case***	***Originator/organization***	***Link***
1	Technical Standard	ISO 23590: Biogas systems — Small and medium-scale anaerobic digestion plants — Safety requirements	Active	Defines safety requirements for digester design, gas handling, storage domes, overpressure protection, and operation. Directly impacts mechanical design and safety devices.	International Organization for Standardization (ISO)	https://www.iso.org
2	Gas Installation Standard	EN 15001-1: Gas infrastructure — Installation pipework with operating pressure ≤ 0.5 bar	Active	Provides design and installation rules for low-	CEN (European Committee for Standardization)	https://standards.cencenelec.eu

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				pressure gas piping networks. Applicable to biogas piping from digester to kitchen burners.		
3	National Environmental Regulation	National Environment Act (2019)	Active	Requires environmental protection measures for waste treatment systems, including odor control, effluent handling, and pollution prevention. May require local environmental approval for installation.	National Environment Management Authority (NEMA Uganda)	https://www.nema.go.ug
4	Waste Management Regulation	National Environment (Waste Management) Regulations, 2020	Active	Governs handling and reuse of organic waste and by-products. Affects feedstock sourcing, storage practices, and digestate management.	NEMA Uganda	https://www.nema.go.ug

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5	Agriculture / Fertilizer Guidance	Uganda National Agricultural Advisory / FAO digestate reuse best practices	Published	Provides guidance for safe agricultural use of digestate as fertilizer; impacts storage, pathogen control, and application procedures.	Ministry of Agriculture, Animal Industry and Fisheries (MAAIF) / FAO	https://www.agriculture.go.ug
6	Occupational Health & Safety Regulation	Occupational Safety and Health Act (2006)	Active	Requires risk assessment, worker training, PPE, and safe handling of combustible gas and biological materials. Impacts O&M procedures and training plans.	Ministry of Gender, Labour and Social Development (Uganda)	https://www.mglsd.go.ug
7	Building / Construction Code	Local Authority Building Control Requirements	Active	Permits and inspections for civil works (foundations, tanks, buried piping). Affects installation approval and site layout.	Local district/municipal authority	N/A (local permit)
8	Technical Guideline / Programma	Africa Biogas Partnership Programme (ABPP) / SNV domestic biogas construction standards	Published	Provides proven constructi	SNV Netherlands Development Organisation	https://snv.org

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	tic Reference			on practices and safety guidelines for small-scale digesters in East Africa; supports locally appropriate design choices.		
9	Contractual / Business Framework	Energy-as-a-Service or Gas Supply Agreement (School–Operator contract)	Planned	Defines ownership, liability, safety responsibility, O&M duties, and payment per volume of gas consumed. Critical for role allocation and risk management.	System Owner / Operator	Internal contract
10	Project / Consortium Reference	EU Project Grant Agreement and Technical Annex	Active	Defines performance indicators, sustainability requirements, reporting, and procurement constraints that influence system design and operation.	European Commission / Project Consortium	Internal documentation
11	Manufacturer	Pumps and mechanical component technical manuals	Active	Defines operating	Component manufacturers	Manufacturer documentation

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	Documentation			limits, maintenance intervals, and installation constraints; impacts reliability and maintenance planning.		

4 Step by step analysis of use case

4.1 Overview of scenarios

Scenario conditions						
No.	***Scenario name***	***Scenario description***	***Primary actor***	***Triggering event***	***Pre-condition***	***Post-condition***
1	Nominal operation	Daily operation of the biogas system: organic waste is fed into the digester, biogas is produced and stored, and gas is delivered to the kitchen for cooking.	Local O&M Personnel	Scheduled daily feeding and cooking demand	Digester operational; sufficient feedstock available; gas lines intact; no safety alarms	Biogas supplied safely to kitchen; waste treated; digestate produced for agricultural reuse
2	Low gas production / energy constrained operation	Gas production is insufficient due to low feedstock input or suboptimal digestion conditions. Cooking demand cannot be fully covered.	Local O&M Personnel	Low gas pressure observed at stove or storage dome	Reduced feedstock, low temperature, or poor mixing	Operator adjusts feeding or mixing; alternative fuel may be used temporarily; system returns to normal after correction
3	Overpressure safety release	Gas pressure exceeds safe threshold and the pressure relief valve automatically vents excess gas.	Safety Valve System (automatic)	Pressure exceeds design limit	Excess gas production or low consumption	Pressure reduced to safe level; system stabilized; operator checks cause
4	Routine maintenance	Preventive inspection and maintenance of pumps, piping, and digester components.	Maintenance Technician	Scheduled maintenance interval or inspection plan	System accessible and safe to service; gas supply temporarily isolated if required	Components cleaned/repaired; system reliability restored; safe operation confirmed
5	Gas leak or safety incident	Suspected gas leak or abnormal odor detected near piping or kitchen area. System shut down for safety.	Kitchen Staff / Local O&M Personnel	Smell of gas or visible piping damage	System operating	Gas supply closed; area ventilated; technician inspects and repairs; system restarted after safety verification

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6	Digestate handling and reuse	Removal of digestate and application as fertilizer in agricultural areas.	Local O&M Personnel	Digestate storage reaches removal threshold	Digestion process completed; storage available	Digestate safely applied to fields; storage capacity restored for continued operation

4.2 Steps – Scenarios

Scenario								
Scenario name		**Nominal operation**						
Step No.	**Event**	**Name of process/activity**	**Description of process/activity**	**Service**	**Information producer (actor)**	**Information receiver (actor)**	**Information exchanged (IDs)**	**Requirements, R-IDs**
1	Start of daily routine	Prepare feedstock	Organic waste is collected from kitchen/canteen and prepared for digestion	EXECUTE	Local O&M Personnel	Anaerobic Digester Unit	Feedstock input batch	Safe waste handling procedure
2	Feedstock available	Load digester	Waste is manually processed and loaded into digester inlet	EXECUTE	Local O&M Personnel	Anaerobic Digester Unit	Organic waste mass	Digester capacity limits respected
3	Loading completed	Anaerobic digestion	Biological conversion of waste into biogas	TIMER	Anaerobic Digester Unit	Anaerobic Digester Unit	Retention time	Minimum digestion time required
4	Gas produced	Store biogas	Produced gas accumulates in storage dome	CREATE	Gas Storage Dome	System Owner / Operator	Available gas volume/pressure	Safe storage pressure limits
5	Cooking demand	Supply gas to kitchen	Gas flows through low-pressure piping to stove	EXECUTE	Gas Storage Dome	Kitchen Staff / End Users	Gas flow	EN 15001 compliant piping
6	Gas available at stove	Cooking	Biogas combusted for meal preparation	EXECUTE	Kitchen Staff	Kitchen Staff	Thermal energy	Normal operation
7	Digestion completed	Remove digestate	Treated slurry is discharged from digester	EXECUTE	Local O&M Personnel	Digestate Outlet	Digestate volume	Hygiene procedures
8	Digestate available	Apply fertilizer	Digestate transported and applied to crops	EXECUTE	Local O&M Personnel	Agricultural Field / School Garden	Organic fertilizer	Safe agricultural reuse guidelines
9	Digestate available	Recirculate liquid fraction	Digestate is separated in phases; liquid fraction is used for dilution of daily input.	EXECUTE	Local O&M PersonneL	Anaerobic digester unit	Feedstock input batch	Dilution for reaching an appropriate humidity
10	End of day	Record operation status	Basic operational check and	REPORT	Local O&M Personnel	System Owner / Operator	Daily status report	O&M checklist completed

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			visual inspection					
Scenario name		Energy constrained operation						
Step No.	**Event**	**Name of process/activity**	**Description of process/activity**	**Service**	**Information producer (actor)**	**Information receiver (actor)**	**Information exchanged (IDs)**	**Requirements, R-IDs**
1	Low flame at stove	Detect low gas pressure	User observes weak flame or insufficient heat	REPORT	Kitchen Staff	Local O&M Personnel	Low pressure alert	Safety awareness training
2	Alert received	Inspect system	Operator checks dome pressure and feedstock level	GET	Local O&M Personnel	Gas Storage Dome	Pressure reading	Manual gauge available
3	Low pressure confirmed	Diagnose cause	Identify insufficient feedstock or digestion issue	EXECUTE	Local O&M Personnel	Local O&M Personnel	Diagnostic assessment	O&M procedure
4	Feedstock insufficient	Add additional waste	Extra organic waste loaded into digester	EXECUTE	Local O&M Personnel	Anaerobic Digester Unit	Additional feedstock	Capacity respected
5	Digestion restarted	Wait for gas production	System allowed to produce gas	TIMER	Anaerobic Digester Unit	Anaerobic Digester Unit	Retention time	Minimum digestion period
6	Gas restored	Resume normal cooking	Gas pressure returns to acceptable level	REPORT	Local O&M Personnel	Kitchen Staff	Gas available notification	Return to nominal operation
Scenario name								
Step No.	**Event**	**Name of process/activity**	**Description of process/activity**	**Service**	**Information producer (actor)**	**Information receiver (actor)**	**Information exchanged (IDs)**	**Requirements, R-IDs**

5 Information exchanged

Information exchanged			
Information exchange, ID	**Name of information**	**Description of information exchanged**	**Requirement, R-IDs**
INF-01	Feedstock input batch	Quantity and type of organic waste collected and loaded into the digester for a feeding cycle.	Must respect digester capacity and allowed feedstock types.
INF-02	Organic waste mass	Estimated or measured mass/volume of waste introduced into the digester.	Recorded daily for operational control.
INF-03	Retention time	Minimum digestion time required to produce biogas after feeding. Represents biological processing period.	Must meet design retention time to ensure stable gas production.
INF-04	Available gas volume/pressure	Current gas level or pressure inside the storage dome indicating available energy.	Must remain within safe pressure limits

