Kenya Climate Innovation Center

DREEM HUB

CHARLES STEWART MOTT FOUNDATION

Harnessing Solar to Sustainably meet Agrifood systems Energy Demands: Review of Horticulture and Dairy Sectors in Kenya

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Knowledge for Better Livelihoods

EXECUTIVE SUMMARY

Kenya’s dairy and horticulture sectors are critical to food security, employment, and rural livelihoods, yet they continue to face persistent energy constraints that limit productivity, value addition, and market access. Unreliable grid electricity and high diesel costs contribute to significant postharvest losses, particularly in horticulture, and reduce income opportunities for smallholder farmers and agribusinesses. At the same time, Kenya’s strong solar resource base presents a viable opportunity to address these challenges in a climate-aligned manner. However, there is limited information on the energy needs for the dairy and horticulture value chains in Kenya. The study aims to examine how solar energy can be harnessed to sustainably meet the energy demands of Kenya’s dairy and horticulture value chains by identifying priority energy use points, assessing the suitability of available solar technologies, and analysing the barriers and enabling conditions for inclusive adoption at scale. The review employed a qualitative evidence synthesis approach, drawing on Kenya-specific empirical studies, value chain diagnostics, documented case studies, policy and institutional reviews, and relevant international literature.

These sources are integrated to analyse energy demand patterns, technology performance, economic impacts, and social and gender considerations across diverse agricultural contexts. The review highlights that energy demand concentrates on specific nodes within the value chains. In the dairy sector, milk cooling, aggregation, and processing are the most energy-intensive stages, while in horticulture, irrigation, pre-cooling, cold storage, and processing dominate energy use. Evidence from case studies in Kenya shows that well-designed and supported solar-powered solutions can effectively reduce spoilage, lower operating costs, enhance product quality, and boost farmer incomes. Despite this potential, adoption remains constrained by high upfront costs, limited access to tailored finance, technical capacity gaps, fragmented policies, and gender-related barriers. The study concludes that scaling solar energy in agriculture requires integrated support combining financing, technical assistance, market linkages, and coordinated policy action to deliver resilient, inclusive, and sustainable agrifood systems. These sources are integrated to analyse energy demand patterns, technology performance, economic impacts, and social and gender considerations across diverse agricultural contexts.

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ACTS	African Centre for Technology Studies
ASAL	Arid and Semi-Arid Land
CDC	Central Deposit Company
DFI	Development Finance Institution
DREEM	Distributed Renewable Energy Ecosystem Model
EPRA	Energy and Petroleum Regulatory Authority
FSD	Financial Sector Deepening
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit
IFAD	International Fund for Agricultural Development
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
KARI	Kenya Agricultural Research Institute
KCIC	Kenya Climate Innovation Center
KDA	Kenya Development Agency
KES	Kenyan Shilling
KIPPRA	Kenya Institute for Public Policy Research and Analysis
KNBS	Kenya National Bureau of Statistics
KOSAP	Kenya Off-Grid Solar Access Project
kWh	Kilowatt-hour
kWh/m^2/day	Kilowatt-hours per square meter per day
kWp	Kilowatt peak
LCOE	Levelized Cost of Energy
MCC	Milk Collection Center
MoALD	Ministry of Agriculture and Livestock Development
NDC	Nationally Determined Contribution
O&M	Operation and Maintenance
PAYG	Pay-As-You-Go
PHL	Post-Harvest Loss
PV	Photovoltaic
REREC	Rural Electrification and Renewable Energy Corporation
RESA	Renewable Energy for Smallholder Agriculture
UPS	Uninterruptible Power Supply

1.0 INTRODUCTION

1.1. Context and Rationale

Energy access represents a critical constraint on agricultural productivity, post-harvest value addition, and rural livelihoods in Kenya, especially in rural areas where electrification and reliable power remain limited (Government of Kenya [GOK], 2025). The dairy sector contributes approximately 14% of agricultural GDP, with smallholder farmers dominating production; however, quality preservation and value addition are hindered by inadequate access to electricity for cooling and processing (Food and Agriculture Organization [FAO], 2024). Kenya's horticulture sector is also a major component of the agricultural economy, contributing a substantial share of agricultural GDP (estimated at 33 %) and supporting millions of jobs, but it faces high post-harvest losses in the absence of adequate energy-dependent cold-chain infrastructure (Ministry of Agriculture and Livestock Development [MoALD], 2025; FAO, 2024). Across these value chains, energy constraints limit reliable irrigation pumping, contribute to significant post-harvest losses in perishable horticultural produce, and restrict farmers' ability to meet quality standards required for structured markets due to a lack of dependable electricity for refrigeration and processing (MoALD, 2025; FAO, 2024).

Kenya's abundant solar energy resource, characterized by global horizontal irradiance levels of approximately 4.5–6.0 $kWh/m^2/day$ and more than 2,000 sunshine hours annually, positions the country favorably for solar-powered agricultural transformation (GOK, 2018; Oloo et al., 2015). Solar energy provides a technically viable and economically attractive alternative to unreliable grid electricity and costly diesel-powered solutions commonly used in irrigation, cooling, and processing across agricultural value chains (International Renewable Energy Agency [IRENA], 2021). Despite this potential, the adoption of solar technologies among smallholder farmers and agri-enterprises remains limited. Evidence suggests that scaling solar-agriculture deployment requires addressing not only technical and economic considerations but also interlinked financial, institutional, social, and gender-specific barriers that constrain uptake. Targeted support mechanisms, including access to finance, capacity building, inclusive business models, and enabling policy frameworks, have been demonstrated to play a crucial role in overcoming these barriers and facilitating inclusive adoption at scale (FAO, 2022; GOGLA, 2024).

In this context, the assessment report synthesizes evidence drawn from Kenya-specific studies, documented case experiences, and pilot implementations to build a robust evidence base for informing policy, investment, and programmatic decisions on solar-agricultural energy integration. The review is undertaken under the Distributed Renewable Energy Ecosystem Model (DREEM) programme, implemented by the Kenya Climate Innovation Centre (KCIC) in collaboration with its spoke partners. It aims to establish a practical and analytical foundation for scaling solar-powered solutions within dairy and horticulture value chains across Kenya's diverse agro-ecological, market, and institutional contexts.

1.2. Policy and Development Imperative

Three interconnected imperatives drive the urgent scale-up of solar-integrated agriculture in Kenya. **First, the climate imperative:** agriculture contributes approximately 37% of Kenya's national greenhouse gas emissions, with continued reliance on diesel-powered irrigation and post-harvest processes, such as cooling and primary processing, representing a significant source of direct emissions (Ndetu et al., 2024). At the same time, agricultural productivity is increasingly constrained by climate variability and rising rainfall volatility, challenges that are particularly acute in arid and semi-arid lands (ASALs), which account for over 80% of Kenya's landmass (World Bank, 2023). The deployment of solar-powered irrigation and energy-enabled value-chain infrastructure offers a "triple-win" pathway by decoupling agricultural growth from fossil fuel use, stabilizing yields under climate stress, and directly supporting Kenya's commitment to reduce greenhouse gas emissions by 32% by 2030 under its Nationally Determined Contributions (Climate Change Directorate, 2021).

Second, the food security and nutrition imperative: post-harvest losses translate directly into reduced food availability and heightened nutrition insecurity. Annual agricultural losses are estimated at approximately KES 72 billion, with losses concentrated in perishable commodities where energy-dependent cooling and preservation technologies are critical (Mbeche et al., 2025). Scaling solar-powered cold storage and processing infrastructure directly address these inefficiencies, improving food supply reliability while increasing farmer incomes and livelihood resilience.

Third, the economic growth and employment imperative: Kenya's agrifood sector employs approximately 40% of the total population and over 70% of the rural workforce yet remains constrained by low productivity and limited value addition, partly driven by persistent energy poverty (Central Bank of Kenya, 2023). Expanding solar-powered agricultural systems presents multi-layered employment opportunities across solar equipment manufacturing and installation, technical services and maintenance, cooperative management, aggregation, and value-added processing. Under the Renewable Energy for Smallholder Agriculture (RESA) framework, scaling solar-agricultural deployment across Africa could generate an estimated 377,000 new direct jobs by 2030, with Kenya well-positioned as a regional hub for these opportunities, particularly for youth and women (FSD Africa, 2024).

1.3. Report Scope and Structure

This review examined five interrelated questions central to scaled solar-agricultural deployment:

(i) Energy needs and demand concentration: Where are energy needs concentrated across dairy and horticulture value chains, and what is the magnitude of opportunity?

(ii) Solar technology readiness and adoption trends: What solar technologies are available and demonstrably applicable to Kenya's dairy and horticulture sectors, and what trends are evident in adoption and deployment scale?

(iii) Barriers to inclusive adoption: What specific barriers, technical, financial, social, institutional, and gender-related, constrain solar adoption among smallholders, processors, and agricultural enterprises? How can gender equality be advanced as an explicit objective alongside solar deployment?

(iv) Enabling factors and support requirements: What support mechanisms, financing instruments, technical assistance, market linkages, and policy frameworks, evidence demonstrates, are necessary to overcome barriers and drive scale?

(v) Enterprise opportunities for scaling: What viable enterprise pathways exist for solar-agricultural deployment across dairy and horticulture value chains? What institutional and financial support do these enterprises require to operate on a scale?

The assessment synthesized evidence from: (1) Kenya-specific quantitative studies on energy needs and sector diagnostics; (2) documented case studies of implemented solar-agricultural systems with field-tested evidence of performance and impact; (3) international literature on technology, financing, and policy mechanisms proven effective in comparable contexts; and (4) expert consultation with implementers, private sector innovators, and development partners working in Kenya's agricultural energy sectors.

2.0. ENERGY NEEDS IN DAIRY AND HORTICULTURE

2.1 Introduction and Policy Relevance

Building on the policy and development imperatives outlined in Section 1.2, this assessment focuses on understanding agricultural energy needs as a foundational step for scaling solar-integrated solutions in Kenya's agrifood systems. Specifically, it seeks to establish an evidence base for unlocking the productive use of solar energy at the last mile by identifying where, how, and to what extent energy demand constrains value creation across priority agricultural value chains (SNV, 2021). The analysis concentrates on the dairy and horticulture sectors, given their economic significance, relatively high energy intensity, and strong potential for energy-enabled productivity and value addition.

Empirical evidence demonstrates that targeted solar-energy interventions can yield substantial economic and productivity gains when aligned with value-chain needs. In the dairy sector, where smallholders account for approximately 80% of national production, solar-powered milk cooling systems have been shown to significantly reduce spoilage and increase farm-level returns by enabling evening milk aggregation and quality preservation (Usagi et al., 2020). Similarly, in horticulture, solar-powered irrigation and climate-controlled storage technologies have demonstrated the potential to reduce energy costs while improving yields, crop quality, and market access (Green Farming, 2015; FAO, 2022). These outcomes underscore the importance of matching energy solutions to specific functional nodes within value chains rather than pursuing generic electrification approaches.

Despite this demonstrated potential, access to reliable and affordable energy remains an under-mapped constraint on agricultural productivity and value addition, particularly in Kenya's ASALs. While grid infrastructure has expanded in high-potential agricultural zones, energy deficits persist in pastoral and semi-pastoral areas at critical nodes such as irrigation, cooling, aggregation, and processing (Usagi et al., 2020; Cheloti et al., 2024). Population growth, increasing climate variability, and deeper market integration in these regions are driving demand for energy-dependent services, yet investment and planning decisions are often made in the absence of systematic data on agricultural energy demand.

In response, empirical studies, county-level value-chain mappings, and documented technology pilots were synthesized to identify where solar-energy interventions offer the highest returns for food security, income generation, and resilience outcomes. The analysis explicitly acknowledges existing evidence gaps, particularly the absence of standardized data on electricity demand (kWh), thermal loads, and time-of-use profiles across agricultural value-chain nodes. Accordingly, this chapter emphasizes qualitative-to-quantitative leverage points for investment and highlights priority areas for targeted energy audits, metering studies, and data collection required to operationalize scalable and bankable solar-agricultural projects (SNV, 2021; FAO, 2022).

2.2. Energy Demand Across the Dairy Value Chain

2.2.1. Production and On-Farm/Near-Farm Cooling

At the smallholder production stage, energy use in Kenya's dairy sector is generally modest, except where mechanical milking or water pumping for fodder production is undertaken (Usagi et al., 2020). The most consequential energy requirement occurs immediately after milking, as milk quality and farm-level returns are highly sensitive to timely and effective cooling. Evidence from smallholder dairy systems in Siaya County illustrates this constraint clearly, documenting a pronounced "cooling gap" in which evening milk held for 12–16 hours before morning collection is highly susceptible to bacterial growth and spoilage in the absence of on-site or near-site cooling infrastructure (Usagi et al., 2020). In response to this challenge, solar photovoltaic (PV) milk cooling systems deployed at farm or primary collection points have demonstrated strong potential as a targeted intervention. Field-based pilots indicate that systems designed to meet daily electricity demands of approximately 5–20 kWh, sufficient to cool 500–2,000 litres of milk under local thermal conditions, can substantially reduce spoilage losses, improve milk quality, and enable participation in quality-based pricing and structured markets (Usagi et al., 2020).

This evidence is particularly salient given that smallholder farmers supply more than 80% of Kenya's national milk output yet remain highly exposed to post-harvest losses during collection and initial handling stages, especially in areas where grid electricity is unreliable or absent (Usagi et al., 2020; Cheloti et al., 2024). Across both farm-level and aggregation nodes, energy demand is therefore strongly concentrated in milk cooling, which consistently emerges as the intervention with the strongest empirical linkage to income gains and quality improvements within the Kenyan dairy context. The relevance of solar-powered cooling extends beyond western Kenya, with value-chain mapping in arid and semi-arid land (ASAL) counties identifying the absence of cooling and basic processing infrastructure as a primary constraint to dairy sector development. In Samburu County, limited access to modern cooling facilities has been shown to restrict market participation and value addition, with renewable energy, particularly solar, identified as a prerequisite for enabling milk preservation in pastoral systems (Cheloti et al., 2024). Comparable challenges are observed in semi-arid counties such as Kajiado and Narok, where sparse grid coverage and underdeveloped aggregation infrastructure constrain cold-chain development, positioning solar and hybrid energy solutions as strategic entry points for upgrading dairy value chains (Wangai et al., 2024).

Although comprehensive, Kenya-wide measurements of electricity demand across dairy value-chain nodes remain limited, available benchmarks adapted from field studies suggest that milk cooling typically requires approximately 0.5–2 kWh per 100 litres of milk, depending on ambient conditions, system efficiency, and cooling technology employed (Usagi et al., 2020). For small collection centres handling 500–2,000 litres per day, this translates into daily electricity requirements in the range of 5–20 kWh. Complementary approaches, including evaporative and passive cooling, have been shown to reduce electrical loads by an estimated 30–50%, thereby improving the technical and economic viability of cooling systems in off-grid and weak-grid contexts (Wangai et al., 2024).

2.2.2. Aggregation and Milk Collection Centers

Milk collection centres (MCCs), typically managed by dairy cooperatives, represent one of the highest-leverage energy nodes within Kenya’s dairy value chains due to their central role in bulking, quality testing, and cold storage. County-level diagnostics from pastoral and semi-pastoral ASAL systems, including Samburu, Kajiado, and Narok, consistently identify the absence of modern cooling and aggregation facilities as the primary constraint limiting dairy value-chain development (Cheloti et al., 2024; Wangai et al., 2024). In these contexts, MCCs are rare or absent, constraining farmers’ ability to aggregate milk, preserve quality over 24-hour collection cycles, and access structured markets. As a result, solar PV-based systems, often combined with battery storage or hybrid configurations, are increasingly positioned as strategic options for enabling milk aggregation and quality preservation in off-grid and weak-grid environments (Cheloti et al., 2024).