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			defined by safety design.
INF-05	Gas flow	Physical flow of biogas from storage to kitchen appliances during consumption.	Low-pressure (<0.5 bar) compliant with EN 15001.
INF-06	Thermal energy	Heat energy delivered by combustion of biogas at the stove.	Must meet minimum cooking performance requirements.
INF-07	Digestate volume	Quantity of treated slurry discharged from the digester after digestion.	Must be handled according to hygiene and environmental guidelines.
INF-08	Organic fertilizer	Digestate applied to agricultural soil as fertilizer.	Must comply with safe agricultural reuse practices.
INF-09	Daily status report	Manual record of daily operation, including feeding, gas availability, and observed issues.	Must be logged for traceability and maintenance planning.
INF-10	Low pressure alert	Notification generated by users when insufficient gas pressure is detected.	Must trigger inspection within defined response time.
INF-11	Pressure reading	Measured pressure value from dome or piping during inspection.	Gauge must be readable and calibrated.
INF-12	Diagnostic assessment	Operator evaluation of system condition and identified cause of low production or malfunction.	Must follow O&M procedures.
INF-13	Additional feedstock	Extra waste added to restore gas production.	Must not exceed digester design capacity.
INF-14	Gas available notification	Confirmation that gas pressure has returned to acceptable level and normal operation can resume.	Communicated clearly to kitchen staff.

6 Requirements

Requirements		
Categories ID	***Category name for requirements***	***Category description***
CAT-01	Operational	Requirements related to daily operation and functionality of the biogas system
CAT-02	Safety	Requirements ensuring safe handling of biogas, pressure, and biological materials
CAT-03	Performance	Requirements related to energy output and service reliability
CAT-04	Environmental	Requirements related to waste treatment and digestate reuse
CAT-05	Maintenance	Requirements related to inspection, serviceability, and lifecycle management
CAT-06	Regulatory & Compliance	Requirements derived from national laws, standards, and permits

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Requirement R-ID	***Requirement name***	***Requirement description***
R-01	Daily feedstock loading	The system shall allow daily manual feeding of organic waste using simple tools without specialized equipment.
R-02	Minimum gas production	The system shall produce sufficient biogas to cover daily cooking demand under nominal operating conditions.
R-03	Low-pressure distribution	Biogas shall be distributed through low-pressure piping (<0.5 bar) compliant with EN 15001 or equivalent safety standards.
R-04	Gas storage safety	The gas storage dome shall maintain pressure within safe design limits.
R-05	Overpressure protection	The system shall include automatic pressure relief valves to prevent overpressure conditions.
R-06	Leak prevention	Gas piping and connections shall minimize leakage risk and allow easy inspection.
R-07	Manual operability	The system shall operate without reliance on digital monitoring or external power supply.
R-08	Operator training	Local personnel shall receive training for safe operation, feeding, inspection, and basic troubleshooting.
R-09	Preventive maintenance	The system shall allow routine inspection and maintenance using locally available tools and skills.
R-10	Fault detection	Operators shall be able to visually or physically detect abnormal conditions (low pressure, smell, or damage).
R-11	Safe shutdown	The system shall allow manual isolation of gas supply during maintenance or emergencies.
R-12	Digestate management	Digestate shall be safely removable and suitable for agricultural reuse.
R-13	Environmental protection	Operation shall prevent uncontrolled release of waste, odors, or pollutants to soil and water.
R-14	Hygiene compliance	Handling of feedstock and digestate shall follow safe sanitation practices.
R-15	Operational logging	Daily operation status and incidents shall be recorded for traceability.
R-16	Local construction feasibility	Civil works and installation shall be achievable using locally available materials and contractors.
R-17	Component durability	Mechanical components (pumps, valves, piping) shall withstand local environmental conditions and expected loads.

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R-18	Regulatory compliance	The installation shall comply with Uganda environmental, safety, and building regulations and obtain required permits.
R-19	Energy service continuity	The system shall restore gas production within an acceptable time after feedstock replenishment.
R-20	Defined responsibility	Ownership, O&M responsibility, and safety liability shall be defined contractually between operator and school/municipality.

7 Common terms and definitions

Common terms and definitions	
Term	***Definition***
Anaerobic digestion	Biological process in which microorganisms break down organic matter in the absence of oxygen to produce biogas and digestate.
Biogas	Combustible gas mixture mainly composed of methane (CH_4) and carbon dioxide (CO_2), produced through anaerobic digestion.
Anaerobic digester	Sealed reactor where organic waste is converted into biogas under controlled anaerobic conditions.
Feedstock	Organic material (food waste, agricultural residues, or organic waste) used as input to the digester.
Digestate	Stabilized slurry remaining after anaerobic digestion, suitable for use as organic fertilizer.
Gas storage dome / gas holder	Low-pressure storage component that temporarily accumulates produced biogas and balances supply and demand.
Low-pressure gas distribution	Piping network operating below 0.5 bar used to transport biogas safely to end-use appliances.
Biogas stove / burner	Cooking appliance designed or adapted to combust biogas for thermal energy generation.
Energy-as-a-Service (EaaS)	Business model in which the user pays for energy consumption rather than owning the energy generation asset.
Retention time	Minimum time that feedstock remains in the digester to ensure effective biogas production.
Nominal operation	Normal system functioning under expected conditions, delivering sufficient biogas for daily cooking demand.

8 Custom information (optional)

Custom information (optional)		
Key	***Value***	***Refers to section***

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5. Uganda: Smart solar irrigation

1. Description of the use case

1.1 Name of the use-case

Use case identification		
ID	***Area/Domain/Zone(s)***	***Name of the use case***
UC4	Area: Energy Systems/irrigation Domains: Customers: Farmers Zones: Process, Field: UGANDA	Uganda: Smart solar irrigation system to improve water efficiency and increase yields.

1.2 Version management

Version management				
Version No.	***Date***	***Name of author(s)***	***Changes***	***Approval status***
0.1	03/11/2025	Nora Stognief - TUB	Draft	
0.2	13/11/2025	SOLEKTRA	DRAFT	
0.3	09/01/2026	Nora Stognief - TUB	Draft	

1.3 Scope and objective of use case

Scope and objectives of the use case	
Scope	This use case is limited to the study of smart solar irrigation systems in refugee communities in Uganda. - Demonstration of smart solar irrigation systems for agricultural production in humanitarian and rural contexts. - Solar-powered pumping combined with monitoring and control to ensure reliable and efficient water delivery.
Technical Objective(s)	- **OBJ-T1:** Deploy a solar-powered irrigation system with integrated IoT-based monitoring. - **OBJ-T2:** Ensure reliable water supply through solar pumping and buffered storage. - **OBJ-T3:** Enable real-time monitoring of water flow and system performance.
Socio-Economic Objective(s)	- **OBJ-S1:** Improve agricultural productivity of participating farmers. - **OBJ-S2:** Ensure affordable and transparent tariff structures. - **OBJ-S3:** Establish community-based governance through Water User Committee (WUC).
Ecological Objective(s)	- **OBJ-E1:** Reduce reliance on diesel-based irrigation systems. - **OBJ-E2:** Promote sustainable water management practices.
Business Objective(s)	- Raise cropping yields - Increase value of crops - Generate evidence for scalable and replicable service-oriented irrigation models.
Related business case(s)	- Intensification of crop production - Sustainable agriculture - Improved food security

1.4 Narrative of use case

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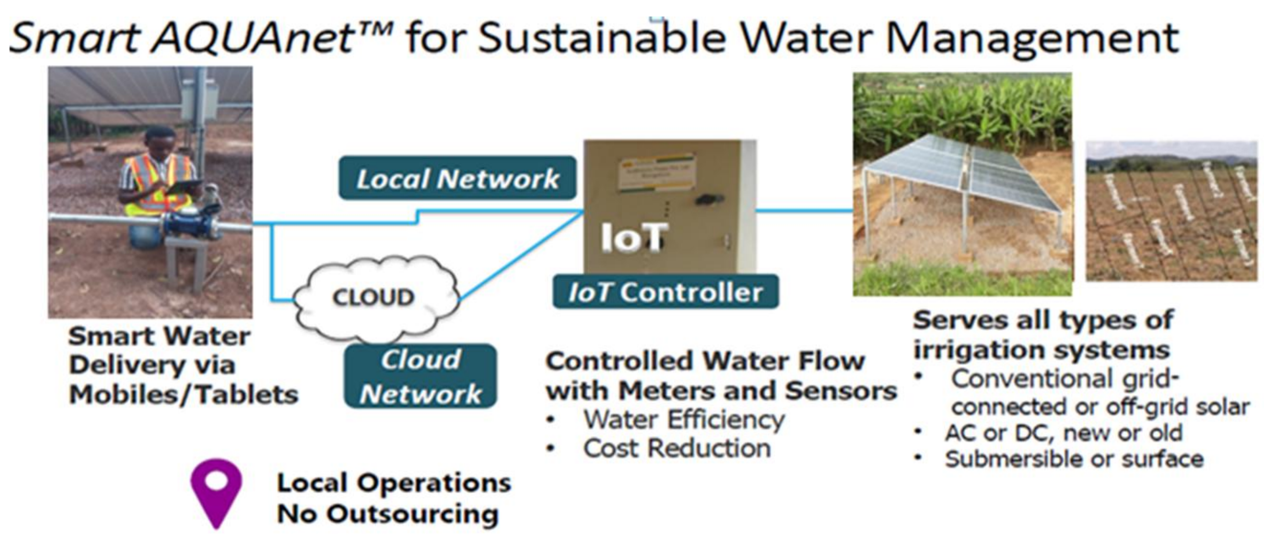
Narrative of use case
Short description
- Background: Farmers in refugee and host communities face limited access to reliable energy and water for irrigation. - Functionality: A solar-powered irrigation system is installed and used to pump and distribute water for crops. The system's performance is monitored remotely, allowing operators to detect issues early and organize maintenance. - Operation and support: Operators oversee system performance and coordinate field technicians when maintenance is required. - Outcomes: The use case demonstrates improved water availability, higher agricultural productivity, and reduced costs, supporting long-term livelihoods and food security.
User story
As a farmer in a water-scarce area, I want a solution that allows me to adjust irrigation based on weather and soil conditions. As a farmer in a water-scarce area, I want to optimize irrigation to increase my yields.
Complete description
Smart irrigation systems are an emerging technology for adjusting irrigation based on actual weather and soil condition. It is suitable for use in places where water scarcity and climate are a challenge. Solar powered irrigation systems enable to intensify crop production, improve water efficiency and reduce the associated costs. The technology developed by SOLEK; AQUAnet is used for water management, where farmers receive the quantity of water according to their request. An operator performs these tasks by software on a tablet by remote monitoring. This technology enables farmers to raise cropping yields, to increase the value to their crops and to encourage business opportunities. The solution is improved with the view to ensure quick maintenance and assistance solutions, to ensure the sustainability of the irrigation system and to improve the control of the water flow. The following analyses will be carried out: i) Integrated WEF nexus: Analysis of how efficient energy use, water management, and food preservation contribute to overall sustainability and resilience; ii) Data integration and analytics: SUNNY will explore methods for integrating data from different systems to optimize decision-making. Algorithms and models that leverage data from solar irrigation, refrigerated storage, and clean cooking systems will be developed to enhance energy efficiency and resource allocation; iii) Remote Monitoring and Control: SUNNY will study how remote monitoring and control technologies can be utilised to manage and optimize the performance of these systems. It will examine the benefits of real-time data analytics for improving irrigation scheduling, temperature control, and cooking efficiency; iv) Energy synergy and sharing: The project will investigate the potential for energy sharing and synergy among these systems. For instance, surplus solar energy from irrigation could be used for refrigeration or cooking, enhancing system efficiency and reliability; v) Technology Standards and Protocols: SUNNY will investigate the development of standardized communication protocols and interfaces that enable seamless interoperability among these systems. This can lead to easier integration and scalability. 

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Business actors: **SOLEK (System Owner), Water User Committee (WUC), Farmers / End Users, Makerere University (Research Partner), Mobile Money Providers (MTN/Airtel)** These actors shape the irrigation business model: SOLEK install and manage the system; WUC governs water distribution and fee collection; farmers are the primary users; Makerere analyzes affordability and water-energy-food nexus data; and mobile operators enable digital payments. Operator: **SOLEK Technical Team and Water User Committee** Operate and maintain pumps, sensors, and distribution networks; monitor performance; manage schedules; and ensure O&M cost recovery. Logical Actors: **PV Production Unit (Solar Panels), Storage Unit (Water Tank/Reservoir), IoT Monitoring & Payments Device, Distribution Network (Pipes, Hoses, Valves)** Logical actors form the system infrastructure: solar PV powers the pump; water is stored in tanks; IoT devices measure and report flow and payments; and the distribution network delivers water to the fields.

1.5 Key performance indicators
1.5.1 Project KPIs

Project KPIs			
ID	***Name***	***Description***	***Reference to mentioned use case objectives***
KPI-01	System Deployment & Operational Reliability	Successful installation and commissioning of the solar-powered irrigation system, achieving ≥90% operational uptime during irrigation season.	OBJ-T1, OBJ-T2
KPI-02	Smart Monitoring & Metered Water Delivery	Implementation of IoT-based monitoring ensuring real-time water flow measurement, credit validation, and accurate telemetry reporting.	OBJ-T3
KPI-03	Agricultural Productivity Improvement	Percentage increase in crop yield of participating farmers compared to baseline season.	OBJ-S1
KPI-04	Affordable & Transparent Payment Compliance	Share of registered farmers actively using the system and maintaining timely mobile-money payments under the agreed tariff structure.	OBJ-S2, OBJ-S3
KPI-05	Environmental & Resource Sustainability Impact	Reduction of diesel-based irrigation and improved water-use efficiency through solar-	OBJ-E1, OBJ-E2

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		powered and scheduled irrigation.	

1.5.2 Ecological KPIs from REFUSE's Ecodesign Toolkit

Ecological KPIs			
ID	**Name**	**Weight**	**Scoring**
Theme 1: Nature-Based Design, Environmental Footprint			*75%*
1.1	Local material sourcing	7%	0.07
1.2	Use of natural/low-impact materials	29%	0.57
1.3	Toxicity potential	0%	0.00
1.4	Local water risk sensitivity	0%	0.00
1.5	Nature-based or low-tech integration	0%	0.00
1.6	Climate change mitigation potential	29%	1.14
1.7	Climate change adaptation support	29%	1.14
1.8	Footprint of material sourcing	7%	0.07
1.9	Circularity of material sourcing	0%	0.00
Theme 2: Durability and Repairability			*82%*
2.1	Design lifetime	12%	0.48
2.2	Ease of disassembly	29%	1.14
2.3	Tools required for maintenance and repair	7%	0.14
2.4	Spare parts availability	29%	0.86
2.5	Spare parts cost	29%	0.00
2.6	Repair documentation	29%	1.14
2.7	Modularity	0%	0.00
2.8	Remote support	29%	1.14
2.9	Upgradeability	29%	1.14
2.10	Resilience to environmental conditions	29%	1.14
Theme 3: Recyclability & End of Life Management			*76%*
3.1	Recyclability	10%	0.29
3.2	Reusability, second life potential	14%	0.29
3.3	Hazardous materials share	14%	0.57
3.4	Ease of material separation	0%	0.00

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3.5	Local disposal/recycling chain	5%	0.00
3.6	Takeback schemes at End of Life (EOL)	19%	0.38
3.7	Materials, components identification	19%	0.76
3.8	EOL documentation	19%	0.76
Theme 4: Service Orientation			*68%*
4.1	Service model	12%	0.23
4.2	Maintenance contract	15%	0.46
4.3	Buy-back schemes	15%	0.31
4.4	Pay-per-use and leasing models	0%	0.00
4.5	Warranty duration	12%	0.35
4.6	Components replacement services	15%	0.46
4.7	Remote monitoring	15%	0.46
4.8	Service impact on lifetime	15%	0.46

1.6 Use case conditions

1.6.1 Technical use case conditions

Technical use case conditions
Assumptions
• Water source availability (existing boreholes, wells and rivers) in Bidibidi provides consistent flow for irrigation throughout the cropping season. • Shared land is available and agreed upon for demonstration without ownership disputes. • Local mobile coverage is sufficient for IoT data transfer from pumps and sensors to LUT's dashboard. • Electricity-free, solar-only pumping is socially and economically accepted by target farmers and the Water User Committee. • Agricultural extension officers and NGOs (e.g., FAO, GIZ) are active in the area and can provide complementary farmer training support. • Makerere University's Food–Water–Energy Nexus study will produce affordability and seasonal water-demand data on time to inform design and tariff structure. • Weather patterns and rainfall variability remain within normal range during the pilot period.
Prerequisites
• Site selection and verification by SOLEK, GLE, and UMAK confirming adequate water flow and land conditions. • Formal authorization from the Office of the Prime Minister (OPM) and local district authorities for system installation. • Completion of hydrological and environmental assessments to ensure sustainability of water extraction. • Procurement and import clearance for solar pumps, storage tanks, pipes, and fittings. • System design validation between SOLEK, GLE, and LUT, ensuring IoT hardware compatibility and data synchronization. • Formation of a Water User Committee (WUC) with defined operation and maintenance responsibilities. • Training of technicians and farmers on safe operation, irrigation scheduling, and data monitoring.

1.6.2 Environmental use case conditions

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Environmental use case conditions
Assumptions
-
Prerequisites
-

1.6.3 Socio-economic use case conditions

Socio-economic use case conditions
Assumptions
Farmers have access to mobile phones and can use mobile-money services for payments. Agricultural extension officers and NGOs (FAO, GIZ) continue supporting farmer training and crop planning. Communities are willing to collaborate through a Water User Committee (WUC) for joint operation and maintenance. Irrigation services are linked to high-value or dry-season crops that improve returns and justify fees. Local acceptance of fee-for-service or seasonal-prepayment models as equitable and transparent. Makerere's socio-economic data will guide realistic tariff setting and demand estimates.
Prerequisites
• Baseline affordability and WEF Nexus assessment (Makerere University, 2025) completed to define payment capacity and adequate water access. • Formation and training of a Water User Committee with gender-balanced representation. • Partnership with local agricultural officers for crop scheduling and extension services. • Integration of billing system with mobile-money APIs for secure, automated transactions. • Community sensitization to explain rules, cost-sharing, and grievance mechanisms. • Local technician training on pump operation, IoT monitoring, and first-level maintenance.