In higher-potential, grid-connected dairy zones such as Nyeri, Bungoma, and Kirinyaga, MCCs are more prevalent and typically operate bulk milk coolers with electricity consumption in the range of 3–10 kWh per 1,000 litres of milk. However, evidence from county energy and agro-processing assessments indicates that power supply variability, including frequent outages and voltage fluctuations, undermines cooling effectiveness and necessitates reliance on diesel backup systems, increasing operating costs and emissions (Wanjala et al., 2024; Wangai et al., 2024). Empirical analysis further demonstrates the economic importance of cooperative-based cooling infrastructure: smallholder farmers participating in cooperatives that provide aggregation and bulk cooling services earn, on average, approximately 10% higher incomes than non-participants, even though energy consumption is not explicitly disaggregated in the analysis (Onyango et al., 2023).

Taken together, this evidence suggests that cooperatives and MCCs constitute institutionally viable platforms for targeted energy interventions. In grid-connected areas, hybrid and backup energy solutions are required to ensure operational reliability, while in ASAL regions, investment in solar-powered MCCs represents a critical entry point for expanding participation in formal dairy markets and upgrading value-chain performance.

2.2.3. Processing and Value Addition

Dairy processing facilities producing pasteurised milk, yoghurt, cheese, and other value-added products are among the most energy-intensive nodes within Kenya’s dairy value chains, as they require both thermal energy for heating and electrical energy for refrigeration, cooling, and packaging. County-level agro-processing assessments in Nyeri, Bungoma, and Taita Taveta consistently identify power supply variability as a major constraint on processing capacity utilisation and competitiveness, resulting in facilities operating well below installed capacity due to unreliable electricity, outdated equipment, and limited processing infrastructure (Wanjala et al., 2024; Mutai et al., 2025; Omamo et al., 2024). These constraints weaken market linkages, limit access to price premiums for quality-differentiated dairy products and increase vulnerability to seasonal milk gluts and price volatility at the farm level.

Energy demand and cost considerations are central to this bottleneck. Benchmarks adapted to Kenyan operating conditions indicate that dairy processing typically requires approximately 0.2–0.5 kWh per litre of processed milk, reflecting combined thermal and electrical loads. For a small-scale processor handling approximately 500 litres per day, this translates into 100–250 kWh of daily energy demand, or 3–7.5 MWh per month. At prevailing Kenya Power grid tariffs of KES 20–25 per kWh, monthly energy expenditures can range from KES 60,000 to 190,000, representing a substantial operating cost burden that discourages investment in value addition (Wanjala et al., 2024; Mutai et al., 2025). In response, county diagnostics, particularly in Nyeri County, recommend investment in standby power systems and modernised equipment as critical enablers for unlocking processing capacity (Wanjala et al., 2024). More broadly, the convergence of evidence across dairy-producing counties suggests that hybrid energy configurations integrating solar thermal systems for process heating with solar photovoltaic (PV) systems, battery storage, and grid or generator backup for refrigeration and cooling offer a viable pathway to improve power reliability, reduce operating costs, and enhance capacity utilisation, thereby strengthening value addition and the resilience of Kenya's dairy value chains.

2.2.4. Cold Storage, Transport, and Market Integration

Cold storage infrastructure, including bulk milk tanks and refrigerated facilities, plays a critical role in complementing initial cooling and processing by managing milk flow fluctuations during peak production periods and strengthening overall supply chain resilience. However, dedicated cold storage capacity remains limited across Kenya's dairy value chains, particularly within ASAL systems, and is underdeveloped even in several grid-connected regions (Wanjala et al., 2024). Where cold storage is available, maintaining milk at safe temperatures of approximately 4–10 °C requires continuous, 24-hour operation, resulting in steady and substantial energy demand. Technical benchmarks indicate an energy intensity of approximately 0.5–1.5 kWh per 1,000 litres per day for insulated bulk storage tanks. For a medium-sized facility with a storage capacity of 5,000 litres operating continuously, this translates into monthly energy requirements of approximately 15–45 MWh, underscoring the high operating costs that often undermine commercial viability in the absence of affordable and reliable energy solutions (Wangai et al., 2024).

Energy constraints at the storage stage are closely linked to challenges in dairy transport and marketing. Refrigerated transport represents an emerging but under-quantified source of energy demand within Kenya's dairy value chains, yet the lack of affordable and reliable cold-chain logistics remains a major barrier to market access for smallholder producers. The resulting "cold chain gap" contributes significantly to post-harvest losses, which in some contexts are estimated to exceed 40%, particularly for producers located far from processing and consumption centres (Cold Solutions Kenya, 2025; United Nations Capital Development Fund [UNCDF], 2025). In the absence of viable alternatives, diesel-powered generators remain the default option for mobile refrigeration, imposing high operating costs, increasing exposure to fuel price volatility, and contributing to greenhouse gas emissions (Wilkes et al., 2018).

Recent pilot initiatives indicate that solar-powered and battery-integrated cold-chain solutions, though still at an early stage of deployment in Kenya, offer a promising pathway for addressing these constraints. Evidence from demonstration projects suggests that transitioning from diesel-based refrigeration to solar-hybrid systems can reduce fuel consumption by up to 48% while improving temperature stability during milk transport and distribution (Cold Solutions Kenya, 2025). Available evidence positions cold storage and refrigerated transport as critical, energy-intensive nodes where targeted renewable energy interventions can deliver substantial gains in post-harvest loss reduction, market integration, and climate resilience. Integrating renewable energy solutions across storage and transport functions, therefore, represents a strategic opportunity to strengthen dairy value-chain performance, particularly in ASAL and remote production zones where grid-based solutions remain impractical.

2.3. Energy Demand Across the Horticulture Value Chain

2.3.1. Production and On-Farm Irrigation

Horticultural production in Kenya, particularly high-value crops such as tomatoes, peppers, and French beans, as well as tree crops including bananas and avocados, is increasingly dependent on irrigation in both high-potential agricultural zones and semi-arid areas experiencing heightened climate stress. This trend reflects rising rainfall variability, shorter growing seasons, and increasing pressure on water resources, which have collectively increased reliance on controlled water application to stabilize yields and crop quality (FAO, 2022; World Bank, 2023). Irrigation-related energy demand arises primarily from borehole and surface water pumping and, in many smallholder horticultural systems, represents the dominant energy end-use at the production stage (SNV, 2021; IRENA, 2021). Literature indicates that irrigation for smallholder plots of approximately 1–2 hectares typically require between 60 and 360 kWh per day, equivalent to 1.8–10.8 MWh per month per farm, depending on water source depth, pumping technology, and cropping intensity (Mutai et al., 2025; Omamo et al., 2024).

Despite its central role in productivity and climate resilience, access to affordable and reliable energy for irrigation remains a binding constraint on smallholder participation in high-value horticulture, particularly in water-scarce and semi-arid zones. Multi-sector diagnostics conducted in Bungoma and Taita Taveta consistently identify affordable irrigation systems as a critical unmet need, constraining crop diversification, yields, and income potential (Mutai et al., 2025; Omamo et al., 2024). Similar findings are echoed in national and regional assessments, which highlight energy costs and power unreliability as major barriers to the adoption of modern irrigation technologies across sub-Saharan Africa (FAO, 2022; IRENA, 2021). While irrigation energy requirements are frequently acknowledged in qualitative value-chain analyses, they remain insufficiently quantified across Kenya’s horticultural systems, limiting the ability to design appropriately sized, cost-effective energy solutions. Addressing this evidence gap through systematic energy profiling and metering at the farm level is therefore essential for enabling scalable solar-powered irrigation interventions and informing targeted policy and investment decisions (SNV, 2021; World Bank, 2023).

2.3.2. Aggregation and Group-Level Storage

At the aggregation stage, horticultural value chains face a distinct set of energy demands compared to dairy, driven primarily by the need for pre-cooling and short-term storage of fresh fruits and vegetables under controlled temperature and relative humidity (T/RH) conditions. Effective pre-cooling is widely recognised as a critical determinant of shelf life, produce quality, and post-harvest loss reduction in horticultural systems, particularly for smallholder producers operating in warm climates (FAO, 2011; FAO, 2022). In the Kenyan context, a pioneering pilot implemented in Kirinyaga County provides rare, quantified evidence on low-energy cooling solutions suitable for smallholder aggregation. The pilot developed and tested a 40 m³ evaporative charcoal cooler for fruits and vegetables, applying passive evaporative cooling principles to achieve temperature and humidity control with minimal electricity requirements (Ronoh, 2020).

Empirical results from the Kirinyaga pilot demonstrate that the evaporative cooler consistently maintained internal temperatures 5–10 °C below ambient conditions while stabilising relative humidity at 80–90%, levels appropriate for short-term storage of a wide range of horticultural produce. These conditions were shown to extend shelf life and preserve produce quality, providing one of the few Kenya-specific, quantitatively documented cases linking improved group-level pre-cooling infrastructure to reduced post-harvest losses and improved income outcomes for smallholder farmers (Ronoh, 2020). Importantly, the intervention combined physical infrastructure with targeted farmer training on operation and maintenance, packaging, and quality standards, reinforcing evidence that post-harvest technologies are most effective when deployed alongside capacity-building measures (FAO, 2011).

From an energy perspective, the evaporative charcoal cooler operates without electricity in its passive configuration, while optional active-circulation variants, using small fans to enhance airflow, require only 0.1–0.3 kWh per day, orders of magnitude lower than conventional mechanical refrigeration systems (Ronoh, 2020). By comparison, a mechanically refrigerated cold room offering similar storage capacity typically consumes 3–5 kWh per day, resulting in higher operating costs and reduced suitability for off-grid and weak-grid contexts (FAO, 2022). These findings highlight the potential role of low-energy, renewable-based aggregation and storage technologies as cost-effective and scalable entry points for strengthening horticultural value chains, particularly in rural and energy-constrained production zones.

2.3.4. Cold Storage and Packhouses

Horticultural packhouses and cold storage facilities play a critical role in enabling value addition, quality assurance, and market access through washing, grading, sorting, packaging, and temperature-controlled storage of fresh produce. In Kenya, however, such infrastructure remains underdeveloped outside a limited number of export-oriented corridors, notably those serving the cut-flower and high-value horticulture export subsectors. Where packhouses are operational, cold rooms typically maintain temperatures in the range of 4–8 °C for short-term storage before export or domestic market distribution. Energy demand within packhouses is heavily concentrated in refrigeration, which accounts for an estimated 40–60% of total electricity use, followed by water pumping and electrically driven processing equipment such as conveyors, sorting lines, and grading motors (FAO, 2022; IRENA, 2021).

County-level diagnostics conducted in Bungoma, Taita Taveta, and Nyeri consistently identify weak post-harvest infrastructure, including limited cold storage capacity, suboptimal packhouse design, and ageing equipment, as major constraints to horticultural value addition and market integration (Wanjala et al., 2024; Mutai et al., 2025; Omamo et al., 2024). Although these assessments do not systematically quantify energy consumption, the recurring emphasis on infrastructure upgrading implies that energy-intensive cold-chain and packhouse equipment constitute a critical bottleneck. This is particularly pronounced in domestic-oriented horticultural value chains, where investment in modern packhouses has lagged behind export-focused segments.

Indicative benchmarks suggest that a 50-ton-capacity packhouse, equipped with refrigeration, water supply systems, and basic sorting and grading equipment, typically consumes 15–25 kWh per day, equivalent to 450–750 kWh per month, depending on throughput, ambient conditions, and equipment efficiency. At prevailing grid tariffs, this translates into monthly energy costs of approximately KES 9,000–18,750, representing a significant operating expense for small and medium-scale operators. Off-grid or weak-grid packhouses remain rare, highlighting a persistent investment gap in decentralised energy solutions capable of supporting cold storage and packhouse operations in rural production zones. Addressing this gap through appropriately sized hybrid renewable energy systems offers a potential pathway to expand post-harvest infrastructure, reduce losses, and improve market access for smallholder horticultural producers.

2.3.5. Processing and Value Addition

Horticultural processing, including dried fruits, juices, sauces, and canned vegetables, remains limited across most Kenyan agricultural zones, constrained by high energy costs, limited access to appropriate processing equipment, and weak market linkages. Energy requirements at this stage are driven primarily by thermal needs for drying, cooking, and pasteurization, alongside electrical demand for cooling and mechanical operations. Evidence from applied agrifood and energy studies indicates that energy costs can account for a substantial share of total processing expenses for small- and medium-scale processors, often rendering value addition economically unviable in contexts characterised by unreliable or expensive power supply (World Bank, 2022).

In Kenya, where horticultural processing activities are present, such as banana-based products in Nyeri and Taita Taveta counties, operations typically rely on grid electricity to meet both thermal and electrical energy needs. In these settings, energy expenditures are frequently estimated to account for approximately 15–25% of total processing costs, undermining cost competitiveness in the absence of a reliable and affordable power supply. These constraints limit the ability of processors to operate at scale and discourage investment in higher-value product lines. Studies consistently identify limited value addition as a structural weakness within Kenya’s horticultural value chains and recommend targeted upgrading of processing facilities alongside strengthened market linkages (Wanjala et al., 2024; Mutai et al., 2025; Omamo et al., 2024).

Although these assessments do not explicitly quantify energy demand at the processing stage, energy reliability and affordability are implicitly embedded within the recommended interventions, reflecting the energy-intensive nature of horticultural processing operations. The absence of systematic energy profiling at this node, therefore, represents a critical evidence gap, constraining the design of appropriately sized and cost-effective renewable or hybrid energy solutions capable of supporting scalable horticultural value addition.

2.4. Comparative Analysis: Energy Demand Concentration Across Value-Chain Nodes

Table 1 summarizes the relative energy demand intensity and concentration across dairy and horticulture value-chain nodes, synthesizing qualitative evidence from the literature review and global technical benchmarks adapted to Kenyan contexts.