1.6.4 Business use case conditions

Business use case conditions
Assumptions
- Water-user groups or cooperatives will be willing to pay service fees or seasonal flat rates for irrigation access. - Crop yields from irrigated plots will be high enough to generate surplus income for cost recovery. - Local financial institutions and NGOs (e.g., FAO, GIZ) continue providing agricultural-finance or grant support for smallholders. - National policies by the Ministry of Agriculture and OPM remain favorable to renewable-energy irrigation pilots in refugee and host communities. - Tariff structures based on "fee-per-liter" or "seasonal package" will be acceptable to users and manageable via mobile-payment channels. - The community will adhere to collective ownership and governance, avoiding disputes over usage time or revenue distribution. - Spare parts and technical expertise remain locally available through SOLEK and trained technicians.
Prerequisites
- Validation of hydrological and economic feasibility study confirming adequate water flow and cost-recovery potential. - Definition of tariff model (fee-based or seasonal prepayment) based on Makerere's Food–Water–Energy Nexus survey findings. - Establishment of digital payment and metering system to record water use and automate billing. - Procurement of insurance or service guarantee mechanism to protect community assets and cover maintenance risks. - Identification of anchor buyers or off-takers (e.g., schools, small agribusinesses) to stabilize demand during off-peak periods. - Confirmation of import tax exemptions or agricultural-equipment incentives from Ugandan authorities to reduce CAPEX.

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1.7 Further information to the use case for classification/mapping

Classification information
Relation to the other use cases
Level of depth
Generic
Prioritization
Obligatory
Generic, regional or national relation
Regional
Nature of the use case
Technical, socio-economic, and business UC
Further keywords for classification

1.7 General remarks

General remarks

2 Diagrams of use case

Diagram(s) of use case

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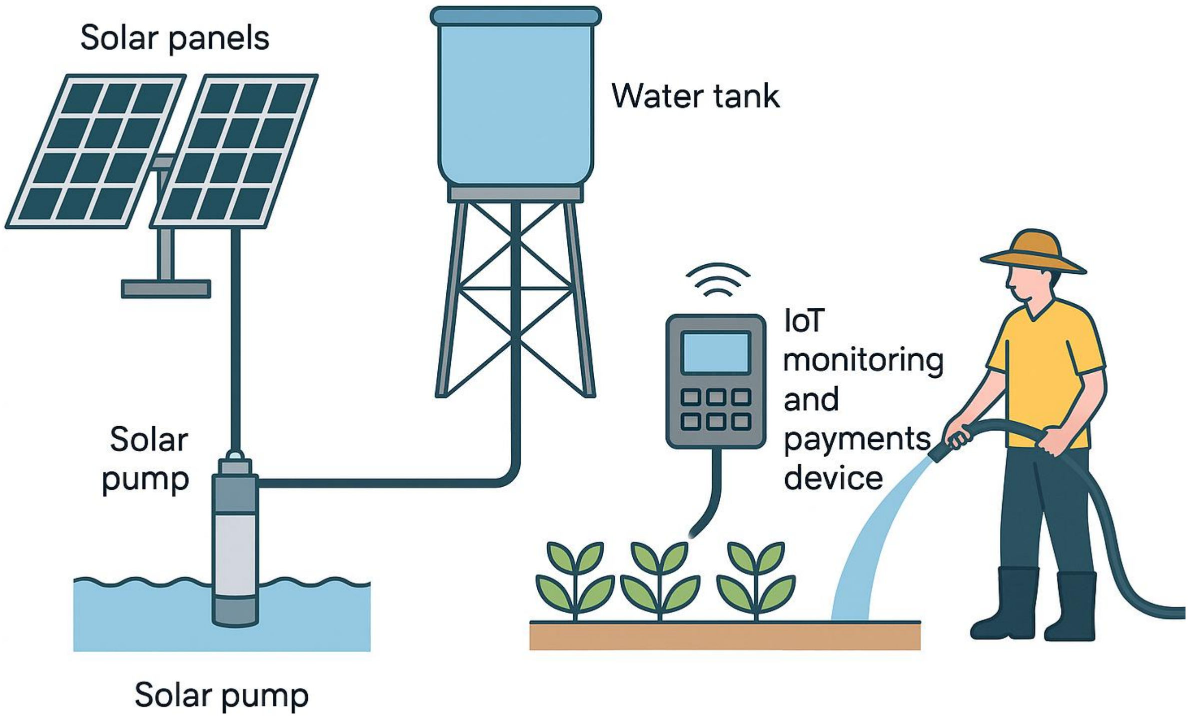

3 Technical details

3.1 Actors

Actors			
Grouping		Group Description	
Business Actor		Physical or legal entities engaged in managing, financing, or benefiting from the irrigation system.	
Operator		Entity responsible for technical and operational management of the irrigation system.	
Logical Actor		Technical components or subsystems responsible for the generation, storage, monitoring, and delivery of irrigation water.	
Actor name	Actor type	Actor description	Further information specific to this use case
Business Actor			
SOLEK (System Owner / Operator)	Business Actor	Designs, installs, owns, and operates the smart solar irrigation system in Bidibidi Refugee Settlement.	Oversees project execution, system performance, maintenance, and long-term sustainability.
Farmer / End User	Business Actor	Uses irrigation services for agricultural production and pays according to defined tariff model.	Main beneficiary; receives training on irrigation scheduling, system use, and payment processes.

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Water User Committee (WUC)	Business Actor	Community-based governance body representing farmers and managing shared access to irrigation services.	Defines irrigation schedules, resolves conflicts, supports fee collection, and ensures equitable water use.
Makerere University (Research Partner)	Business Actor	Conducts socio-economic, affordability, and impact research under the Food–Water–Energy Nexus.	Uses system and user data to refine pricing models and assess socio-economic outcomes.
Mobile Money Service (MTN / Airtel)	Business Actor	Processes digital payments for irrigation services via mobile money.	Integrated with SOLEK billing interface for automated payment confirmation and receipts.
Operator			
SOLEK Operations Team	Operator	Responsible for daily operation, monitoring, billing oversight, and coordination of maintenance activities.	Ensures operational continuity, tariff enforcement, reporting, and farmer support.
Local Technician (SOLEK Field Technician)	Operator	Installs, tests, maintains, and repairs solar pumping and water distribution infrastructure.	Based locally; provides hands-on troubleshooting and capacity building for users.
SOLEK IoT System Administrator	Operator	Manages the SOLEK IoT dashboard and device connectivity.	Monitors telemetry flow, flags anomalies, and supports KPI reporting for SUNNY.
PV Production Unit (Solar Array)	Logical Actor	Generates DC electricity required to power the irrigation pump.	Sized according to water demand and optimized for high solar irradiance conditions.
Pump and Controller Unit	Logical Actor	Converts electrical energy into hydraulic energy to lift water from the source.	Includes smart controls enabling variable flow based on solar availability.
Storage Unit (Water Tank / Reservoir)	Logical Actor	Stores pumped water before distribution to end users.	Acts as a buffer enabling irrigation during low-sun or peak-demand periods.
Distribution Network (Pipes, Valves, Hoses)	Logical Actor	Transports water from the storage tank to farmers' plots.	Operated under WUC-defined schedules and access rules.

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IoT Monitoring and Payments Device	Logical Actor	Measures water flow, tracks consumption, and validates payment status.	Installed between tank and outlets; communicates with SOLEK IoT Platform.
Flow and Pressure Sensors	Logical Actor	Measure water flow rate and detect pressure anomalies or leakages.	Data transmitted via IoT device for performance monitoring and maintenance alerts.
SOLEK IoT Platform (Monitoring Dashboard)	Logical Actor	Centralized digital platform receiving data from IoT devices and sensors.	Enables analytics, reporting, system optimization, and consortium-wide monitoring.

3.2 References

References						
No.	***Reference type***	***Reference***	***Status***	***Impact on use case***	***Originator/organization***	***Link***
1	Technical / Research Study	*Assessment of the Water-Energy-Food (WEF) Nexus in Bidibidi Refugee Settlement towards Sustainable Energy Technologies* (Prof. Michael Lubwama et al., Makerere University, Oct 2025)	Ongoing	Highlights that >94 % of water access comes from boreholes and solar tap systems; notes scarcity of surface water and limited communal land for irrigation. Recommends context-specific design and smaller demonstration units.	Makerere University (College of Engineering, Design, Art and Technology)	SUNNY Project WEF Report 2025 – Internal consortium reference
2	Environmental/ Regulatory Framework	Uganda Water Policy (1999, rev. 2021)	Active	Defines priority use of groundwater and requires environmental assessment for	Ministry of Water and Environment (MWE)	https://mwe.go.ug/

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				abstraction permits; affects design and scale of irrigation interventions.		
3	Humanitarian Land-Use Planning	*Bidibidi Refugee Settlement Master Plan* (UNHCR & Office of the Prime Minister, 2020)	Active	Identifies that settlement layout provides limited communal agricultural land and is mainly residential, requiring plot-level solutions.	UNHCR / OPM (Uganda)	https://data.unhcr.org/en/documents/details/81237
4	Environmental Safeguard Guidelines	NEMA Guidelines for Water Resource Use (2020)	Active	Requires hydro-geological surveys and permits prior to groundwater use for irrigation; informs site selection and scale.	National Environment Management Authority (NEMA)	https://nema.go.ug/
5	Technical Reference	*Solar-Powered Irrigation Systems in East Africa: Opportunities and Challenges* (FAO, 2021)	Published	Highlights that viability depends on reliable water sources and community ownership; recommends small-scale solar pumping with storage.	FAO Regional Office for Africa	https://www.fao.org/
6	Sector Policy	Uganda National Irrigation Policy (2018)	Active	Encourages private-sector participation but prioritizes surface-water catchment systems over groundwater; relevant for scaling.	Ministry of Agriculture, Animal Industry and Fisheries (MAAIF)	https://www.agriculture.go.ug/
7	Consortium Coordination	*SUNNY Work Package 5 – GLE & SOLEK Technical Inputs* (2024–2025)	Internal	Defines roles and deliverables for demonstration design and IoT	GLE / SOLEK Consortium	Internal project repository

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				integration; will be updated after Makerere validation.		

4 Step by step analysis of use case

4.1 Overview of scenario

Scenario conditions						
No.	**Scenario name**	**Scenario description**	**Primary actor**	**Triggering event**	**Pre-condition**	**Post-condition**
1	User Enrollment & WUC Formation	Register farmers, constitute Water User Committee (WUC), define roles.	WUC	Community mobilization completed	Authorities approve; beneficiary list validated	WUC charter adopted; users onboarded
2	Tariff definition (fee/seasonal)	Set fee-per-liter or seasonal prepayment based on WEF/affordability study.	WUC	Makerere findings shared	Hydrological and socioeconomic inputs available	Tariff schedule ratified; communicated to users
3	Payment and Irrigation Operation	User pays via mobile money; credit posted; time slot/valve allocation recorded.	Farmer / End User	Payment confirmation received	Billing gateway online; user registered	Credit active; slot assigned; receipt issued
4	Pumping, Storage & Metered Delivery	PV powers pump; water stored in tank; IoT device meters flow to users.	IoT Monitoring & Payments Device	Slot start time reached	Adequate water source; system commissioned	Water delivered; volume logged; balance updated
5	Monitoring, alerts & O&M	Warning alert to SOLEK's IoT Dashboard. abnormal pressure/flow generates alerts; technician dispatched.	SOLEK Technician	Threshold breach or device alert	Connectivity active; spares available	Issue resolved; service continuity maintained

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6	Periodic review & adjustment	Evaluate yields, payments, and service quality; adjust tariff/schedule if needed.	WUC	Monthly/seasonal review meeting	Complete datasets and stakeholder feedback	Updated rules/tariffs published; users informed

4.2 Steps – Scenarios

Scenario								
Scenario name	**User Enrollment & WUC Formation**							
Step No.	***Event***	***Name of process/activity***	***Description of process/activity***	***Service***	***Information producer (actor)***	***Information receiver (actor)***	***Information exchanged (IDs)***	***Requirements, R-IDs***
1	Mobilization meeting	Farmer registration	Farmers and community leaders identify participants for irrigation pilot.	Community engagement	WUC / SOLEK Team	Water User Committee (WUC)	User registry (Inf01)	R-01: Local authority approval
2	Committee formed	WUC constitution	Select representatives and define governance rules.	Institution setup	WUC	SOLEK Operations Team	WUC charter (Inf02)	R-02: Gender balance required
3	Baseline data	Water and land assessment	Collect hydrological and land use data with Makerere University.	Survey service	Makerere University	SOLEK Operations Team	Hydro-data (Inf03)	R-03: Baseline survey completed
Scenario 2	***Tariff definition (fee/seasonal)***							
Step No.	***Event***	***Name of process/activity***	***Description***	***Service***	***Information producer***	***Information receiver***	***Information exchanged***	***Requirements***
1	Research completed	Affordability analysis	Makerere University shares WEF nexus and affordability findings.	Research reporting	Makerere University	Water User Committee (WUC)	Study report (Inf04)	R-04: Validated survey data
2	Data review meeting	Stakeholder consultation	WUC and SOLEK review hydrological and socio-economic inputs.	Governance consultation	Water User Committee (WUC)	SOLEK Operations Team	Draft tariff proposal (Inf05)	R-05: Water availability confirmed
3	Tariff drafting	Fee structure definition	Define fee-per-liter or seasonal prepayment structure.	Tariff configuration	SOLEK Operations Team	Water User Committee (WUC)	Tariff schedule draft (Inf06)	R-06: Cost-recovery model validated
4	Ratification vote	Tariff approval	WUC ratifies and formally adopts tariff structure.	Governance approval	Water User Committee (WUC)	Farmer / End User	Final tariff schedule (Inf07)	R-07: Majority approval required
5	Public communication	User notification	Tariff communicated to all registered users.	Communication service	Water User Committee (WUC)	Farmer / End User	Tariff notice (Inf08)	R-08: Public notice issued
Scenario name	***Payment and Irrigation Operation***							

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Step No.	Event	Name of process/activity	Description of process/activity	Service	Information producer (actor)	Information receiver (actor)	Information exchanged (IDs)	Requirements, R-IDs
1	Payment made	Mobile money top-up	User prepays irrigation credit via mobile money.	Payment processing	Farmer / End User	Mobile Money Service (MTN/Airtel)	Payment request (Inf09)	R-09: Network coverage
2	Payment confirmation	Billing update	Payment confirmation transmitted to SOLEK billing system.	Billing service	Mobile Money Service (MTN/Airtel)	SOLEK Operations Team	Payment confirmation (Inf10)	R-10: Secure API connection
3	Credit activation	Credit validation	Credit validated and synced with IoT Monitoring and Payments Device.	Billing synchronization	SOLEK Operations Team	IoT Monitoring and Payments Device	Credit record (Inf11)	R-11: Valid user account
4	System start	Pump activation	IoT device authorizes Pump and Controller Unit to operate.	Irrigation service	IoT Monitoring and Payments Device	Pump and Controller Unit	Activation signal (Inf12)	R-12: Sufficient solar input
5	Water delivery	Metered distribution	Water delivered through Distribution Network and volume measured.	Water delivery	IoT Monitoring and Payments Device	SOLEK IoT Platform (Monitoring Dashboard)	Volume record (Inf13)	R-13: Pressure within limits
Scenario 4	**Pumping, Storage & Metered Delivery**							
Step No.	**Event**	**Name of process/activity**	**Description**	**Service**	**Information producer**	**Information receiver**	**Information exchanged**	**Requirements**
1	Solar irradiation available	Power generation	PV Production Unit (Solar Array) generates electricity.	Energy generation	PV Production Unit (Solar Array)	Pump and Controller Unit	Power supply signal (Inf14)	R-14: Adequate solar input
2	Pump start command	Water abstraction	Pump and Controller Unit lifts water from source.	Pumping service	Pump and Controller Unit	Storage Unit (Water Tank / Reservoir)	Water inflow record (Inf15)	R-15: Water source level adequate
3	Tank filling	Water storage	Storage unit accumulates water for scheduled irrigation.	Storage service	Storage Unit (Water Tank / Reservoir)	IoT Monitoring and Payments Device	Storage level data (Inf16)	R-16: Tank capacity sufficient
4	Irrigation slot active	Metered release	IoT device authorizes water release to distribution network.	Metering & validation	IoT Monitoring and Payments Device	Distribution Network (Pipes, Valves, Hoses)	Flow authorization (Inf17)	R-17: User credit active
5	Water distribution	Controlled irrigation	Water delivered to farmer plots under WUC schedule.	Irrigation delivery	Distribution Network (Pipes, Valves, Hoses)	Farmer / End User	Volume record (Inf18)	R-18: Pressure within limits
6	Data upload	Telemetry transmission	Usage data sent to SOLEK IoT Platform.	Monitoring service	IoT Monitoring and Payments Device	SOLEK IoT Platform (Monitoring Dashboard)	Telemetry data (Inf19)	R-19: Connectivity stable
Scenario name	**Monitoring, alerts & O&M**							
Step No.	**Event**	**Name of process/activity**	**Description of process/activity**	**Service**	**Information producer (actor)**	**Information receiver (actor)**	**Information exchanged (IDs)**	**Requirements, R-IDs**

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1	Threshold breach	Alert generation	Abnormal flow or pressure detected by sensors.	Monitoring service	Flow and Pressure Sensors	IoT Monitoring and Payments Device	Alert signal (Inf20)	R-20: Real-time monitoring active
2	Alert escalation	Dashboard notification	Alert transmitted to SOLEK IoT Platform.	Monitoring service	IoT Monitoring and Payments Device	SOLEK IoT Platform (Monitoring Dashboard)	Alert ID (Inf21)	R-21: Continuous connectivity
3	Ticket creation	O&M workflow	SOLEK Operations Team assigns Local Technician.	Maintenance coordination	SOLEK IoT Platform (Monitoring Dashboard)	SOLEK Operations Team	Ticket ID (Inf22)	R-22: Response ≤ 48h
4	Site visit	Inspection & repair	Technician inspects pump, valves, or sensors; repairs or replaces parts.	Field maintenance	Local Technician (SOLEK Field Technician)	SOLEK Operations Team	Repair log (Inf23)	R-23: Spare parts certified
5	Closure	Verification & reporting	System tested and status updated on dashboard.	Verification service	Local Technician	SOLEK IoT Platform (Monitoring Dashboard)	Closure report (Inf24)	R-24: Dashboard updated
Scenario 6		***Periodic Review & Adjustment***						
Step No.	***Event***	***Name of process/activity***	***Description of process/activity***	***Service***	***Information producer (actor)***	***Information receiver (actor)***	***Information exchanged (IDs)***	***Requirements, R-IDs***
1	Data aggregation	Performance analysis	SOLEK IoT Platform compiles system performance data.	Analytics service	SOLEK IoT Platform (Monitoring Dashboard)	SOLEK Operations Team	KPI report (Inf25)	R-25: Complete dataset available
2	Financial review	Revenue analysis	Payment and cost data evaluated.	Financial analysis	SOLEK Operations Team	Water User Committee (WUC)	Revenue summary (Inf26)	R-26: Billing reconciliation complete
3	Agricultural review	Yield assessment	Farmers share crop yield feedback.	Stakeholder feedback	Farmer / End User	Water User Committee (WUC)	Yield feedback (Inf27)	R-27: Seasonal cycle completed
4	Adjustment proposal	Rule modification	WUC proposes tariff or schedule adjustments if needed.	Governance update	Water User Committee (WUC)	SOLEK Operations Team	Adjustment proposal (Inf28)	R-28: Consensus reached
5	Decision adoption	Updated publication	Updated tariff or schedule formally adopted and communicated.	Policy communication	Water User Committee (WUC)	Farmer / End User	Updated rules notice (Inf29)	R-29: Public communication issued