Table 1: Energy Demand Intensity Across Dairy and Horticulture Value-Chain Nodes

Value-Chain Node	**Dairy – Primary Energy End-Use**	**Horticulture – Primary Energy End-Use**	**Relative Energy Intensity**	**Grid vs. Off-Grid Feasibility**	**Concentration of Demand**
Production / On-Farm	Minimal (except water pumping in specific zones)	Irrigation pumping (particularly in semi-arid areas)	Low (dairy); Very high (horticulture)	Grid, diesel; increasing solar uptake	Low (dairy); Very high (horticulture)
Aggregation / Collection	Milk cooling at MCCs (refrigeration)	Group-level storage and pre-cooling (refrigeration or evaporative)	Medium (≈0.5–2 kWh per 100 L milk)	Grid-dependent; solar feasible	High (dairy)
Processing / Value Addition	Pasteurisation, yoghurt, cheese (thermal + electrical)	Juices, dried products, canning (thermal + mechanical)	High (≈0.2–0.5 kWh per litre processed)	Grid-dependent; backup/hybrid required	Very high (dairy)
Cold Storage	Bulk insulated tanks (24/7 refrigeration)	Cold rooms and packhouses (24/7 refrigeration)	Medium–high (≈0.5–1.5 kWh per 1,000 L/day)	Grid-dependent; hybrid systems viable	Medium–high
Transport	Refrigerated logistics (diesel or solar–battery hybrid)	Refrigerated vehicles for domestic and export markets	High (externally driven)	Primarily diesel; solar–battery nascent	Medium–high (export-oriented chains)
Marketing / Retail	Minimal (ambient-temperature domestic sales dominate)	Retail refrigeration in export corridors	Low (dairy); Medium (horticulture exports)	Grid-dependent	Low (dairy); Medium (horticulture)
Highest Demand Concentration	Aggregation (MCCs) and Processing	Irrigation, Aggregation, and Processing	—	—	Diary: MCCs; Horticulture: Irrigation

Key observations: First, dairy value chains exhibit a pronounced concentration of energy demand at aggregation (milk collection centres, MCCs) and processing nodes, where continuous refrigeration for milk preservation and thermal processes for value-added product manufacturing dominate electricity consumption. These nodes represent critical control points where energy reliability directly influences product quality, market access, and farmer incomes. Second, horticulture value chains display a more distributed energy demand profile, with substantial demand at the production stage due to irrigation and at aggregation and cold-storage nodes for pre-cooling and short-term storage. In semi-arid production systems, irrigation often accounts for the largest share of total energy consumption, reinforcing the importance of production-stage energy interventions alongside post-harvest infrastructure. Third, off-grid solar solutions are most technically and economically feasible at production and aggregation nodes, particularly for dairy cooling and horticulture pre-cooling, where modular and decentralised systems can be appropriately sized to match dispersed infrastructure and variable throughput. By contrast, processing facilities typically require higher and more stable power loads, making grid-connected or hybrid mini-grid configurations more suitable for ensuring operational continuity.

Finally, as highlighted in Figure 1, post-harvest management infrastructure, including cooling, storage, and processing, emerges as the highest-return energy investment opportunity for the Dream Hub across both value chains. Evidence from Kenya-specific case studies demonstrates that targeted energy investments at these nodes yield measurable gains in income, reductions in post-harvest losses, and improved resilience of value chains to climate and market shocks.

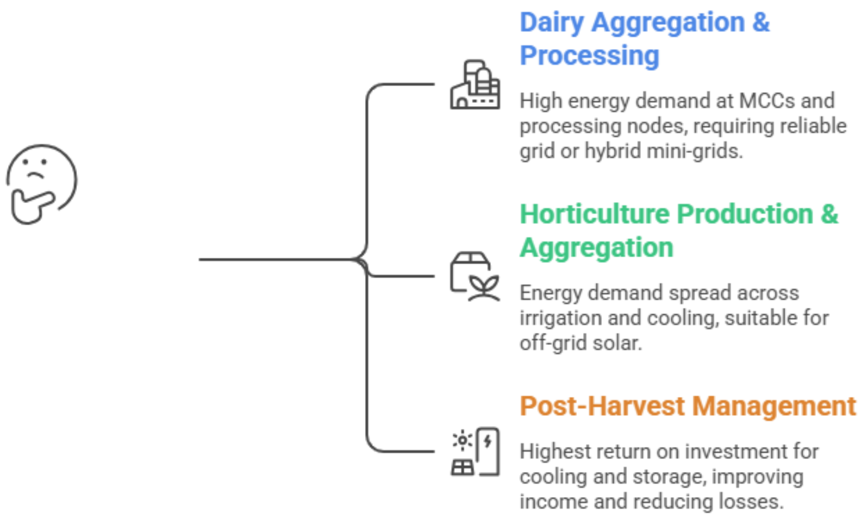

Figure 1. Illustration showing priority investment points for energy infrastructure across dairy and horticulture value chains.

2.5. Potential for solar energy and trends in its adoption to meet the energy requirements of Kenya's dairy value chains

Solar energy adoption in Kenya's dairy value chains has followed a more concentrated and problem-driven trajectory than in horticulture, reflecting the centrality of milk cooling and basic processing as binding constraints to quality, market access, and income. Unlike horticulture, where energy demand is distributed across multiple nodes, dairy energy demand is highly concentrated at aggregation and early processing stages, making targeted solar interventions particularly impactful.

At the production and aggregation levels, solar PV direct-drive milk cooling systems represent the most mature and widely evidenced renewable energy application in the Kenyan dairy sector. Empirical evidence from multi-year deployments shows that these systems have been successfully integrated into both smallholder farm routines and cooperative-managed MCCs, with operational scales ranging from 50–100 litres per day at the household level to 1,000–5,000 litres per day at cooperative aggregation points. Adoption has been driven primarily by the need to reduce spoilage during overnight storage and delayed collection, a critical loss points in smallholder dairy systems.

In parallel, solar thermal pasteurisation has emerged as a niche but contextually important solution in arid and pastoral dairy systems, where grid electricity is absent, and reliance on firewood constrains value addition and environmental sustainability. Although limited in throughput and scale, solar thermal pasteurisation directly enables safe milk processing and market participation in off-grid pastoral contexts, addressing a distinct segment of the dairy value chain that solar PV cooling alone cannot reach. These cases point to a clear trend toward right-sized, function-specific solar solutions in the dairy sector: PV-based cooling technologies dominate where aggregation and cooperative structures exist, while solar thermal solutions serve remote pastoral systems where basic processing is otherwise unattainable. Table 2 synthesises these solar applications, empirical cases, and deployment considerations across Kenya's dairy value chains.

Table 2: Solar Energy Applications, Empirical Evidence, and Deployment Considerations Across Kenya's Dairy Value Chains

Solar Application	**Value-Chain Node**	**Case / Empirical Evidence (Kenya)**	**Technology & Design Characteristics**	**Indicative Energy Requirement**	**Performance & Value-Chain Effects**	**Scalability & Deployment Context**	**Key Constraints & Risks**	**Key References**
Solar PV Direct-Drive Milk Cooling	Production & Aggregation (Farm & MCCs)	Multi-year deployments at farm and cooperative levels; income impacts documented in Siaya County; system sizes ranging from 50–100 L/day (household) to 1,000–5,000 L/day (MCCs)	PV array directly coupled to refrigeration compressor; no batteries; thermal storage via insulated milk tank; simplified O&M suited to rural contexts	~5–20 kWh/day depending on milk volume and ambient conditions	Reliable milk chilling; significant reduction in spoilage; improved milk quality; higher effective prices; lower rejection rates at cooperatives	High scalability at farm and MCC levels; well-suited to off-grid and weak-grid zones; adaptable across diverse production scales	Temporal mismatch with evening milk production; performance sensitive to insulation quality and operational practices	Foster et al. (2016, 2017); Salvatierra Rojas et al. (2018); Usagi et al. (2020)
Solar Thermal Pasteurisation	Processing (On-site, pastoral dairy systems)	Field trials in arid pastoral northern Kenya using solar pasteurisation units with ~80 L capacity (40 L optimal batch size)	Flat-plate solar water heater coupled to jacketed stainless-steel milk vat; batch pasteurisation; no electricity required	Thermal energy only; batch-based processing	Achieves microbiologically safe milk (<10 cfu/mL; coliform-free); enables local value addition; improves milk safety and market access	Context-specific scalability; most suitable for off-grid pastoral regions with small volumes and limited infrastructure	Limited throughput; batch operation; requires user training and hygiene control; less suitable for high-volume systems	Wayua & Wangoh (2011); Wayua et al. (2013)

2.6. Potential for solar energy and trends in its adoption to meet the energy requirements of Kenya’s horticulture value chains

Evidence from Kenya indicates that solar energy adoption across horticulture value chains is being shaped by small-scale, context-specific applications, rather than large, uniform deployments. At aggregation points, low-energy solutions such as charcoal evaporative coolers, demonstrated through a 40 m³ pilot in Kirinyaga County, illustrate how passive and near-passive technologies can deliver meaningful reductions in post-harvest losses under smallholder conditions, particularly in off-grid and semi-arid environments. At the production stage, adoption of solar-powered irrigation systems sized for 0.25–1 hectare plots are emerging as the most widespread solar application, driven by the need to stabilize yields and enable dry-season production in water-stressed zones, despite persistent financing and market-access barriers.

In contrast, solar adoption at processing and cold-storage nodes is evolving through hybrid and clustered approaches, reflecting higher energy intensity and reliability requirements. County diagnostics from Nyeri, Bungoma, and Taita Taveta point to increasing use of solar–grid–backup configurations at individual facilities, while mini-grid systems in the range of 20–50 kWp, designed to serve 3–5 co-located processors or packhouses, are emerging as a scalable model where spatial clustering allows. These cases suggest a clear trend toward right-sized, node-specific solar solutions, with technology choice and system scale closely aligned to value-chain function, infrastructure concentration, and institutional capacity. Table 2 synthesizes these applications, performance characteristics, and deployment considerations across Kenya’s horticulture value chain

Table 3: Solar Energy Applications, Performance, and Deployment Considerations Across Kenya's Horticulture Value Chains

Solar Application	Value-Chain Node	Case / Empirical Evidence (Kenya)	Technology & Design Characteristics	Indicative Energy Requirement	Performance & Value-Chain Effects	Scalability & Deployment Context	Key Constraints & Risks	Key References
Evaporative & Passive Cooling	Aggregation / Group-level storage	40 m³ charcoal evaporative cooler pilot in Kirinyaga County (high-potential horticulture zone)	Charcoal evaporative cooler (≈40 m³) using passive evaporative principles; optional low-power fans for airflow enhancement	Passive (0 kWh); active variants require ~0.1–0.3 kWh/day	Maintains produce at 5–10 °C below ambient with 80–90% RH; extends shelf-life, preserves quality, and reduces post-harvest losses; income effects observed through improved prices and reduced distress sales	Highly suitable for ASAL and semi-arid zones with low humidity and large diurnal temperature ranges; ideal for off-grid aggregation points using small solar or wind-assisted systems	Performance sensitive to ambient humidity; not suitable for long-term cold storage or export-grade requirements	Ronoh (2020)
Solar-Powered Irrigation	Production / On farm	Smallholder horticulture systems serving 0.25–1 ha plots in semi-arid counties (Bungoma, Taita Taveta)	PV-coupled submersible or surface pumps with controllers and inverters; typically integrated with drip or micro-irrigation systems	~0.5–1.5 kWp PV for a 1 ha plot under dry-season conditions	Enables dry-season and year-round production; stabilizes yields, supports crop diversification, and improves income resilience; competitive LCOE relative to diesel over 5–10 years	Strong potential in semi-arid and water-stressed zones; scalable for 0.25–1 ha smallholder plots; key climate adaptation pathway	High upfront capital costs (KES 150,000–300,000 per kWp); limited access to credit; weak standardization and after-sales support in rural areas	Practical Action (2014); Mutai et al. (2025); Omamo et al. (2024)
Hybrid Renewable–Grid–Backup Systems	Processing & Cold Storage	Agro-processing diagnostics from Nyeri, Bungoma, and Taita Taveta counties	Integrated systems combining solar PV (30–50% of average load), grid supply, battery storage (10–20 kWh), and diesel backup	Facility-scale loads; designed to smooth grid volatility and reduce diesel reliance	Improves power reliability and capacity utilization; reduces downtime and spoilage risks in processing and cold storage; lowers long-term energy costs	Best suited to high-potential zones with grid access but poor reliability; adaptable to packhouses and	Higher system complexity requires technical capacity for operation, maintenance, and system integration	Wanjala et al. (2024); Mutai et al. (2025); Omamo et al. (2024)

						medium-scale processors		
Mini-Grids for Processing Clusters	Processing clusters / Packhouses	Emerging clustered processing hubs serving 3–5 facilities within 1–2 km radius	Solar PV mini-grids (20–50 kWp) with battery storage (50–100 kWh) and backup generation supplying multiple facilities	Shared loads across 3–5 processing or cold-storage facilities	Reduces per-facility capital costs; improves load management and reliability; enables specialised O&M and shared services	High potential where processors or cooperatives are co-located within 1–2 km; suitable for agro-processing hubs	Requires coordinated governance, anchor demand, and clear tariff/management arrangements	Wanjala et al. (2024)

2.7. Case Studies of Solar Energy Adoption in Kenyan Dairy and Horticultural Value Chains

Empirical evidence from documented case studies across Kenya's agricultural value chains demonstrates the technical feasibility, economic viability, and operational challenges of solar technology adoption. This section synthesizes evidence from multiple case studies across dairy and horticultural sectors, identifying adoption patterns, critical success factors, and context-specific constraints.

2.7.1. Dairy Value Chain Case Studies

i. Savanna Circuit Technologies: Solar-Powered Mobile Milk Chillers

Savanna Circuit Technologies, founded in 2017, manufactures solar-powered mobile milk chillers designed to integrate into dairy cooperative milk collection systems. The core technology comprises portable solar refrigeration units (MaziwaPlus pre-chillers) paired with a digital dairy management system enabling real-time quality monitoring and production tracking (Savanna Circuit, 2023). Rather than fixed infrastructure, Savanna's approach emphasizes mobile, modular chilling technology that cooperatives can lease at lower capital commitment than traditional fixed cold-chain infrastructure.

The company operates a lease-based business model: cooperatives pay monthly service fees enabling access to cooling technology without requiring large upfront capital investment. This model reduces financial barriers for smallholder-dominated cooperatives while preserving Savanna Circuit's ownership and maintenance responsibility for equipment. The MaziwaPlus system integrates solar power generation, battery storage, and automated temperature control, producing ice for milk cooling during peak collection periods (morning and evening) with excess ice capacity providing backup cooling for emergencies.

Savanna Circuit has deployed mobile chillers across high-potential dairy zones in Western Kenya (Kaptabuk village, Trans Nzoia County, Uasin Gishu, and Elgeyo Marakwet), South Rift (West Pokot), and Eastern Kenya regions. The company reports reaching over 22,000 smallholder farmers across 10 dairy zones and facilitating transport of approximately 2.4 million liters of milk annually (Savanna Circuit, 2023). Deployment targets both grid-connected (South Rift) and off-grid contexts (pastoral and semi-pastoral ASAL regions), demonstrating technology adaptability across different electrification contexts.

A documented pilot implementation in Kaptabuk village (West Pokot County, 2019) illustrates key outcomes. Following technology deployment, participating cooperatives registered zero milk losses during transport via Savanna chillers, with on-farm quality monitoring providing feedback enabling operational improvement (Savanna Circuit, 2022). Over 12 months, participating cooperatives demonstrated 150% improvement in key dairy performance indicators: milk quality (measured through bacterial counts and compositional parameters), production volume, and farmer income. Income improvement was particularly pronounced for women and youth groups, whose participation in dairy activities increased through improved income viability (Savanna Circuit, 2022).

A more recent application demonstrates technology expansion beyond traditional dairy toward fish cold chains. Savanna's EcoSav Universal Chiller, currently in pilot deployment in Lake Victoria fishing communities, couples solar-powered mobile refrigeration with centralized ice-water dispensing, addressing spoilage challenges in fish value chains while maintaining compatibility with dairy sector deployment (Savanna Circuit, 2024). This diversification illustrates technology modularity and applicability across temperature-sensitive agricultural value chains.

The Savanna model achieves sustainability through several mechanisms. Manufacturing facility in Nairobi (rather than importing complete systems) reduces capital cost and improves maintenance supply chains. Local manufacturing enables integration of locally-sourced components and rapid technical support, reducing downtime from equipment failure. The lease-based business model creates stable revenue streams enabling company reinvestment in technology development and maintenance network expansion. Digital management system (MaziwaPlus Dairy Management System) enables remote system monitoring and predictive maintenance, reducing surprise failures and associated trust erosion (Savanna Circuit, 2023).