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5 Information exchanged

Information exchanged			
Information exchange, ID	***Name of information***	***Description of information exchanged***	***Requirement, R-IDs***
Inf01	User registry		R-01
Inf02	WUC charter		R-02
Inf03	Hydro-data		R-03

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Inf04	Payment confirmation		R-04
Inf05	Credit record		R-05
Inf06			R-06
Inf107			R-07
Inf08			R-08
Inf09			R-09
Inf10			R-10
Inf11			R-11
Inf12			R-12

6 Requirements

Requirements		
Categories ID	***Category name for requirements***	***Category description***
Requirement R-ID	***Requirement name***	***Requirement description***
R-01	Local authority approval	
R-02	Gender balance required	
R-03	Baseline survey completed	
R-04	Network coverage	
R-05	Secure API connection	
R-06	Sufficient solar input	
R-07	Pressure within limits	
R-08	Data upload hourly	
R-09	Real-time alert	
R-10	Response ≤ 48 h	
R-11	Spare parts certified	
R-12	Dashboard update	

7 Common terms and definitions

Common terms and definitions	
Term	***Definition***
Smart Solar Irrigation System (SSIS)	A solar-powered water-pumping and distribution system equipped with IoT sensors and payment technology for efficient irrigation management.
WUC (Water User Committee)	A community-based group responsible for managing irrigation schedules, tariffs, and maintenance activities.

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WEF Nexus (Food–Water–Energy Nexus)	An integrated approach that recognizes the interdependence of water, energy, and food systems for sustainable resource management.
IoT Monitoring and Payments Device	A smart unit that measures water flow, validates payments, and transmits real-time data to SOLEK's IoT monitoring platform.
PV Production Unit	The solar array that converts sunlight into electrical energy to power the irrigation pump.
Water Storage Tank	A reservoir that stores pumped water for later use, ensuring availability during cloudy periods or at night.
Distribution Network	The system of pipes, hoses, and valves that delivers irrigation water from the storage tank to the farmers' plots.
Flow Sensor	A device that measures the rate of water movement through the irrigation line for accurate billing and efficiency monitoring.
Makerere University (Research Partner)	The academic partner conducts socio-economic and hydrological studies to inform affordability and system design.
GLE (Great Lakes Energy)	The technical partner leading field implementation and O&M of the solar irrigation system in Uganda.
Seasonal Prepayment Model	A tariff structure where farmers pay in advance for irrigation services for an entire cropping season.
Hydro-Geological Assessment	A study evaluating groundwater availability and recharge potential, required before installation of solar-pumping systems.

8 Custom information (optional)

Custom information (optional)		
Key	***Value***	***Refers to section***

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6. UGANDA: REFRIGERATED FOOD STORAGE

1. Description of the use case

1.1 Name of the use-case

Use case identification		
ID	Area/Domain/Zone(s)	Name of the use case
UC5	Area: Energy Systems Domains: Customers Zones: Process, Field	Uganda: Refrigerated food storage unit with improved remote operation through IoT

1.2 Version management

Version management				
Version No.	Date	Name of author(s)	Changes	Approval status
0.1	11/11/2025	Nora Stognief - TUB	Draft	

1.3 Scope and objective of use case

Scope and objectives of the use case	
Scope	This use case is limited to the study of refrigerated food storage in refugee communities in Uganda.
Technical Objective(s)	- Enable food storage - Continuous operation of the RFS despite intermittent power generation - Enable remote monitoring - Increase energy efficiency
Socio-Economic Objective(s)	- Improve food security - Reduce health hazards by improving food quality - Increase farmers' income - Training and job creation for local technicians
Ecological Objective(s)	- Reduce food waste - Reduce GHG emissions
Business Objective(s)	- Reduce post-harvest losses for farmers - Avoid high up-front investment costs for farmers
Related business case(s)	- Improved food security

1.4 Narrative of use case

Narrative of use case
Short description
One of the main problems with food in Africa is its conservation, particularly at farmer level. AKO's refrigerated food storage solution leverages innovative technology to extend the shelf life of perishable crops in remote farming communities, combating post-harvest losses and food waste. The system utilizes solar power for energy independence, reducing carbon emissions, and promoting sustainability. Solar panels serve as roofing, generating electricity to power the inverter technology and refrigeration system. Additionally, a 8-12 hours power backup system ensures continuous operation. The solution will also be IoT enabled, giving access to remote monitoring. By creating

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decentralised community storage units using the pay-as-you-store model, farmers do not need to pay the cost of the entire unit upfront and do not need expertise related to maintenance of the unit. Furthermore, by making the unit solar powered it makes the solution net positive to the environment and a constant source of energy while bridging the energy poverty gap. Refrigerated food storage not only reduces food waste but also preserves food quality, thereby limiting the health problems that can be associated with it.
User story
As a farmer in the Bidibidi settlement, I want a reliable and continuous food storage solution to reduce post-harvest losses. As a farmer in the Bidibidi settlement, I want to a pay-as-you-store model so I do not have to invest a high amount of money upfront. As a farmer in the Bidibidi settlement, I want a food storage solution maintained by trained local technicians to reduce downtimes. ...
Complete description
One of the main problems with food in Africa is its conservation, particularly at farmer level. AKO's refrigerated food storage solution leverages innovative technology to extend the shelf life of perishable crops in remote farming communities, combating post-harvest losses and food waste. The system utilizes solar power for energy independence, reducing carbon emissions, and promoting sustainability. Solar panels serve as roofing, generating electricity to power the inverter technology and refrigeration system. Additionally, a 28-hour power backup system ensures continuous operation. The solution will also be IoT enabled, giving access to remote monitoring. By creating decentralised community storage units using the pay-as-you-store model, farmers do not need to pay the cost of the entire unit upfront and do not need expertise related to maintenance of the unit. Furthermore, by making the unit solar powered it makes the solution net positive to the environment and a constant source of energy while bridging the energy poverty gap. Refrigerated food storage not only reduces food waste but also preserves food quality, thereby limiting the health problems that can be associated with it. Existing solar-powered refrigerated food storage systems have several limitations that are addressed by AKO's solution: Intermittent Power Generation: Solar energy generation is dependent on sunlight, which is not constant, impacting the consistent operation of the refrigeration system. The solution developed by AKO will make it possible to have a 8-12-hour power backup system ensuring continuous operation. ~~compared with an average of 12h to 24h for mid to large-sized systems.~~ High Initial Investment: While there may be long-term savings from reduced energy costs, the initial investment can be a barrier, especially in resource-constrained areas. In SUNNY, by creating a decentralised community storage unit using the pay-as-you-store model, farmers do not need to pay the cost of the entire unit upfront. Operation, Maintenance and Expertise: Solar-powered systems, including refrigeration, require regular maintenance and technical expertise on both solar technology and refrigeration systems. The solution developed by AKO will be IoT enabled, giving access to remote monitoring, including temperature control. Local workforce will be trained in the maintenance of the technology to take greater account of the local value chain. Energy Efficiency: While solar panels generate clean energy, the overall energy efficiency of the system (including conversion and cooling processes) can impact its effectiveness in maintaining desired temperature levels. The power capacity of the RFS will be reduced from 8kw to 5kW, to match with the cooling requirements of the storage space to ensure energy-efficient operation. AKO will focus on testing the effectiveness of its cold storage technology in the context of the water-energy-food nexus, addressing both community and business needs for energy while promoting economic growth in the agricultural sector. The testing plan includes evaluating energy efficiency, performance, reliability, user-friendliness, remote monitoring capabilities, compatibility with various energy sources and data analytics. The goal is to ensure that the technology operates optimally, maintains desired temperature levels for perishable goods, and supports economic development. Stakeholder feedback and data analysis will contribute to refining the technology's performance and impact within the local context.

1.5 Key performance indicators

1.5.1 Project KPIs

Project KPIs			
ID	***Name***	***Description***	***Reference to mentioned use case objectives***
1	CAPEX reduction compared to existing alternative	Target: 15%	Avoid high up-front investment costs for farmers. Enable access to cold storage through shared, service-based infrastructure.
2	OPEX reduction compared to existing alternative	Target: >25%	Reduce operating costs through solar-powered operation and centralized maintenance.

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			Improve affordability of refrigerated storage services.
3	Percentage increase in lifetime of products used in the demonstrator locations	Target: >10%	Increase system reliability and durability through professional operation, preventive maintenance, and remote monitoring.
4	Energy efficiency enhancement for the refrigerated food storage (RFS) solution	Target: 20%	Increase energy efficiency of the refrigeration system. Ensure continuous and reliable cold storage operation in off-grid contexts.
5	GHG emissions mitigated with SUNNY solutions	Target: 0.5 tCO2eq/year *150 users	Reduce greenhouse gas emissions by replacing diesel-based or inefficient cooling solutions with solar-powered refrigeration.
6	Number of people benefiting to an enhanced access to energy	Target: 150	Improve access to reliable energy services for agricultural value chains. Support farmer livelihoods and food security.
7	Reduction (%) of food waste thanks to RFS	Target: 25-30%	Reduce post-harvest losses. Improve food security and income stability for farmers.

1.5.2 Ecological KPIs from REFUSE's Ecodesign Toolkit

Ecological KPIs			
ID	***Name***	***Weight***	***Scoring***
Theme 1: Nature-Based Design, Environmental Footprint			*60%*
1.1	Local material sourcing	16%	0.32
1.2	Use of natural/low-impact materials	12%	0.24
1.3	Toxicity potential	16%	0.32
1.4	Local water risk sensitivity	8%	0.32
1.5	Nature-based or low-tech integration	4%	0.08
1.6	Climate change mitigation potential	16%	0.48
1.7	Climate change adaptation support	12%	0.36
1.8	Footprint of material sourcing	12%	0.24
1.9	Circularity of material sourcing	4%	0.04
Theme 2: Durability and Repairability			*75%*
2.1	Design lifetime	10%	0.31
2.2	Ease of disassembly	12%	0.36
2.3	Tools required for maintenance and repair	12%	0.36
2.4	Spare parts availability	12%	0.24
2.5	Spare parts cost	12%	0.36
2.6	Repair documentation	12%	0.36

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2.7	Modularity	12%	0.36
2.8	Remote support	12%	0.48
2.9	Upgradeability	8%	0.24
2.10	Resilience to environmental conditions	12%	0.36
Theme 3: Recyclability & End of Life Management			*64%*
3.1	Recyclability	12%	0.35
3.2	Reusability, second life potential	15%	0.46
3.3	Hazardous materials share	12%	0.23
3.4	Ease of material separation	15%	0.46
3.5	Local disposal/recycling chain	8%	0.00
3.6	Takeback schemes at End of Life (EOL)	8%	0.00
3.7	Materials, components identification	15%	0.46
3.8	EOL documentation	15%	0.62
Theme 4: Service Orientation			*63%*
4.1	Service model	19%	0.76
4.2	Maintenance contract	10%	0.00
4.3	Buy-back schemes	5%	0.00
4.4	Pay-per-use and leasing models	19%	0.76
4.5	Warranty duration	5%	0.05
4.6	Components replacement services	10%	0.19
4.7	Remote monitoring	19%	0.76
4.8	Service impact on lifetime	14%	0.00

1.6 Use case conditions

1.6.1 Technical use case conditions

Technical use case conditions
Assumptions
- Continuous operation of the RFS is required for reliable food storage - Electricity generation from solar panels is intermittent - Lack of sufficient and qualitative data is a decisive limitation in the field of Humanitarian Energy -
Prerequisites
- Identify implementation site - Procurement and shipping

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- Implement backup system

1.6.2 Environmental use case conditions

Environmental use case conditions
Assumptions
-
Prerequisites
-

1.6.3 Socio-economic use case conditions

Socio-economic use case conditions
Assumptions
- Farmers' livelihoods suffer from post-harvest losses - Continuously operating food storage solutions improves food security - Most farmers cannot afford the initial investment for an entire RFS unit - Factors like traditional cooking methods, gender roles, and religious practices play an important role in the design of energy interventions - Assessing preferences, perceptions, and understanding influencers to decisions is crucial to design context-embedded energy delivery models that can successfully sustain in the local setting - Inadequate participation of underrepresented groups, inadequate infrastructure, and weak linkages among actors can hinder the effectiveness and inclusivity of local value chains - Improving the reliability and affordability of renewable energy solutions requires improvements in terms of local acceptance
Prerequisites
- Implement pay-as-you-store system - Gain comprehensive and in-depth knowledge of the local context, including technical infrastructures, environmental conditions, social resources, and societal habits - Approach target groups and assess their preferences and perceptions - Identify elements for building a local value chain considering both hard and soft infrastructure

1.6.4 Business use case conditions

Business use case conditions
Assumptions
- Business models must consider local, national, and international regulations, as well as the existing market analysis - Simplifying technologies reduces O&M costs - Quick problem-solving by skilled staff reduces downtime and expensive repairs - Use of IoT to partially automate maintenance will reduce operating costs
Prerequisites
- Train local technicians - Set up advisory and replication boards - Develop an adapted financial and pricing strategy - Collect empirical data to validate business assumptions

1.7 Further information to the use case for classification/mapping

Classification information
Relation to the other use cases

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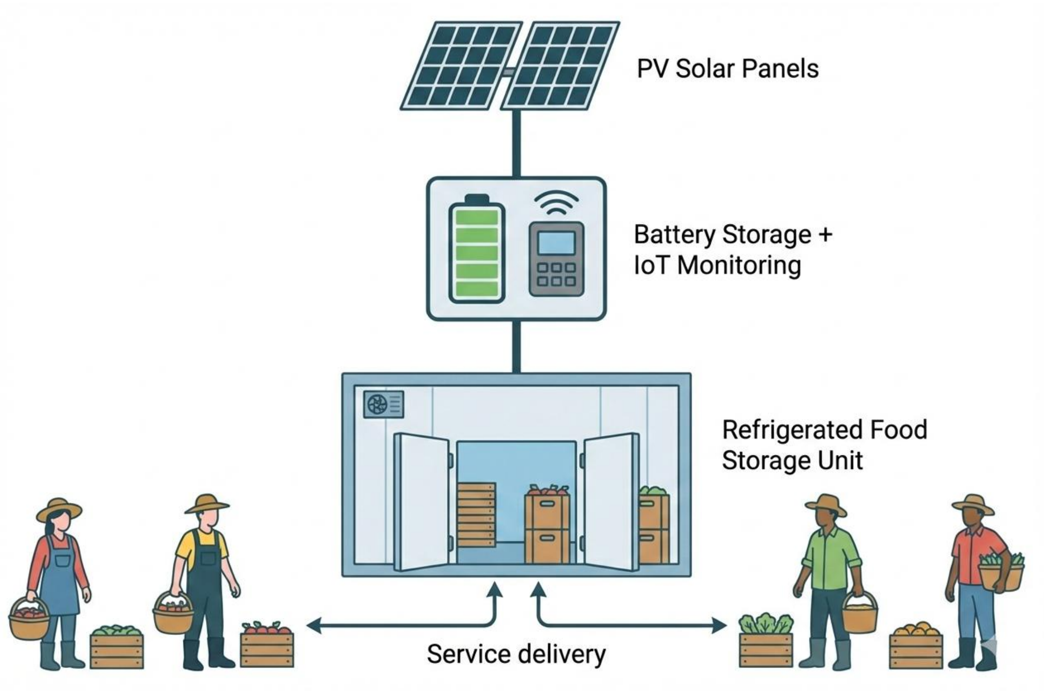
Level of depth
Generic
Prioritization
Obligatory
Generic, regional or national relation
Regional
Nature of the use case
Technical, socio-economic, and business UC
Further keywords for classification
Refrigerated food storage, Power backup system, Internet of Things, Remote monitoring, Food security

1.7 General remarks

General remarks

2 Diagrams of use case

Diagram(s) of use case


3 Technical details

3.1 Actors

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Actors			
Grouping		**Group Description**	
Business Actor		Physical or legal person that has his own interests, defined as "Business Goals"	
Operator		Business Actor that operates a system	
Logical Actor		Technical entity that takes part in the execution of a use case. A logical actor can be mapped to a physical component	
Actor name	**Actor type**	**Actor description**	**Further information specific to this use case**
Business Actor			
AKO (System Owner & Operator)	Business Actor	Actor who owns and operates the refrigerated food storage (RFS) system.	Responsible for asset ownership, system operation, user onboarding, payment validation, monitoring, and coordination of maintenance.
Farmer	Business Actor	Farmer in need of a food storage solution	Uses the cold storage service to store perishable produce and pays on a pay-as-you-store basis.
Local Technician	Business Actor	Responsible for maintenance and support	Performs installation, routine maintenance, and first-level repairs of the RFS system.
Data management operator	Business Actor		Oversees data collection, performance monitoring, and reporting through the IoT dashboard.
Mobile Money Provider	Business Actor	Digital payment service provider.	Processes mobile-money payments and provides payment confirmations to the system.
Operator			
	Operator	Actor who operates the RFS	Manages day-to-day operation, user onboarding, payment validation, and coordination of maintenance activities.
Logical Actor			
Production Unit	Logical Actor	Solar panels	Generate renewable electricity to power the RFS system.
Power backup system	Logical Actor	28-hour power backup system	Stores energy to ensure continuous operation during periods without solar generation.
IoT system	Logical Actor	IoT system for remote operation and maintenance	Monitors temperature, energy consumption, system status, and transmits data to the monitoring platform.