Despite demonstrated impact, Savanna's expansion reveals specific constraints. Battery replacement costs (approximately KES 80,000–120,000 per unit every 3–5 years) represent ongoing operational expenses potentially exceeding initial technology affordability projections. Rural technician capacity, while improved, remains a bottleneck in extended geographic areas; facilities in very remote locations experience extended downtime awaiting technician availability. Adoption in pastoral ASAL regions, while attempted, shows slower uptake compared to high-potential zones, suggesting that adoption barriers extend beyond technology availability to include product marketing and farmer awareness gaps.

ii. Baridi: Solar Bulk Milk Chillers for Cooperative-Level Cooling

Baridi, established in 2018, specializes in customized solar-powered cold storage solutions for East African livestock value chains. The company's primary dairy application focuses on bulk milk chillers (1,000-liter capacity per unit) designed for cooperative milk collection infrastructure. Baridi systems integrate: (1) solar photovoltaic arrays (3–5 kW) powering refrigeration compressors; (2) advanced thermal storage using phase-change materials or ice banks providing multi-hour cooling capacity; (3) IoT-enabled monitoring (Wingu asset management platform) tracking generation and consumption data in real-time; and (4) pay-as-you-store business model with mobile money payment integration (Baridi, 2023).

The technology architecture prioritizes reliability and operational simplicity appropriate for rural contexts. Containerized deployment (10-foot shipping container format) enables rapid installation and relocation; modular design allows staged capacity expansion. Thermal storage design is intentionally oversized (90MJ capacity) to ensure reliable operation during extended cloudy periods, prioritizing reliability over cost minimization, a deliberate design choice reflecting lessons from earlier solar failures in off-grid settings.

Baridi received funding through the Shell Foundation–supported "Harvesting Green Energy for Smallholder Farmers" project, enabling deployment of five 1,000-liter solar bulk milk chillers across dairy cooperatives in South Rift and Western Kenya (Baridi, 2025). This funding mechanism combining development finance with private sector financing reflects emerging models for solar agriculture infrastructure scaling. Parallel deployment in potato processing facilities in Kisii and Kakamega Counties (supported by USDA, North Carolina State University, and KALRO) expanded the company's application scope beyond dairy toward vegetable value chains.

Early deployment data (2023–2025) reports that Baridi chillers process substantial daily volumes installations consistently operate at 80–100% capacity utilization. Mobile money integration (M-Pesa payment) reportedly achieves higher payment collection rates and user convenience compared to cash-based alternatives, addressing previously identified revenue collection challenges in cooperative settings (Baridi, 2023; Baridi, 2025).

Company field visits to 30+ dairy cooperatives across South Rift, Eastern, and Western Kenya revealed systematic market constraints. Cooperatives consistently cited electricity costs as the primary operational burden; many pay KES 20,000–40,000 monthly for grid electricity or diesel generator operation, compressing cooperative margins and reducing farmer milk prices. Installed chiller technology was frequently outdated, creating operational inefficiency and water waste (cooling system inefficiency necessitates excess water use). Baridi's assessment identified a clear market opportunity: cooperatives actively seek cost-reduction alternatives but lack financing mechanisms for capital equipment investment (Baridi, 2024).

Financial viability analysis suggests Baridi's cooperative-level model is economically sustainable where utilization rates exceed 70%. At standard usage fees (KES 50–100 per 100-liter batch), 1,000-liter chillers installed in high-throughput cooperatives (>2,000 liters daily) generate monthly revenue of KES 100,000–200,000, enabling operational cost coverage (maintenance, technician salaries) plus facility reinvestment. However, lower-volume cooperatives (<1,000 liters daily) face marginal economics, requiring subsidy or cross-subsidization mechanisms to justify investment (Baridi, 2023).

iii. Kaptabuk Cooperative Milk Collection Center: Integrated Community Infrastructure

Kaptabuk village (West Pokot County) serves as a documented example of integrated solar dairy infrastructure serving smallholder pastoral dairy farmers. The cooperative operates a community milk collection center equipped with solar-powered bulk milk chilling capacity (Savanna Circuit deployment) integrated with cooperative administrative facilities and farmer training space. The facility serves approximately 400 member farmers across 15 satellite milk collection points, consolidating milk for twice-daily transport to regional dairy processors.

The collection center operates a revenue-sharing model: farmers deliver milk to satellite collection points; consolidators transport milk to the central facility for solar-powered chilling and quality assessment (testing for adulterants, bacterial counts); processed milk is transported to processors; cooperative retains a collection service fee (KES 2–3 per liter) for infrastructure and operational costs. Farmer income varies seasonally (peak production in wet seasons, lower in dry seasons), creating variable revenue for cooperative operations, a constraint mitigated through diversified revenue generation (service fees from value-added products, training fees, vehicle hire).

Kaptabuk's sustainability reflects several deliberate design choices. Community governance structure includes women and youth participation (approximately 30% female cooperative leadership); this inclusive governance reportedly improves financial accountability and reduces conflicts over infrastructure use. Technical training integrated with technology deployment (solar operations, chiller maintenance, milk quality testing) built local technical capacity, reducing dependence on external technician support. Market linkage support from Savanna Circuit enabled cooperative access to premium processors willing to pay quality premiums for chilled milk, financial incentives supporting farmer motivation to deliver quality milk.

Over five years of operation (2019–2024), Kaptabuk achieved documented improvements: (1) milk quality compliance: 95%+ of delivered milk meets processor bacterial standards (compared to 40–50% pre-cooling infrastructure); (2) price realization: quality premiums for compliant milk add approximately KES 5–10 per liter compared to bulk-tank milk; (3) farmer income: average annual income per farmer increased from KES 25,000–35,000 (pre-infrastructure) to KES 60,000–85,000 (post-infrastructure) a 100%+ increase; (4) market participation: 85%+ of member farmers now market milk through cooperative (compared to 30% pre-infrastructure, with remainder selling to informal traders at lower prices).

However, sustainability challenges persist. Dry season production decline (50–70% volume reduction during drought years) creates financial strain on cooperative operations, particularly when loan obligations (capital equipment financing) have fixed payment schedules misaligned with seasonal income. Climate shocks (2022–2023 East African drought) resulted in extended collection center underutilization and deferred maintenance, illustrating vulnerability of community-scale infrastructure to climate variability.

2.7.2. Horticultural Value Chain Case Studies

i. SokoFresh: Distributed Cold Storage as a Service

SokoFresh, established in 2018, developed a radically different approach to agricultural cold storage, moving from centralized facility-based models (which require large capital investment and concentrate spoilage risk) to distributed farm-level cold storage deployed as a service. SokoFresh manufactures modular solar-powered cold storage units (5–20 m^3 capacity) installed at farmer collection points or field edges, enabling same-day cooling of freshly-harvested horticultural produce. The company operates a "cooling-as-a-service" financial model: SokoFresh owns and maintains equipment; farmers pay a usage fee proportional to stored volume and duration. Integration with SokoFresh's digital platform (market linkage system) enables farmers to post available produce, access buyer information, and arrange market transactions, essentially combining cold storage infrastructure with market access service (SokoFresh, 2023; SokoFresh, 2024).

SokoFresh's founder, Denis Karema, identified that horticultural post-harvest losses in Kenya (30–50% of production) stem not from lack of technology but from misalignment between technology economics and smallholder affordability. Conventional cold storage facilities require capital investment of USD 15,000–30,000 for smallholder-serving capacity, placing acquisition beyond individual farmer reach. Cooperatives, though better positioned to finance shared infrastructure, face governance complexities and capital constraints. SokoFresh's innovation was not technological (solar cold storage is established) but business model: converting capital expenditure into operational expenditure through pay-per-use service provision (SokoFresh, 2024).

SokoFresh piloted (2020–2021) the model through two demo cold storage units installed in contrasting horticultural zones (avocado production zone and vegetable production zone). Pilot data demonstrated core proof-of-concept: (1) famers willingly use and pay for cooling services when economically attractive, (2) cooling reduces spoilage to 2% (compared to 30–40% ambient storage), (3) reduced spoilage enables 20% average income increase per farmer through price realization (storage enables waiting for better market prices rather than fire-selling immediately at harvest), and (4) technology proves reliable in field conditions with appropriate maintenance protocols (SokoFresh, 2024).

Based on pilot success and investor interest, SokoFresh expanded deployment (2022–2024) to approximately 30 portable cold storage hubs across Kenya's horticultural zones (avocado, tomato, leafy greens, tree fruit production zones). Over 14,500 farmers have been onboarded to the platform (as of early 2025), with cumulative usage involving thousands of storage transactions (SokoFresh, 2024). The company closed its first seed investment in 2023 and became the first company to receive funding from Acumen's PEII+ initiative (supported by UK aid via Powering Renewable Energy Opportunities and other impact investors), positioning the company for sustained expansion (PREO, 2024).

SokoFresh developed two distinct sub-models to address different value chain segments. The B2C model (direct farmer engagement) serves smallholder farmers producing commodities (avocado, tomato, leafy vegetables), where price point sensitivity is high and individual farm volumes are moderate (10–100 kg per harvest). For this segment, SokoFresh deployed smaller units (5–10 m^3) at village/community level, with fee structures of approximately USD 0.10–0.20 per kg per day,low absolute cost but economically meaningful for smallholders.

A B2B model serves exporters, processors, and wholesalers aggregating production from multiple smallholders. For B2B clients, SokoFresh customized larger units (15–20 m^3 capacity) with specification tailored to commodity requirements: temperature and humidity settings optimized for specific crops, storage duration protocols aligned with export logistics, aggregation procedures suited to bulk handling. B2B pricing differs substantially (cost-plus margins reflecting asset ownership and maintenance), but absolute volumes and utilization rates are higher, creating stronger unit economics (SokoFresh, 2024).

SokoFresh reports transformative farmer outcomes. A representative case involved an avocado farmer in Murang'a County who, before SokoFresh, sold avocados immediately at harvest for KES 2,000–3,000 per 50-kg bag to satisfy urgent cash needs and prevent spoilage. Through SokoFresh storage (5 days storage cost ≈ KES 100), the farmer identified better market timing, waiting for urban market price peaks, and achieved KES 5,000–6,000 per bag, a 100%+ price increase. Improved income enabled the farmer to purchase a water pump for his farm, illustrating how cold chain improvement cascades into broader livelihood improvements (PREO, 2024).

SokoFresh users report 20% average income growth; spoilage reduction to 2% represents savings equivalent to approximately 28–48 additional kg per 100-kg harvest (compared to 30–40% baseline spoilage). For farmers selling 500 kg at harvest (approximately 5 bags), spoilage reduction and price improvement translate to income increases of KES 15,000–25,000 per growing season,substantial for smallholders with annual incomes of USD 500–1,500.

SokoFresh's viability relies on several sustainability factors: (1) high utilization rates (target >75% for economic viability); (2) reliable technology reducing unscheduled downtime (cold storage failures are catastrophic for perishable products); (3) payment collection through mobile money reducing transaction costs and security risks; (4) market linkage functionality driving repeat usage (if platform provides genuine market access, farmers use storage more frequently).

Operational challenges persist. Equipment security in field settings (theft/vandalism) required implementation of motion sensors and asset tracking; remote locations may lack reliable mobile network for digital transactions, limiting platform functionality; technology durability in high-humidity environments (tropical horticulture regions) requires ongoing field testing and design iteration. Market access functionality, while valuable, proves more complex than anticipated; connecting smallholder farmers to buyers requires matching mechanisms more sophisticated than simple inventory listings (buyer preferences for consistent supply, specific quality standards, batch sizes—factors varying by buyer). SokoFresh's market platform is iterating toward increasingly sophisticated matching, but this is an ongoing challenge area (SokoFresh, 2024).

ii. Integrated Pest Management (IPM) Hubs with Solar-Powered Storage: Kisii and Kakamega Sweet Potato Value Chain

A multi-partner initiative (USDA, North Carolina State University, KALRO, Baridi) deployed 10 metric tons of solar cold-storage capacity across sweet potato markets in Kisii and Kakamega counties with high sweet potato production (> 200,000 MT annually) but limited post-harvest infrastructure. Sweet potato spoilage rates exceed 40% due to inadequate storage; rapid deterioration (5–7 days shelf life at ambient temperature) forces farmers to accept low farm-gate prices or experience total loss. The intervention integrated three components: (1) IPM/production training for farmers (integrated pest management reducing pest-related losses and improving product quality); (2) collective marketing platforms enabling farmer producer groups to aggregate supply; (3) solar-powered cold storage at farmer group collection points enabling 2–4 week storage extension.

Baridi solar cold rooms (3 kWp PV, 90MJ thermal storage, 10-foot containerized facilities) were installed at six farmer collection points serving 18 farmer producer groups. Storage capacity of 10 MT enables staggered marketing; instead of selling immediately at harvest when prices are depressed, farmers could store up to 3–4 weeks, enabling access to higher market prices (20–30% price seasonality is typical for sweet potato). Cold storage temperature maintained at 13–15°C and 85–90% relative humidity conditions optimal for sweet potato storage without inducing chilling injury (which would occur at <10°C).

Farmer groups managed storage collectively, sharing costs through a service fee (KES 5–10 per 50-kg bag per day). Governance structure included formal revenue-collection protocols, transparent cost allocation, and democratized decision-making regarding storage rotation. Training in postharvest handling (washing, curing, grading) was delivered to farmer group leaders, emphasizing quality standards for different market channels (wholesale, institutional buyers, retail).

Over 18 months of operation (2023–2024), participating farmers reported: (1) spoilage reduction: spoilage during storage period <5% (compared to 40%+ at ambient temperature); (2) extended marketing window: farmers maintained market access over 4–6 weeks (compared to 2–3 days pre-storage); (3) price improvement: access to dry-season markets enabled 25–35% price premiums compared to harvest-season sales; (4) income growth: estimated annual income increase per participating farmer of KES 20,000–35,000 (15–25% improvement relative to baseline); (5) group cohesion: revenue sharing through storage fee collection and collective marketing strengthened group organization and member trust.

The Kisii-Kakamega case reveals tensions between technical success and scaling viability. Technical performance was strong; cold storage units operated reliably with <5% downtime. However, financial sustainability proved more complex. At prevailing sweet potato prices (KES

1,500–2,500 per 50-kg bag) and storage fees (KES 5–10 per bag per day for 3-week storage = KES 105–210 total cost per bag), cost-benefit ratio was favorable (price improvement exceeding storage cost). However, when market prices are weak (during high-supply periods) or when farmers misjudge market timing and store produce that subsequently declines in quality, storage becomes economically negative. Farmer groups struggled with decisions about who bears losses from poor market timing (should group share losses, or individual farmers?). These governance challenges, while addressable through training and clear protocols, proved more complex than technology provision alone.

The cost per unit capacity deployed (approximately USD 25,000–30,000 per 10-MT facility) remains a scaling constraint. Development finance or subsidy mechanisms enabled initial deployment; sustainable scaling requires either (1) private sector financing mechanisms reducing reliance on donor capital, or (2) demonstrated business case attractive to commercial lenders or equipment financing companies, neither of which currently exists at scale in Kenya for agricultural cold storage.

iii. Cross-Cutting Insights from Case Studies

Analysis of the documented case studies reveals several cross-cutting insights transcending individual technologies or value chains.

Insight 1: Business Model Matters More Than Technology.

The case studies demonstrate that technical solar cooling/storage solutions are well-established and reliable in Kenyan contexts. Quality variations persist, but core technology functionality is no longer a binding constraint. Rather, business model design, how costs are allocated, who owns assets, how revenue is collected, what services are bundled with technology determines whether adoption achieves scale and sustainability. SokoFresh's innovation was not a new solar technology but a novel business model (pay-per-use cold storage). Savanna Circuit's success relied on lease-based access rather than purchase requirements. Baridi's urban model succeeded because it targeted users (urban butchers) with demonstrable financial ability and willingness-to-pay, rather than focusing on poorest smallholders. These insights suggest that KCIC programming should emphasize business model development and innovation as co-equal to technology sourcing.

Insight 2: Application Context Determines Appropriate Technology Configuration.

Dairy cooling for pastoral ASAL regions (Savanna Circuit, Baridi early deployments) favored mobile/modular solutions reflecting geographic mobility and collectivity through cooperatives. Horticultural cold storage for smallholder vegetables (SokoFresh) favored distributed units deployed at farm/field edges, reflecting individual farm operation and seasonal harvest concentration. Urban meat market storage (Baridi) favored containerized walk-in facilities reflecting year-round operation, high throughput, and security concerns. This variation suggests no single "optimal" solar cold storage configuration; rather, technology specification must reflect application-specific constraints and opportunities.

Insight 3: Financing Mechanism Determines Adoption Scale More Than Technology Cost.

All case studies identified capital cost as a barrier overcome through alternative financing structures: Savanna Circuit's lease model, SokoFresh's pay-per-use service, Baridi's development finance mechanisms. Notably, none of the documented case studies succeeded through low-cost technology alone; they succeeded through redesigned financial mechanisms reducing upfront user capital requirements. This suggests that development of tailored agricultural solar financing products may provide higher leverage for adoption scaling than marginal technology cost reduction.

Insight 4: Gender Inclusion Improves Economic Outcomes Beyond Equity Considerations.

Kaptabuk Cooperative's deliberate inclusion of women in governance (30% female leadership) reportedly improved financial accountability; Savanna Circuit's finding that income improvement was "particularly pronounced for women and youth" suggests that value chain improvements benefit different demographic groups unequally. SokoFresh's distributed model (farm-level storage) may particularly benefit women farmers, who often manage vegetable production but face market access constraints. Gender-intentional program design, not treating gender as optional add-on—appears associated with improved sustainability outcomes.

Insight 5: Market Linkage Integration Substantially Improves Value Realization.

SokoFresh's integration of storage with market linkage functionality, Kaptabuk's deliberate processor relationship development, and Baridi's targeting of users (butchers, traders) with established market relationships all demonstrate that cold chain technology alone is insufficient; linkage to markets enabling value capture is essential. Storage without market access produces infrastructure utilization challenges (capacity underutilized if market demand is not understood); conversely, integrated cold chain + market access drives high utilization and strong financial returns. KCIC programming should emphasize market system approaches ensuring technology deployment is coordinated with market linkage development.

Insight 6: Local Manufacturing and Technical Capacity Are Critical for Sustainability.

Savanna Circuit's emphasis on local manufacturing (Nairobi-based facility, local component sourcing) created employment, reduced import dependency, enabled responsive customer support, and improved supply chain reliability. SokoFresh, similarly, manufactures units locally rather than importing. In contrast, Baridi, operating a bespoke consulting model, sources components from multiple suppliers, creating complexity. The case studies suggest local manufacturing, where feasible, strengthens sustainability more than import-dependent models.

iv. Comparative Analysis: Smallholders vs. SMEs vs. Service-Provider Models

The case studies illustrate three distinct adoption pathways that benefit different operator classes:

Smallholder-Direct Adoption Model (Savanna Circuit, partial SokoFresh deployment): Individual farmers or small farmer groups directly access technology through lease or service-fee arrangements. This model works where individual farm volumes are substantial (>50–100 kg product daily) but individual capital is insufficient (<USD 2,000). Adoption requires low-friction service provision, reliable technology, and strong market linkage to justify usage fees. Success is strongest in established market-oriented value chains (dairy, export horticulture).

SME/Processor-Centric Model (Baridi B2B, SokoFresh processor partnerships): Small and medium enterprises (processors, exporters, wholesalers) directly own/operate solar cold infrastructure. This model works where SMEs have capital access (approximately USD 5,000–20,000) and operational capacity to manage equipment. SMEs benefit strongly from technology economics (high utilization, financial ability-to-pay). This model is particularly suited to horticulture (exporters requiring cold facilities) and urban informal sectors (meat traders) with demonstrated financial viability.

Cooperative/Community Model (Kaptabuk, Kisii-Kakamega multi-partner initiatives): Farmer cooperatives or development programs own shared infrastructure. This model works where individual farmers lack capital but can collectively access financing; where product volumes justify shared equipment, and where governance capacity supports collective asset management. This model predominates in pastoral dairy regions where cooperatives are established organizational structures.

These pathways are not mutually exclusive; KCIC programming can simultaneously support technology adoption across all three models, tailoring support mechanisms (financing, training, market linkage) to each pathway's specific requirements.

3.0 BARRIERS TO INCLUSIVE SOLAR ADOPTION IN AGRICULTURAL CONTEXTS: A REVIEW OF TECHNICAL, FINANCIAL, SOCIAL, INSTITUTIONAL, AND GENDER DIMENSIONS

The transition to renewable energy in smallholder agriculture remains a critical development priority across sub-Saharan Africa. Solar photovoltaic (PV) systems present transformative opportunities for agricultural productivity, food security, and climate resilience, yet adoption rates among farmers, agricultural processors, and related enterprises remain persistently low. While technical potential is well established, a complex interplay of technical, financial, social, institutional, and gender-specific barriers continues to constrain inclusive adoption of solar-agricultural technologies (Barron-Gafford et al., 2024; Falchetta et al., 2023; World Bank, 2019). This review synthesizes evidence on these multi-dimensional constraints and identifies pathways through which gender equality can be advanced alongside solar technology deployment in agricultural value chains.

The dual research objective examined here addresses: (1) the specific barriers constraining inclusive solar adoption among smallholder farmers, agricultural processors, and enterprises; and (2) mechanisms through which solar-agricultural programming can simultaneously advance gender equality. This framing recognizes that technology adoption and social inclusion are intertwined; technologies adopted without attention to gender dynamics may reinforce existing inequalities, while deliberately gender-responsive programming can use solar transitions as entry points for broader social transformation.

3.1. Multi-Dimensional Barrier Framework: Technical Foundations

Solar energy adoption in agricultural contexts operates within a complex technical landscape. Unlike residential solar applications, agricultural solar systems must integrate with diverse production and processing activities, irrigation, water pumping, milk cooling, crop drying, mechanical processing each with distinct technical requirements and operational contexts (KCIC, 2025). Understanding technical barriers therefore requires attention to both systemic constraints affecting all applications and application-specific challenges.

i. Equipment Cost and Local Manufacturing Gaps

High capital cost represents the primary financial barrier to solar adoption. Surveys of Kenyan smallholders consistently identify equipment cost as the constraint cited by 70–80% of non-adopters, with system installation costs ranging from USD 5,000–15,000 depending on application scale and requirements, substantially exceeding typical smallholder annual income of USD 500–2,000 (KCIC, 2025). This cost structure reflects Kenya's position as an import-dependent market, with import duties, transportation markup, and retail distribution margins inflating effective prices 30–40% above international commodity prices (KCIC, 2025).

Kenya's renewable energy manufacturing sector remains underdeveloped. Domestic capacity for photovoltaic panel manufacturing is absent due to the economies-of-scale requirements and capital intensity inherent in silicon processing; local assembly operations (such as Solinc) perform only final-stage module assembly from imported cells and frames, realizing minimal cost reductions of 5–10% relative to fully imported modules (KIPPRA, 2022.; PVknowhow, 2025). Balance-of-system components inverters, charge controllers, mounting structures similarly depend heavily on imports, with only basic mounting structures feasible for local fabrication (KCIC, 2025). This manufacturing constraint perpetuates import dependency and limits the local value-chain development that could support both cost reduction and employment generation.

Recent policy interventions have addressed import tariff structures. Kenya reduced import duties on renewable energy equipment from 40% to 25% in 2024, with subsequent zero-rating for certain agricultural applications, representing a significant policy shift. However, implementation has been inconsistent, and retail price reductions have not proportionally reflected government tariff reductions due to interposed retail distribution markups (KCIC, 2025). Full zero-rating of balance-of-system components and simplified import pathways would reduce effective system costs by an estimated 8–12%, providing meaningful demand stimulus.

ii. System Sizing, Design, and Technical Expertise

A second category of technical barrier emerges from insufficient expertise in system design and sizing. Agricultural solar installations frequently suffer from either under sizing where systems cannot reliably meet energy demand or oversizing, which imposes unnecessary capital cost and operational complexity (KCIC, 2025). Poor sizing results from three reinforcing factors: farmers and technicians lack expertise in assessing agricultural energy needs; no standardized methodologies exist for agriculture-specific system design; and solar resource data remains inconsistent, with many designers relying on outdated irradiance estimates.

Application-specific design challenges illustrate complexity. For solar-powered irrigation systems, installers commonly underestimate daily water requirements, resulting in insufficient supply during peak demand periods. Farmers encountering undersized systems often supplement solar generation with diesel-powered backup, negating intended economic and environmental benefits, or reduce irrigated area, limiting agricultural productivity gains (KCIC, 2025). Similarly, milk cooling systems are frequently undersized for peak thermal loads, failing to maintain required temperatures during high-ambient periods or peak collection times. Crop drying systems show systematic mismatch between system design and product requirements, weather patterns, and diurnal temperature variation, resulting in inconsistent drying quality and farmer dissatisfaction.

Poorly designed systems generate customer dissatisfaction and reluctance to adopt replacement systems, creating negative feedback effects that undermine broader market development. International experience demonstrates that participatory design processes and farmer-centered system specifications produce better outcomes; the Renewable Energy for Smallholder Agriculture (RESA) approach promoted by IFAD emphasizes technical capacity building as integral to effective technology deployment (IFAD, 2024).

iii. Installation Quality and Safety Standards

Installation quality variability constitutes a third technical barrier with direct implications for system safety, performance, and longevity. Poor installations create multiple failure modes: electrical safety hazards including fire risk and electrocution; inadequate system performance from incorrect electrical connections, improper grounding, and inadequate system integration; accelerated equipment failure from vibration damage, moisture ingress, and thermal stress; and customer dissatisfaction undermining confidence in solar technology (KCIC, 2025).

Installation quality deficiencies stem from systemic rather than individual factors. Rural areas experience limited installer training and certification opportunities; quality standards and enforcement mechanisms for solar installations remain absent; installer economic incentives focus on cost minimization rather than quality assurance; and customers typically lack knowledge to assess installation quality. The regulatory environment contributes to this challenge: while electrical installations exceeding 1 kW require licensing from the Energy and Petroleum Regulatory Authority (EPRA), full electrician licensing requirements are burdensome for solar-specific installers, and rural enforcement is inconsistent, creating parallel markets of both licensed and unlicensed installers without corresponding quality differentiation (EPRA, 2024).

iv. Maintenance and Operational Reliability

Post-installation maintenance represents a critical yet frequently neglected technical requirement. Preventable system failures result from inadequate maintenance: photovoltaic panel accumulation of dust and dirt can reduce output by 40–50%; battery electrolyte levels left unmaintained cause sulfation and premature capacity loss; mechanical components lacking lubrication experience accelerated bearing wear; and system monitoring neglect results in delayed failure detection (KCIC, 2025). Limited technical capacity in rural areas means system failures frequently result in extended downtime spanning weeks or months as farmers await technician availability. During extended outages, farmers often return to diesel alternatives, eroding confidence in solar technology and undermining long-term adoption.

The maintenance challenge intersects with gender dimensions: responsibility for system operation may fall to household members (often women) without training or authority to make maintenance decisions or expenditures. Systematic post-installation maintenance training and technician service networks remain underdeveloped across East African agricultural zones.

v. Weather Variability and System Reliability Requirements

Solar generation inherently varies with weather conditions, creating reliability challenges for applications requiring consistent daily energy supply. Cloudy days reduce output 30–60% relative to clear-sky conditions; seasonal variation in rainfall and cloud cover affects output; and erratic rain patterns during rainy seasons can result in multiple consecutive low-generation days (KCIC, 2025). Applications like direct-drive irrigation require either system oversizing of 40–60% to maintain average output during cloudy periods, complementary water storage infrastructure, or hybrid systems incorporating diesel or grid backup. Weather variability particularly affects daytime-only applications without energy or thermal storage; applications incorporating water storage (irrigation reservoirs) or thermal storage (ice storage for milk cooling) can absorb daily generation variability within their design parameters, though appropriately sizing for weather variability increases system cost.

Weather variability intersects with climate change impacts; increasingly variable rainfall patterns and extended dry periods in pastoral and semi-arid pastoral (ASAL) zones amplify the reliability challenges for solar-dependent systems, requiring either hybrid system design or robust water storage infrastructure (Cheloti et al., 2024).

3.2. Financial Barriers and Financing Gaps

Financial barriers operate across multiple dimensions: absolute capital cost, financing terms mismatch with agricultural income patterns, income volatility and lender risk perception, and the limited development of financing products for agricultural productive-use applications.

i. The High Upfront Capital Cost Barrier and Financing Gap

The fundamental financial barrier stems from the simple mismatch between technology capital costs and smallholder asset base. System costs of USD 5,000–15,000 far exceed the typical smallholder's ability to finance from farm income alone. While lifecycle economics are strongly favorable total ten-year costs are substantially lower than diesel alternatives, the upfront capital barrier is insurmountable without external financing. This mirrors broader patterns documented in renewable energy financing literature: high upfront costs present the primary barrier to adoption of renewable energy technologies by low-income households and enterprises (Griffith-Jones, 2018; World Bank, 2022).

Formal financial institutions have historically been reluctant to finance agricultural solar systems. Commercial banks and microfinance institutions cite several risk factors: perceived high risk from unfamiliar technology and limited historical repayment data; weak collateral valuation (solar systems cannot be easily repossessed; used systems have poorly developed secondary markets); mismatch between available loan terms and technology payback periods (banks offer 1–3 year terms while solar system payback extends 5–7 years); and high interest rates for agricultural borrowers (14–20% annually) that reduce system affordability relative to diesel alternatives (KCIC, 2025; World Bank, 2022).

This financing gap perpetuates a vicious cycle: without financing options, only relatively affluent farmers adopt solar; limited adoption generates insufficient demonstration effects and farmer-to-farmer learning; small market sizes discourage financial institutions from developing products, maintaining financing constraints.

ii. Financing Terms and Mechanisms Mismatch

Even where financing becomes available, terms frequently mismatch the agricultural and technology context. Loan term mismatch represents a concrete example: a farmer with a 7-year system payback period cannot safely borrow at a 2–3 year term, as required debt service exceeds cash flow during years 1–2. Loan size mismatch is equally problematic: microfinance institutions typically provide maximum loans of USD 1,000–2,000, insufficient for complete solar systems; farmers must combine multiple loans, increasing complexity and cost. Seasonal cash flow patterns create a third mismatch: agricultural income is concentrated around harvest periods, typically once or twice annually, while banks typically require fixed monthly payments (KCIC, 2025). Collateral requirements present a fourth barrier: conventional bank lending requires collateral (land titles, productive assets) that smallholders frequently lack or are unwilling to pledge against productive equipment.