3.2 References

References						
No.	**Reference type**	**Reference**	**Status**	**Impact on use case**	**Originator/organization**	**Link**

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01	Technical Standard	IEC 62257 – Recommendations for small renewable energy and hybrid systems for rural electrification	Active	Provides guidance on the design and deployment of off-grid renewable energy systems, influencing system sizing, safety, and reliability requirements.	International Electrotechnical Commission (IEC)	https://www.iec.ch
02	Financial / Business Framework	Pay-as-you-go and service-based energy delivery models	Active	Influences pricing structure, payment mechanisms, and business model assumptions for the pay-as-you-store approach.	Industry practice / market standards	
03	Environmental / Sustainability Framework	EU Horizon Europe sustainability and impact reporting requirements	Active	Guides monitoring of environmental performance, food waste reduction, and greenhouse gas mitigation indicators.	European Commission	https://research-and-innovation.ec.europa.eu
04	Sector Guidance	FAO guidance on post-harvest loss reduction and cold chain development	Active	Provides best practices for reducing food losses and improving food security, informing system use and operational assumptions.	Food and Agriculture Organization of the United Nations (FAO)	https://www.fao.org

4 Step by step analysis of use case

4.1 Overview of scenarios

Scenario conditions						
No.	***Scenario name***	***Scenario description***	***Primary actor***	***Triggering event***	***Pre-condition***	***Post-condition***
1	User onboarding & registration (Success)	Farmers are registered, informed about rules of use, and enabled to access pay-as-you-store service.	AKO	Community onboarding / farmer requests service access	RFS unit is installed and operational; onboarding materials	Farmer registered; user profile created; farmer trained/briefed

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					available; basic service rules defined	
2	Produce intake, storage allocation & payment (Success)	Farmer delivers produce; storage space is allocated; pay-as-you-store payment is processed and validated; access is granted.	Farmer	Farmer arrives with produce to store	Farmer registered; storage capacity available; payment channel available	Produce stored; payment recorded; receipt/confirmation issued; storage session logged
3	Continuous monitoring & normal operation (Success)	The system monitors temperature, energy use, and equipment status; data is visible to the operator for oversight.	IoT system	Periodic telemetry update / monitoring interval	IoT system active; power available; temperature sensors working	Temperature remains within safe range; telemetry stored; no alerts triggered
4	Payment failure / invalid payment (Alternative – Failure)	Farmer attempts payment but payment is not confirmed; storage access is not granted or is paused until payment succeeds.	Mobile Money Provider	Payment attempt by farmer	Farmer registered; payment channel reachable; service rules enforce payment requirement	Payment rejected or pending; farmer notified; storage access not granted (or temporarily limited per policy)
5	Temperature excursion / quality risk (Alternative – Failure)	Temperature exceeds safe limits; alert is triggered; operator intervenes to protect produce and restore conditions.	IoT system	Temperature threshold breach	Monitoring active; threshold rules configured; operator reachable	Alert logged; mitigation action taken; temperature returned to acceptable range (or produce flagged per SOP)
6	Power deficit / extended low solar (Alternative – Failure)	Battery backup drops below minimum; refrigeration performance is degraded; system switches to protective mode and operator is alerted.	Power backup system	Low battery / low PV generation event	Solar + battery installed; energy thresholds configured	Load managed (protective mode); alert issued; operator action initiated (e.g., reduce load, prioritize cooling, schedule intervention)
7	Connectivity loss (Alternative – Failure)	IoT data transmission fails; system continues local operation; operator is alerted when connectivity resumes or via local check.	IoT system	Network loss / telemetry not received	System operational; device configured to	Data gap recorded; local operation continues; connectivity

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					operate offline	restored and backlog synced (if supported)
8	Maintenance & repair workflow (Success after failure)	A ticket is created based on alert or inspection; technician is dispatched; repair is completed and verified.	Local Technician	Alert triggers ticket / scheduled maintenance event	Spare parts available; site access granted; technician available	Fault resolved; system restored; ticket closed; repair report stored

4.2 Steps – Scenarios

Scenario								
Scenario name	User onboarding & registration							
Step No.	***Event***	***Name of process/activity***	***Description of process/activity***	***Service***	***Information producer (actor)***	***Information receiver (actor)***	***Information exchanged (IDs)***	***Requirements, R-IDs***
1	Farmer expresses interest	Community onboarding	Operator introduces the refrigerated food storage service and explains rules of use.	EXECUTE	AKO	Farmer	Inf01	R-01
2	Farmer identified	User registration	Farmer details are recorded in the system and a user profile is created.	CREATE	AKO	Data management operator	Inf01	R-01
3	Registration confirmed	User orientation	Farmer receives basic guidance on storage access, payment, and hygiene rules.	EXECUTE	Operator	Farmer	Inf02	R-02
4	Onboarding completed	Account activation	Farmer account is activated and ready for service use.	UPDATE	Data management operator	Operator	Inf02	R-02
Scenario name	Produce intake, storage allocation & payment (success)							
Step No.	***Event***	***Name of process/activity***	***Description of process/activity***	***Service***	***Information producer (actor)***	***Information receiver (actor)***	***Information exchanged (IDs)***	***Requirements, R-IDs***
1	Produce delivered	Produce intake	Farmer delivers perishable produce to the refrigerated food storage unit.	EXECUTE	Farmer	Operator	Inf03	R-03

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2	Storage requested	Storage allocation	Available storage space is allocated based on produce type and quantity.	CREATE	Operator	IoT system	Inf03	R-03
3	Payment initiated	Pay-as-you-store payment	Farmer initiates payment via mobile-money service.	GET	Farmer	Mobile Money Provider	Inf04	R-04
4	Payment validated	Payment confirmation	Payment is validated and recorded in the system.	UPDATE	Mobile Money Provider	Data management operator	Inf05	R-05
5	Access granted	Storage activation	Storage session is activated and produce is placed in cold storage.	EXECUTE	Operator	Farmer	Inf05	R-05

Scenario name	Monitoring, alerting & maintenance							
Step No.	***Event***	***Name of process/activity***	***Description of process/activity***	***Service***	***Information producer (actor)***	***Information receiver (actor)***	***Information exchanged (IDs)***	***Requirements, R-IDs***
1	System running	Continuous monitoring	IoT system monitors temperature, energy consumption, and system status.	CREATE	IoT system	Data management operator	Inf06	R-06
2	Anomaly detected	Alert generation	Temperature or energy threshold is exceeded and an alert is generated.	CREATE	IoT system	Operator	Inf07	R-07
3	Alert received	Ticket creation	Operator creates a maintenance ticket based on the alert.	CREATE	Operator	Local Technician	Inf08	R-08
4	Technician dispatched	Maintenance intervention	Technician inspects the system and performs necessary repairs or adjustments.	EXECUTE	Local Technician	IoT system	Inf09	R-09
5	Issue resolved	Ticket closure	System is restored to normal operation and ticket is closed.	UPDATE	Data management operator	Operator	Inf09	R-09

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5 Information exchanged

Information exchanged			
Information exchange, ID	***Name of information***	***Description of information exchanged***	***Requirement, R-IDs***
Inf01	User registration data	Farmer identification details required to create a user profile in the RFS system.	R-01
Inf02	Onboarding and training record	Confirmation that the farmer has received orientation on system use, payment rules, and hygiene practices.	R-02
Inf03	Storage request and allocation data	Information on produce type, quantity, and allocated storage space and duration.	R-03
Inf04	Payment request	Mobile-money payment initiated by the farmer for pay-as-you-store service.	R-04
Inf05	Payment confirmation	Confirmation that payment has been successfully processed and validated.	R-05
Inf06	Telemetry data	Operational data including temperature, energy consumption, battery status, and system health.	R-06
Inf07	System alert	Notification generated when temperature, energy, or system thresholds are exceeded.	R-07
Inf08	Maintenance ticket	Record created to initiate maintenance or repair following an alert or inspection.	R-08
Inf09	Repair and maintenance report	Documentation of maintenance actions taken and confirmation of system restoration.	R-09

6 Requirements

Requirements		
Categories ID	***Category name for requirements***	***Category description***
C-TECH	Technical requirements	Requirements related to system operation, monitoring, and performance.
C-ORG	Organisational requirements	Requirements related to user management, operations, and workflows.
C-BUS	Business requirements	Requirements related to payments, pricing, and service delivery.
Requirement R-ID	***Requirement name***	***Requirement description***
R-01	User registration required	Farmers must be registered in the system before accessing the refrigerated food storage service.

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Requirements		
Categories ID	**Category name for requirements**	**Category description**
C-TECH	Technical requirements	Requirements related to system operation, monitoring, and performance.
C-ORG	Organisational requirements	Requirements related to user management, operations, and workflows.
R-02	User onboarding and training	Farmers must receive basic orientation on storage rules, payment process, and hygiene practices.
R-03	Storage usage tracking	Storage allocation and usage must be recorded for each farmer and storage session.
R-04	Digital payment required	Payments for storage services must be made via mobile-money channels.
R-05	Payment validation	Storage access must only be granted after successful payment confirmation.
R-06	Continuous system monitoring	The system must continuously monitor temperature, energy, and operational status.
R-07	Alert generation	System anomalies must automatically trigger alerts to the operator.
R-08	Maintenance workflow	Maintenance tickets must be created and tracked following alerts or inspections.
R-09	System restoration	Maintenance actions must restore the system to normal operating conditions and be documented.

7 Common terms and definitions

Common terms and definitions	
Term	**Definition**
Refrigerated Food Storage (RFS)	A cold storage facility designed to preserve perishable agricultural produce under controlled temperature conditions.
Pay-as-you-store	A service-based pricing model where users pay only for the duration or volume of storage used.
IoT (Internet of Things)	Network of sensors and devices used to monitor and transmit system performance data remotely.
Telemetry	Automatically collected operational data such as temperature, energy consumption, and system status.

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Mobile Money	Digital payment service allowing users to make financial transactions using mobile phones.
Operator	Entity responsible for the day-to-day operation and management of the RFS system.
Local Technician	Trained individual responsible for installation, maintenance, and repair of the RFS system.
Cold chain	Temperature-controlled supply chain used to preserve perishable goods from harvest to consumption.

8 Custom information (optional)

Custom information (optional)		
Key	***Value***	***Refers to section***

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