Recent innovations in development finance have demonstrated viable alternatives. Concessional lending specifically structured for solar-agricultural systems, with 8–10% interest rates, longer terms (5–7 years), and seasonal payment schedules, have improved access significantly. Pay-as-you-go (PAYG) models integrated with mobile money enable farmers to make weekly or bi-weekly payments (USD 5–20) rather than lump-sum purchases, reducing upfront barriers. Equipment-secured lending models where systems themselves serve as collateral reduce collateral requirements (KCIC, 2025). These innovations are not yet widely available but represent viable models for scaling.

iii. Income Volatility, Risk, and Agricultural Uncertainty

Income uncertainty fundamentally constrains farmer access to credit. Smallholder agricultural income is volatile due to commodity price fluctuation driven by global markets, production variability from weather and pest/disease impacts, and climate shocks causing complete production loss (KCIC, 2025). This income volatility increases perceived borrower risk; lenders respond by increasing interest rates, requiring larger collateral, and offering shorter terms all making agricultural financing unaffordable during normal years. Income smoothing through agricultural insurance products protecting against production or price shocks can reduce lender risk perception and improve financing access. Flexible repayment mechanisms allowing payment deferrals during crisis periods reduce default pressure. Household economic diversification where creditworthiness assessment considers not just agricultural income but also off-farm employment, small business income, and remittances can expand the borrower base suitable for productive-use financing (KCIC, 2025).

iv. Limited Development of Financing Products for Productive-Use and Group Assets

A final financing barrier reflects the limited development of microfinance products for productive-use applications, particularly shared community assets. Microfinance institutions and commercial banks traditionally finance working capital (seeds, fertilizers) and short-term agricultural inputs; equipment financing distinct from production credit is less developed. Agricultural financial products rarely extend to long-term capital assets like solar systems, positioning solar financing as a frontier application requiring dedicated product development.

Group-owned infrastructure presents additional complexity: banks prefer lending to individuals; group lending involves more complex governance structures and monitoring requirements; cooperatives often struggle to access capital for shared equipment (KCIC, 2025). This financing gap is particularly consequential in pastoral and semi-pastoral regions where cooperatives form the primary organizational structure for milk collection and marketing. Without accessible financing for cooperative-owned solar milk collection centers, technology adoption remains constrained even where technical and policy conditions favor expansion.

3.3. Social and Cultural Barriers

i. Limited Awareness and Information Gaps

Large segments of the rural population lack basic awareness of solar energy as a technology option. Surveys indicate 70–80% of smallholders in pastoral and semi-pastoral ASAL regions lack awareness of locally available solar systems (KCIC, 2025). Information gaps extend beyond simple awareness to encompass misconceptions about economics, technical function, and reliability. Many farmers misunderstand payback periods and lifecycle costs; some harbor technical misconceptions such as beliefs that solar systems generate power at night or that storage batteries require continuous replacement. Limited understanding of system reliability leads some farmers to discount solar technology based on reports of unreliable systems without distinguishing between design faults and operational/maintenance failures (KCIC, 2025).

These information gaps drive ineffective adoption decisions based on incomplete information, reducing adoption rates and increasing customer dissatisfaction. When farmers adopt systems with unrealistic expectations, for example, assuming 24/7 power generation without storage, inevitable disappointment generates negative word-of-mouth that undermines broader market development (The Conversation, 2016). International evidence demonstrates that information provision alone is insufficient; effective information dissemination requires multiple channels and peer demonstration effects (Shrestha et al., 2023).

ii. Cultural Perceptions, Technology Familiarity, and Social Conformity

Solar energy technology, though rapidly expanding, remains relatively new in rural agricultural contexts. Cultural factors influence adoption decisions: traditional farmers possess deep expertise in conventional technologies (diesel engines, mechanical generators); solar represents unfamiliar technology creating psychological resistance. Some farmers perceive solar systems as complex, believing operation and maintenance require engineering expertise and are beyond farmer capability. Negative experiences with failed previous technologies (failed aid-provided initiatives, unreliable equipment) generate skepticism and technology mistrust that extends to new technologies including solar (Opiyo, 2016; Munro et al., 2019).

Social conformity significantly influences technology adoption in many communities. If community leaders or respected farmers adopt solar systems and demonstrate benefits, adoption spreads through peer effects. Conversely, if early adopters experience problems or influential community members resist adoption, diffusion slows substantially. This social conformity effect means early adoption is particularly critical; successful early adopter demonstrations generate positive feedback amplifying adoption (Opiyo. N., 2019).

iii. Gender Dynamics and Intra-Household Decision-Making

Gender roles significantly shape agricultural technology adoption and benefit capture. In most Kenyan agricultural households, men typically own land and agricultural equipment; women's asset ownership is substantially more limited. Household decisions regarding major productive investments, including energy investments are typically male-dominated, even when women perform substantial productive labor. Women conduct the majority of post-harvest handling, processing, and packaging work; perform most water collection and animal watering labor; and bear disproportionate responsibility for cooking and heating using traditional fuels. Yet this substantial productive and domestic work often does not translate into decision-making authority over corresponding energy investments (Shrestha et al., 2023; Winther et al., 2018).

This gender gap in decision-making creates paradoxes: women experiencing energy burdens firsthand may recognize and advocate for solar investment but lack authority to pursue it. Conversely, men (not directly experiencing specific energy burdens) may not prioritize energy investments, resulting in adoption rates below what would maximize household welfare. International evidence demonstrates that women with control over income and assets reallocate resources toward household well-being priorities including improved energy access, water, and nutrition (Bryan and Garner, 2022; Njuki et al., 2014). When solar systems are deployed without explicit attention to gender dynamics, benefit capture may be unequal, men may capture income benefits even when women provide the productive labor that generates those returns.

This gender dynamic in decision-making has direct implications for technology adoption; programmatic attention to household engagement rather than individual-level outreach can improve both adoption rates and equitable benefit distribution.

3.4. Institutional and Policy Barriers

iv. Weak and Inconsistent Policy Implementation

While Kenya has adopted formal renewable energy policy frameworks (Energy Act 2019, National Energy Policy 2025–2034), implementation remains inconsistent, creating uncertainty for technology investors and users. Import duty changes announced in 2024 reducing renewable energy equipment tariffs from 40% to 25% and subsequently zero-rating certain agricultural applications, have been inconsistently implemented; some balance-of-system components continue subject to full duty despite policy intent (KCIC, 2025). Net metering regulations adopted in 2024 remain incomplete in implementation; regulatory protocols for net metering application and payment mechanisms are not finalized, creating uncertainty for potential grid-connected adopters (EPRA, 2024; Muhoro & Gitonga Associates, 2025).

Agricultural and energy policies remain siloed with minimal coordination; agricultural energy strategies are not integrated across relevant ministries (Agriculture, Energy, Water, and Finance). County governments implement varying interpretations of national policies, creating geographic inconsistency (KCIC, 2025). This policy fragmentation and inconsistent implementation creates uncertainty that discourages both private sector investment and farmer adoption.

v. Licensing, Regulatory, and Quality Standards Barriers

Agricultural solar system installation is nominally subject to electrical licensing requirements (installations >1 kW require Energy and Petroleum Regulatory Authority licensing), yet implementation is irregular. Full electrician licensing is expensive and time-consuming; solar-specific installers often find requirements burdensome relative to typical system installation labor. Rural enforcement of licensing requirements is sporadic and inconsistent; both qualified and unqualified installers operate in parallel without clear quality differentiation, creating market confusion.

Equally important, specific agricultural solar quality standards are absent. While licensing addresses basic electrical safety, agricultural solar systems require standards addressing design adequacy for applications (irrigation sizing, cooling adequacy, drying performance), mechanical and structural integrity for rural environmental conditions, and long-term reliability. The absence of quality standards means poor-quality installations are not systematically prevented; customer capacity to identify quality installation problems is limited (SNV, 2021).

vi. Weak Inter-Agency Coordination and Institutional Fragmentation

Agricultural energy represents a cross-sectoral issue falling across multiple government institutions with overlapping but uncoordinated mandates. The Ministry of Agriculture focuses on productivity but typically has limited energy expertise. The Ministry of Energy drives energy policy but has limited agricultural focus. The Energy and Petroleum Regulatory Authority regulate energy sector actors but has limited agricultural stakeholder engagement. County governments implement nationally-delegated functions with varying capacity and coordination mechanisms. This institutional fragmentation results in missed coordination opportunities (agricultural extension services not trained in solar energy; energy advisory not integrated with agricultural programming), policy misalignment (energy policies not tailored for agricultural contexts), and institutional accountability gaps (no single agency identified as responsible for agricultural energy outcomes) (SNV, 2021; ACTS, 2025; GIZ, 2025).

This fragmentation particularly affects pastoral and semi-pastoral ASAL zones where institutional capacity is limited; county governments in these areas often lack adequate staffing and expertise to coordinate agricultural energy programming, limiting both policy consistency and technical support availability. (SEI, 2025; Kenya Climate Smart Agriculture Strategy, 2017).

3.5. Gender-Specific Barriers and Opportunities for Gender-Transformative Solar Programming

While gender dimensions intersect with all barrier categories discussed above, gender-specific barriers deserve explicit attention as foundations for gender-transformative programming.

i. Asset Ownership, Collateral Access, and Financing Constraints

Women's capacity to invest in solar systems is constrained by multiple factors related to asset access and economic agency. Land title insecurity and limited equipment ownership constrain women's access to collateral-based financing. Women's income is typically lower and more volatile than men's income, reducing personal borrowing capacity. Where households experience economic stress, women's income is frequently prioritized for immediate household consumption needs rather than productive investment. Time constraints from women's domestic and care responsibilities (water collection, fuelwood gathering, cooking, childcare) limit time available for technology learning, maintenance training, and system operation (Shrestha et al., 2023).

These asset and economic constraints can be partially addressed through financial innovation: group-based lending reduces collateral requirements through group liability; gender-responsive loan design can incorporate smaller loan sizes, flexible repayment schedules, and reduced collateral requirements; women's cooperative financing programs specifically structured for group asset ownership; and microfinance products explicitly designed for women-led enterprises including solar-powered processing equipment. (Power Africa, 2023; Accion, 2025; World Bank, 2022.)

ii. Gendered Division of Labor and Differential Energy Burdens

Women bear disproportionate energy burdens in agricultural value chains. Women conduct the substantial majority of post-harvest labor including product cleaning, processing, packaging, and value addition activities often constrained by energy poverty. Women typically collect water for household use and livestock watering; solar-powered water pumping systems offer direct labor reduction for women's water-collection work. Traditional biomass energy collection (fuelwood, charcoal) falls predominantly on women, creating health burdens from smoke exposure and time burdens from collection labor. Yet these dimensions of women's energy burden, post-harvest processing constraints, water collection workload, fuelwood collection labor, are not consistently recognized in technology assessment and system design.

Gender-transformative solar programming must explicitly integrate women in energy needs assessment, ensuring women's priorities (reducing post-harvest labor, enabling income-generating processing activities, reducing fuelwood collection labor) drive system design. Prioritizing women-led solar enterprises (cooperative cold storage operations, solar-powered drying facilities for high-value products, solar-powered water systems) addresses women's specific energy needs while enabling income generation and economic empowerment. Gender budgeting ensuring adequate KCIC resource allocation to gender-focused programming (women's training programs, women's entrepreneur support, women's cooperative financing) proportional to women's agricultural participation strengthens institutional commitment to gender equality.

iii. Women's Leadership and Representation in Solar Technology Systems

International evidence demonstrates that women's participation in solar technology deployment is significantly lower than men's participation. Ashoka's recent survey of 140 innovators in East African smallholder farming and renewable energy found only one-third were women, a marked gender disparity considering women comprise a substantial share of agricultural labor (Ashoka East Africa, 2025). In solar training and technician development programs, women remain substantially underrepresented; women comprise less than 20% of solar installer trainees in most East African programs (KCIC, 2025).

This gender underrepresentation in technology professions perpetuates multiple problems: women miss economic opportunities in growing solar sectors; male-dominated technical professions continue reinforcing gender stereotypes; and technology systems designed and maintained predominantly by men may not adequately address women's specific needs and preferences. Deliberately recruiting women into technician training programs (targeting 40%+ representation), supporting women solar entrepreneurs, and creating career pathways for women in solar energy sectors addresses both gender equity and system design quality objectives.

3.6. Application-Specific Context and Adoption Pathways

Adoption barriers and corresponding interventions vary substantially depending on application type and geographic context.

i. Off-Grid and Pastoral/Semi-Pastoral ASAL Contexts

In pastoral and semi-pastoral ASAL counties (Samburu, Kajiado, Narok, Turkana), grid electricity is sparse or absent. Diesel generators constitute the de facto energy source for any powered operations, imposing high operating costs and environmental externalities. This creates a two-part constraint: absence of energy access itself, and absence of energy-dependent infrastructure (milk cooling at collection points, cold storage, mechanized processing facilities). Livestock production remains substantial in these zones (cattle, goats, camels), representing significant protein production potential; yet limited milk marketing infrastructure constrains market participation and income generation.

Samburu County exemplifies this pattern: despite substantial livestock populations, only one functional dairy cooperative and minimal cooling facilities exist; modern processing capacity is essentially absent (Cheloti et al., 2024). In such contexts, solar energy is explicitly identified as the enabling technology for milk collection infrastructure, preservation, and market development. Development programs including dream Hub have begun pilot-scale deployments of solar-powered milk collection centers (MCCs) in ASAL regions, bundling solar equipment with cooperative capacity building (operator training, quality standards, maintenance protocols) and market linkage support (Cheloti et al., 2024; Wangai et al., 2024).

Success factors in these contexts include: (1) cooperative-managed infrastructure with revenue-generating fee-for-service business models ensuring financial sustainability; (2) integration of technical capacity building with equipment deployment; (3) explicit attention to institutional governance and cost-sharing mechanisms within cooperatives; and (4) market linkages connecting MCCs to processors and urban milk buyers. In these off-grid contexts, solar-diesel hybrids often provide optimal technical solutions, allowing solar to provide primary power during high-generation periods while diesel backup addresses weather variability and reliability requirements.

ii. Grid-Connected High-Potential Agricultural Zones

In well-electrified high-potential agricultural zones (Nyeri, Bungoma, Taita Taveta, Siaya, Kirinyaga), grid infrastructure exists but power reliability, quality, and affordability remain significant operational constraints. Agro-processing facilities experience frequent outages and voltage fluctuations disrupting cooling, heating, and mechanical equipment operation, limiting processing capacity utilization and forcing reliance on costly diesel backup (Wanjala et al., 2024). County-level policy recommendations increasingly emphasize grid-connected solar plus battery/hybrid systems as critical to unlock processing potential and improve economic viability (Wanjala et al., 2024; Mutai et al., 2025). Energy costs continue rising; solar PV plus grid hybrids increasingly offer economically attractive alternatives even in well-electrified zones.

In these zones, solar adoption has traditionally focused less on production-point milk cooling (where farm sizes are smaller and cooperatives less prevalent) and more on processing facilities and cooperative infrastructure. However, this pattern is shifting; even in well-electrified areas, solar plus grid hybrids are increasingly economically attractive as grid tariffs increase and alternative energy reliability remains poor. Financing and business model development are the binding constraints in these contexts rather than awareness or technical feasibility; agro-processors seeking to adopt clean energy transition solutions frequently cannot access tailored financing from conventional financial institutions, creating a market gap that dedicated green finance mechanisms can address (FSD Kenya, 2025).

3.7. Pathways Toward Gender-Transformative Solar-Agricultural Programming

Advancing gender equality through solar-agricultural programming requires explicit integration of gender analysis into all program components rather than treating gender as an add-on element.

Household Engagement Rather Than Individual Targeting. Outreach and promotion should engage households as decision-making units rather than targeting individuals. Both men and women should participate in technology discussions, benefits assessment, and system design processes. Gender-specific benefits communication, highlighting benefits important to women (reduced workload, income opportunities, health improvements) alongside benefits important to men (farm productivity, income generation, competitive advantage) ensures full household buy-in for technology adoption.

Women's Organizational Emphasis. Prioritizing women's groups and all-women producer organizations (cooperatives, dairy groups, horticultural enterprises) for solar programming reduces intermediary barriers and concentrates resources where gender equality gains are most feasible. Women's cooperatives show evidence of greater gender equity in benefit distribution and decision-making; allocation of solar financing and technical support resources toward women's organizations accelerates inclusion.

Women's Economic Leadership. Supporting women solar entrepreneurs, female technicians, and women cooperative leaders creates multiple benefits: women gain economic opportunity and income; female role models encourage other women's participation; women-led solar businesses often serve women customers more effectively. Deliberate recruitment of women into solar technician training (targeting 40%+ representation) and entrepreneur programs develops local women-led solar enterprises.

Gender-Responsive Financing Products. Financial products explicitly designed for women smaller loan sizes, flexible repayment schedules matched to income seasonality, reduced collateral requirements, women's group-based lending—significantly improve women's access to capital for solar productive-use applications. Development of financing specifically for women-led enterprises (solar-powered cold storage, processing equipment, water systems) addresses both financing gaps and gender inclusion objectives.

Integration of Energy and Gender in Needs Assessment and Programming. Participatory needs assessment processes that explicitly investigate how gender relations shape energy needs, technology preferences, and benefit distribution identify context-appropriate programming approaches. Energy needs assessments should disaggregate energy needs by gender, recognizing that women and men may have different priorities and constraints. Integration of gender-focused extension and cooperative development support with solar technology deployment ensures gender dimensions are addressed systematically rather than episodically.

4.0. ENABLING FACTORS FOR SUCCESSFUL AND INCLUSIVE SOLAR-AGRICULTURAL DEPLOYMENT

While barriers to solar adoption are substantial and multi-dimensional, documented evidence from Kenya and the broader East African context increasingly identifies specific enabling factors that, when systematically deployed, accelerate inclusive adoption and improve sustainability outcomes. This section synthesizes enabling factors across four critical dimensions, technology, financing mechanisms, support services, and policy frameworks, identifying how each dimension contributes to overcoming barriers identified in preceding sections.

4.1. Technology Enabling Factors

i. Modular and Application-Specific System Design

Successful solar-agricultural adoption requires technology configurations tailored to specific agricultural applications and operational contexts rather than standardized, one-size-fits-all designs. Case study evidence demonstrates this principle clearly: Savanna Circuit's mobile, modular milk chillers succeeded in pastoral dairy systems precisely because mobility matched the geographic reality of dispersed collection points; conversely, fixed-infrastructure designs had failed in these contexts. Similarly, SokoFresh's distributed, farm-level cold storage units proved more appropriate for smallholder horticulture than centralized facilities designed for institutional buyers.

Modular system design offers multiple sustainability advantages. Modularity enables staged capacity expansion matching business growth; farmers or cooperatives need not finance full capacity upfront, reducing initial capital barriers. Modular architecture simplifies maintenance and component replacement; individual system failures do not compromise entire installations. For women and youth users with limited prior technical experience, modular systems create lower operational complexity thresholds, improving accessibility (Savanna Circuit, 2023).

Enabling mechanism: Technology development programs (innovation hubs, research institutions, manufacturer associations) should systematize design processes ensuring agricultural solar systems are explicitly matched to user context, production scale, seasonality patterns, geographic factors, existing infrastructure rather than defaulting to imported standardized designs. KCIC's technology validation programs and university-based research centers can coordinate this matching process, documenting design specifications for common agricultural applications (irrigation sizing for crop types, cooling adequacy for dairy vs. fish vs. meat, drying specifications for regional products) (KCIC, 2025).

ii. Reliability and Oversizing for Weather Variability

Case study evidence repeatedly shows that customer satisfaction and repeat adoption depend fundamentally on reliable system performance. Users who experience system failures, particularly during critical periods (dry seasons, peak production periods), rapidly lose confidence, generating negative word-of-mouth that undermines broader market adoption. Baridi's deliberate design choice to oversize thermal storage (90MJ capacity) for robust operation during extended cloudy periods directly reflects lessons from earlier solar failures in off-grid settings.

Reliability is particularly critical for applications without alternative backup options. Milk cooling systems that fail during peak collection periods result in spoilage and farmer income loss; farmers experiencing this loss are unlikely to maintain system investment through repairs or recommend systems to peers. In contrast, systems designed with sufficient redundancy and weather-tolerance build customer confidence and generate positive demonstration effects.

The reliability imperative creates a design principle: agricultural solar systems should be oversized 15–25% relative to average daily requirements to accommodate weather variability and operational peaks, prioritizing customer satisfaction and demonstration effects over marginal cost reductions (Baridi, 2023; Savanna Circuit, 2023).

Enabling mechanism: Solar system design standards for agriculture should incorporate reliability requirements and weather-tolerance specifications rather than minimum-cost configurations. Extension services, technician training programs, and equipment dealers require clear guidance on appropriate sizing for regional climate patterns (dry/wet seasons, rainfall variability, cloud cover seasonality). County-level climate data integration with system design toolkits enables context-appropriate sizing guidance.

iii. Local Manufacturing and Supply Chain Development

Savanna Circuit's emphasis on local manufacturing (Nairobi-based facility, locally-sourced components where feasible) generated multiple enabling advantages: reduced equipment costs through elimination of import margins; improved maintenance supply chains enabling rapid technician access to spare parts; employment generation locally; reduced foreign exchange requirements; improved customer confidence in locally-manufactured products (Savanna Circuit, 2023).

Local manufacturing creates additional market development advantages. When equipment is manufactured domestically, financial flows remain within the economy, supporting broader economic development. Local manufacturers understand market-specific requirements and can innovate for local conditions; manufacturers also provide employment for technicians, engineers, and skilled trades, contributing to broader energy sector development (KCIC, 2025).

The case studies suggest local manufacturing is particularly valuable for balance-of-system components (mounting structures, thermal storage systems, certain wiring and control systems) where economies of scale are less pronounced than for photovoltaic panels. Full panel manufacturing remains infeasible for Kenya at current market scales; however, final-stage assembly and customization can create local value addition.

Enabling mechanism: Government procurement policies should prioritize locally-manufactured components where quality and cost are competitive; this creates stable demand supporting local manufacturing investment. Trade policy reform (tariff reductions for component inputs) reduces manufacturing costs, improving competitiveness relative to imported finished systems. Industrial parks and manufacturing support programs can facilitate solar manufacturing cluster development. Kenya Industrial Research and Development Institute (KIRDI) and similar institutions can provide technical support to manufacturers optimizing designs for local conditions (Mutai et al., 2025).

4.2. Financing Mechanisms Enabling Factors

i. Diversified Financing Models Matched to User Context

The case studies demonstrate that no single financing mechanism serves all adopter classes effectively. Smallholder farmers with limited collateral require different financing structures than SMEs with asset bases; pastoral cooperatives require different products than individual horticulturists. Successful scaling has emerged through financing product diversification:

Lease-based models (Savanna Circuit): Reduce upfront capital requirements by converting capital expenditure to operational expenditure through monthly service fees. Particularly effective where technology ownership and maintenance responsibility is complex for rural users; leasing transfers these responsibilities to the equipment provider/financier. Typical terms: 8–10% effective interest rates incorporated in service fees; 5–7 year effective tenor; monthly payment structures aligning with seasonal cash flow (flexible payment deferrals during low seasons) (Savanna Circuit, 2023).

Pay-per-use models (SokoFresh, Baridi): Users pay fees based on usage (cold storage fees per kg-day, fuel replacement fees per unit), eliminating upfront capital requirements entirely. Effective where usage is variable or uncertain; users pay only for capacity actually utilized. Requires reliable payment collection (mobile money integration proves critical); creates strong incentives for asset provider to maintain equipment quality (customer dissatisfaction reduces utilization and revenue). Typical tariffs: USD 0.10–0.20 per kg-day for cold storage (smallholder-oriented), USD 0.05–0.15 per unit for bulk users, enabling 20–30% annual revenue returns at high utilization rates (SokoFresh, 2024; Baridi, 2023).

Concessional term financing (KCIC PUSE program, development finance): Direct loans with 8–10% interest rates, 5–7 year terms, and flexible collateral requirements specifically structured for solar-agricultural systems. Requires government/donor capital or development finance institution support but enables ownership pathways for cooperatives and enterprises with moderate capital access. Effective where financing institutions can accept modest risk premiums relative to commercial lending; typical loan sizes USD 10,000–100,000 (KCIC, 2025).

Blended finance (equity + concessional debt): Impact investors providing quasi-equity capital enabling enterprises to de-risk early operational phase; combined with concessional debt financing equipment expansion once business model is validated. Particularly valuable for innovative enterprises (SokoFresh, Baridi) demonstrating new business models; enables scaling beyond what concessional debt alone supports (PREO, 2024).

Enabling mechanism: Financial sector policy reform should enable financing product diversification through regulatory flexibility (mobile money payment integration, equipment-based collateral acceptance, seasonal repayment scheduling). Development finance institutions should deploy capital through multiple instruments (concessional loans, guarantees, equity co-investment) rather than single-instrument approaches. Commercial bank capacity building on agricultural renewable energy financing reduces interest rate premiums and improves product design (FSD Kenya, 2025).

ii. Risk Mitigation Instruments

Lender risk perception represents a substantial barrier to credit availability for agricultural enterprises. Risk mitigation instruments, insurance products, credit guarantees, cash flow support mechanisms directly reduce lender risk, improving credit availability and terms.

Weather-indexed agricultural insurance: Protects borrowers against production loss from drought or excessive rainfall, enabling predictable income streams supporting debt service. Protects lenders against borrower default from climate shocks. Increasingly available in Kenya through various providers; integration of insurance with renewable energy financing (bundled products) reduces overall cost and improves lender comfort with agricultural lending.

First-loss credit guarantees: Development finance institutions provide partial guarantee (covering first 20–30% of loan losses) to commercial lenders, enabling risk-sharing that improves lender willingness to offer agricultural renewable energy credit. Guarantees cost less than full credit provision while meaningfully improving market development (World Bank agricultural finance programs utilize this model).

Cash flow support during establishment: Equipment providers (through lease models) or development programs (through grant/subsidy combinations) absorb first-year cash flow shortfalls while farmers/enterprises establish operational systems and realize benefits. Particularly important for initial 12–24 months when technology is new and operators are learning; reduces borrower default risk substantially (Savanna Circuit lease model incorporates this implicitly through initial service fee structures allowing operational ramp-up) (Savanna Circuit, 2023).

Enabling mechanism: Insurance product development requires coordination between agricultural insurance providers and renewable energy financing institutions; bundled products reduce transaction costs. Credit guarantee programs require government/donor capital alongside commercial bank participation; Central Bank regulatory support enables guarantee instruments as acceptable collateral substitutes. Development finance institutions should pilot risk mitigation product combinations, documenting outcomes to support scaling (FSD Kenya, 2025).

iii. Equity Considerations in Financing Product Design

Smallholders, women, youth, and pastoral communities face systematically different financing barriers requiring targeted product features:

Women-focused financing: Smaller initial loan sizes (USD 2,000–5,000 vs. standard USD 10,000+ minimums); flexible collateral requirements (group-based collateral, equipment-based lending); women-group-based lending (reducing individual collateral/creditworthiness requirements); repayment schedules aligned with women's income seasonality (often different from men's income patterns due to differentiated value chain roles). Targeting women-led enterprises (solar-powered processing equipment, water systems, cooperative cold storage) directly addresses both financing gap and gender inclusion objectives (Bryan and Garner, 2022).

Youth-focused financing: Training programs teaching financial literacy, business planning, and technology operation before access to credit; mentorship linking youth entrepreneurs with experienced solar enterprises; smaller initial financing enabling entry-level system deployment with expansion potential (modular systems particularly valuable). Youth representation in technician training programs (targeting 20–30% youth trainees) creates career pathways in growing solar energy sector, addressing youth employment constraints (KCIC, 2025).

Smallholder cooperatives: Cooperative-level financing distinct from individual-farmer lending, recognizing governance structures and collective asset management; longer payback periods (7–10 years) reflecting capital-intensive infrastructure investments; flexible revenue models accommodating seasonal production variability. Cooperative Savings and Credit Associations (SACCOs) can develop specialized solar financing products leveraging existing cooperative relationships and governance structures.

Enabling mechanism: Microfinance institutions and commercial banks require targeted training on women/youth/smallholder-appropriate product design; Central Bank can incentivize product development through interest rate subsidies or guarantee programs for products serving underserved populations. KCIC and development finance institutions should pilot gender/youth/smallholder-targeted financing products, documenting outcomes and lessons learned for market scaling (FSD Kenya, 2025).

4.3. Support Services and Capacity Building Enabling Factors

i. Post-Installation Technical Support and Maintenance Systems

Technical support availability after system installation proves critical for sustained operation and customer satisfaction. Case studies reveal that extended system downtime (weeks or months awaiting technician availability in remote areas) drives customer frustration and system abandonment. Savanna Circuit's investment in geographic technician distribution and predictive maintenance systems (remote monitoring via MaziwaPlus system) directly addresses this challenge through proactive maintenance and rapid technician response (Savanna Circuit, 2023).

Effective post-installation support requires: (1) local technician networks with geographic coverage enabling 48-72 hour response times for emergency issues; (2) spare parts availability at community level reducing lead times for component replacement; (3) preventive maintenance schedules reducing emergency failures; (4) customer training on routine maintenance operations that users can perform (panel cleaning, electrolyte checking, basic troubleshooting); (5) remote diagnostic capacity (IoT-enabled systems) enabling problem diagnosis before technician dispatch.

For women and youth users, support systems must be particularly accessible. When system operation and maintenance authority falls to household members without training, support service availability directly affects system utilization and benefit realization. Inclusive support systems should explicitly train women and youth operators, providing them authority and knowledge to make maintenance decisions (Kaptabuk Cooperative governance model demonstrates this—integrated training in solar operations and maintenance built local women's technical capacity) (Kaptabuk, 2019–2024).

Enabling mechanism: County governments should establish technician training hubs providing 3–6 month certification programs in solar installation and maintenance; certification standards (developed by EPRA and industry associations) ensure quality assurance. Equipment manufacturers and service providers should contractually commit to spare parts availability and response time standards; franchise or agency models can extend technician networks into remote areas. Community technician models (training community members as basic maintenance providers) reduces dependence on specialized technicians for routine maintenance (KCIC, 2025).

ii. Farmer/Operator Training and Capacity Building

System owners require training in operation, basic maintenance, system optimization, and business management (for service providers). Training effectiveness depends on context-appropriate content delivery:

Practical, hands-on training embedded in technology deployment proves more effective than classroom instruction alone. Training-while-doing (learning concurrent with system operation) enables practitioners to understand system performance under varied weather conditions and operational loads. Farmer Field Schools and demonstration plots provide effective implementation mechanisms (IFAD, 2024).

Local-language training materials adapted to user literacy levels and cultural contexts improve comprehension and retention. Visual learning materials (diagrams, videos) often prove more accessible than text-based materials for farmers with limited formal education. Mobile-based learning platforms (M-Learning) increasingly provide scalable training delivery mechanisms in Kenya's mobile-connected rural areas (KCIC, 2025).

Women-inclusive training requires explicit attention. Traditional training programs often default to male participants; where women perform substantial maintenance labor (particularly for household water systems, post-harvest processing equipment), women's participation in training is essential for system sustainability. Women-only training cohorts, peer learning groups, and women-led farmer field schools can build women's confidence and participation (Ashoka East Africa, 2025).

Enabling mechanism: Agricultural extension services (Ministry of Agriculture County officers, veterinary extension for pastoral zones) can be trained and resourced to deliver solar training alongside existing agricultural advisory services. KCIC and technician certification programs should develop standardized training curricula and materials; county-level adaptation enables local language and context-appropriate delivery. Cooperative/farmer organization training programs can embed solar technology training within existing group meeting structures, reducing training access barriers (KCIC, 2025).

iii. Business Development and Market Linkage Support

Technical capacity alone is insufficient; entrepreneurs and cooperatives require business development support to translate technology deployment into sustainable enterprises. SokoFresh's success substantially reflects business model innovation and market linkage integration; Kaptabuk's sustainability reflects deliberate market linkage development with premium processors (PREO, 2024; Kaptabuk, 2019–2024).

Business development support encompasses: (1) business planning and financial management training; (2) market research support identifying customer demand and pricing opportunities; (3) product quality and standardization support (enabling premium market access); (4) linkage facilitation connecting suppliers, distributors, and customers within value chains; (5) cooperative governance and member benefit distribution support ensuring equitable benefit sharing and member motivation.

For women and youth entrepreneurs, targeted business development support addresses additional barriers. Women entrepreneurs often lack networks enabling market access; peer learning groups and mentorship by successful women entrepreneurs can build networks and confidence. Youth entrepreneurs lack business experience; structured business planning and mentorship programs substantially improve enterprise sustainability.

Enabling mechanism: KCIC's GreenBiz and enterprise acceleration programs should expand capacity, offering advanced business development support alongside technology support. County-level business development services (attached to county trade offices or agricultural departments) can provide basic business advisory services to rural entrepreneurs. Cooperative development programs (Ministry of Industry, Cooperative Development cooperatives support staff) should integrate renewable energy enterprise development into broader cooperative capacity building. Private sector associations (Kenya Private Sector Alliance renewable energy sector board, agriculture commodity associations) should establish peer learning and mentorship networks linking established enterprises with emerging entrepreneurs (KCIC, 2025).

4.4. Policy and Regulatory Enabling Factors

i. Integrated Policy Frameworks Linking Energy, Agriculture, and Climate

Agricultural solar deployment is constrained by siloed policy frameworks where energy policy, agricultural policy, and climate policy develop independently without integration. Policy integration explicitly linking renewable energy expansion to agricultural productivity and climate adaptation objectives creates enabling policy environments.

Kenya's National Energy Policy (2025–2034) and National Climate Change Action Plan (2023–2027) increasingly reference agricultural renewable energy as priority application, representing positive policy integration. However, implementation mechanisms remain fragmented; coordinating mechanisms linking Ministry of Energy, Ministry of Agriculture, and Ministry of Water across renewable energy projects remain underdeveloped (Mutai et al., 2025).

County-level integration is particularly critical. Counties are simultaneously responsible for: (1) energy sector coordination (delegation from Ministry of Energy); (2) agricultural extension and productivity support; (3) climate action planning and financing. Weak coordination at county level means agricultural solar initiatives compete for resources rather than reinforce each other. Conversely, counties with strong inter-departmental coordination (Kisii, Kakamega, Makueni) show stronger solar-agricultural program implementation (Mutai et al., 2025).

Enabling mechanism: National government should establish inter-ministerial coordination mechanism (e.g., Agricultural Renewable Energy Taskforce) with representation from Ministry of Energy, Ministry of Agriculture, Ministry of Water, Ministry of Finance, and relevant state corporations. This mechanism should coordinate policy development, financing, and capacity building across sectors. County governments should establish similar inter-departmental coordination committees, with funding and technical support from national government to strengthen implementation capacity (Mutai et al., 2025).

ii. Quality Standards and Regulatory Clarity

Regulatory uncertainty around solar installation quality, safety, and performance creates market confusion and customer vulnerability to poor-quality systems. Establishing clear, agriculture-specific quality standards addresses this enabling barrier.

Current regulatory framework addresses basic electrical safety (EPRA licensing for installations >1 kW) but lacks specific agricultural solar system standards addressing: (1) design adequacy for specific applications (irrigation sizing methodologies, cooling adequacy specifications); (2) mechanical/structural integrity for rural environmental conditions; (3) long-term reliability and performance expectations; (4) maintenance and spare parts availability. Without these standards, poor-quality installations are not systematically prevented; customers cannot reliably assess installation quality (Mutai et al., 2025).

Agricultural solar quality standards should be developed through collaborative process involving: (1) equipment manufacturers and installers (understanding technical feasibility and cost implications); (2) farmers and user representatives (clarifying required performance standards); (3) government agencies (ensuring public interest alignment); (4) research institutions (validating standards through performance testing). Kenya's National Quality Council and Bureau of Standards can facilitate standard-setting processes modeled on international precedents (East African Standards for renewable energy systems, International Electrotechnical Commission standards adapted for African contexts).

Enabling mechanism: EPRA should convene standard-setting working groups for agricultural solar systems (separate groups for irrigation, cooling/cold storage, drying applications). Standards should specify: minimum performance requirements, design methodologies, installation protocols, maintenance schedules, installer certification requirements. Regulatory implementation should include graduated enforcement (initially awareness and voluntary compliance, progressing to mandatory compliance with penalties for non-compliance). Installer training programs should align with certification standards, ensuring qualified installers meet regulatory requirements (KCIC, 2025; Mutai et al., 2025).

iii. Tariff Structure and Trade Policy

Import duty structures substantially affect system affordability. Kenya's 2024 policy shift (zero-rating agricultural solar equipment) represents significant enabling change; however, inconsistent implementation and incomplete zero-rating (some balance-of-system components remain subject to duty) perpetuate cost barriers (KCIC, 2025).

Full zero-rating of all agricultural renewable energy components (photovoltaic panels, inverters, charge controllers, mounting structures, batteries, wiring) and simplified import pathways (pre-clearance processes reducing customs delays) would reduce effective system costs 8–12%, providing meaningful demand stimulus. Additionally, accelerated depreciation allowances for renewable energy capital investments (enabling rapid cost recovery through tax deductions) improve enterprise economics, particularly for equipment-intensive businesses like cold chain operators.

Value-added tax (VAT) on renewable energy equipment presents additional cost barrier. While specific exemptions exist for some development projects, broader VAT exemptions for agricultural renewable energy systems would improve affordability. Kenya's VAT treatment should be benchmarked against regional precedents (Ethiopia, Uganda) where VAT exemptions or reduced rates are applied to renewable energy equipment (World Bank, 2022).

Enabling mechanism: Ministry of Finance should conduct tariff impact analysis, modeling cost implications of full zero-rating and VAT exemption scenarios. National Treasury should incorporate renewable energy incentives into broader climate finance strategy and budget allocations. East African Community coordination should promote tariff harmonization, reducing incentives for differential tariff rates driving product-specific trade distortions. Parliament should review and extend/expand tariff and tax incentives beyond current 2026 sunset clauses, providing long-term certainty for investment (Mutai et al., 2025).

iv. Financing Policy and Risk Management Frameworks

Central Bank policy and financial sector regulation substantially affect credit availability and terms for agricultural renewable energy financing. Enabling policies include:

Guidelines on agricultural renewable energy lending: Central Bank guidance to commercial banks on appropriate interest rates, collateral requirements, and tenor for solar-agricultural systems reduces lending risk perception and standardizes product terms. Regulatory recognition of equipment-based collateral (where solar systems themselves serve as loan collateral, potentially with lender security interests) expands financing accessibility by reducing collateral requirements (World Bank, 2022).

Support for concessional financing mechanisms: Central Bank can facilitate development finance institution access to domestic funding (Treasury bond issuance, domestic credit lines) at concessional rates, enabling sub-market-rate lending for agricultural renewable energy. Regulatory encouragement for blended finance arrangements (combining public concessional capital with private commercial capital) leverages limited public resources and mobilizes private capital for development outcomes.

Agricultural insurance integration: Central Bank coordination with insurance regulators to develop weather-indexed agricultural insurance products specifically for renewable energy-using enterprises improves credit availability. Insurance products reduce lender risk perception, enabling better lending terms and wider credit availability (FSD Kenya, 2025).

Enabling mechanism: Central Bank should issue guidelines on agricultural renewable energy lending, explicitly encouraging commercial bank participation and defining acceptable collateral/tenor/rate structures. Ministry of Finance should establish concessional financing facility (potentially through development banks like Cooperative Bank of Kenya, Agricultural Finance Corporation) dedicated to solar-agricultural systems. Ministry of Interior (county governments) should facilitate county climate funds (mandated by Climate Finance Regulations 2018) for financing county-identified agricultural solar projects, potentially unlocking USD 50–100 million in available capital (FSD Kenya, 2025; Mutai et al., 2025).

4.5. Cross-Cutting Enabling Factors and Implications

i. Ecosystem Approach and Institutional Coordination

Enabling factors do not operate independently; rather, their impact is multiplicative when systemically deployed through coordinated institutional action. Technical excellence (modular, reliable, locally-manufactured systems) without accessible financing remains ineffective; superior financing products without technical capacity for maintenance underperform. The Kenya Climate Innovation Center model, combining technology development, enterprise acceleration, financing facilitation, and policy advisory services, demonstrates value of coordinated institutional approaches spanning multiple enabling dimensions (KCIC, 2025).

Ecosystem development requires explicit coordination mechanisms: (1) inter-institutional forums enabling communication and alignment among technology providers, financiers, support service organizations, and government agencies; (2) performance monitoring systems tracking enabling factor deployment and impact (technology deployment rates, financing volumes, technician availability, adoption outcomes); (3) feedback mechanisms enabling course correction as implementation reveals bottlenecks or unintended consequences.

ii. Inclusive Development and Gender Integration

The case studies demonstrate that inclusive adoption (reaching smallholders, women, youth, pastoral communities) is not secondary to or detracting from performance; rather, inclusive approaches often outperform gender-neutral approaches in sustainability and economic outcomes. Kaptabuk's deliberate women-inclusive governance (30% female leadership) correlates with improved financial accountability and member satisfaction; Savanna Circuit's finding that income benefits were "particularly pronounced for women and youth" demonstrates differential benefit capture by gender (Savanna Circuit, 2022; Kaptabuk, 2019–2024).

Enabling factor deployment should be deliberately inclusive: financing products with gender-responsive features (smaller loan sizes, flexible repayment, women's group-based lending); training programs with women/youth-specific components; business development support emphasizing women/youth entrepreneurs; policy frameworks explicitly addressing gender equity in energy access and economic opportunity.

This integration recognizes that energy poverty, technology access, and economic opportunity are not distributed equally; deliberately inclusive approaches are both equitable and economically efficient.

5.0. ENTERPRISE OPPORTUNITIES FOR SOLAR INTEGRATION IN AGRICULTURAL VALUE CHAINS: PATHWAYS TO SCALE

While technical feasibility of solar-agricultural systems is well established, scaling adoption among smallholders and dispersed value chain actors requires viable enterprises capable of aggregating demand, reducing transaction costs, and delivering services profitably. Solar technology adoption at scale is inherently an enterprise problem it depends on diverse actors (smallholders, SMEs, cooperatives, retailers, technicians, financiers) coordinating across value chains to deliver equipment, services, financing, and technical support in rural contexts where transaction costs are high and market information is limited (IFAD, 2024; World Bank, 2022). This chapter identifies specific enterprise opportunities for solar integration across dairy and horticulture value chains, characterizes the support requirements enabling enterprises to operate at scale, and highlights cross-cutting success factors and constraints.

Enterprise opportunities exist across multiple stages of agricultural value chains and across diverse organizational forms. Figure [1] illustrates these dimensions: value chain stages from production through aggregation, processing, and distribution; enterprise types ranging from individual smallholder farmers to SMEs, producer cooperatives, and specialized service providers; and corresponding solar applications appropriate to each stage. Understanding this multi-dimensional opportunity space and the support mechanisms required to activate these opportunities, is essential to advancing inclusive solar adoption at scale.

5.1. Enterprise Opportunities Across Value Chain Stages and Enterprise Types

i. Production Stage: Individual Farmer and Smallholder Adoption

At the production stage, individual smallholders and farming SMEs represent the primary adoption units. Solar technologies at production directly address energy-intensive activities: solar-powered irrigation for crop production and livestock watering, solar-powered water pumping for domestic and productive use, and solar power for lighting and household use (KCIC, 2025). Evidence from pilot implementations demonstrates substantial productivity gains: solar-powered irrigation systems enable smallholders to extend cultivation into dry seasons, increasing annual production 40–80% depending on baseline water availability (Wanjala et al., 2024; ACTS, 2025). Production-stage adoption creates entry points for farmer engagement with solar technology, building familiarity and confidence that facilitates later adoption of more complex systems.

However, individual farmer adoption alone operates at limited scale. Smallholders typically adopt modest systems (1–3 kW) suited to household and basic production needs; scaling to handle processing, cooling, or significant irrigation requires either farm consolidation or cooperative aggregation. More importantly, technology adoption at production stage does not automatically generate the institutional linkages required for value chain integration farmers may adopt irrigation but continue selling through informal channels rather than accessing structured markets. Enterprise development at production stage therefore emphasizes not individual adoption in isolation but rather farmer-inclusive business models where technology adoption is bundled with market linkages, quality standards, and value chain organization.

Enterprise opportunities at production include: (1) farmer cooperative models where individual members adopt solar irrigation with cooperative support for training and maintenance; (2) outgrower models where contracted SME operators or processors supply solar systems and technical support to contracted farmer suppliers, securing raw material supply; and (3) farmer-led enterprises where farming households with larger landholdings establish solar-powered production operations (irrigated horticulture, smallholder dairy) serving local markets or cooperative supply chains (Wangai et al., 2024).

ii. Aggregation Stage: Cooperatives and Collection Infrastructure

At the aggregation stage the collection and consolidation of agricultural production into volumes suitable for processing or retail solar technology opens distinct enterprise opportunities. In dairy value chains, milk collection centers (MCCs) established and operated by producer cooperatives represent the primary aggregation point; solar cooling enables MCCs to serve larger geographic areas by preventing milk spoilage and extending shelf life (Cheloti et al., 2024; University of Hohenheim, 2020). In horticulture, aggregation cooperatives conduct initial sorting, grading, packaging, and cooling of produce before transfer to processors or markets; solar power applied to these aggregation functions can reduce post-harvest losses and enable value addition.

Cooperative-managed solar infrastructure at aggregation represents a cornerstone enterprise model for scaling solar adoption. Unlike individual farmer adoption requiring expensive individual systems, cooperative-owned infrastructure achieves economies of scale: a solar-powered MCC serving 200–400 dairy farmers reduces per-farmer capital cost by 70–80% compared to individual on-farm cooling. Cooperatives generate revenue through fee-for-service models (typically 3–5% of farmer milk volumes), creating financial sustainability without ongoing external subsidies (Wangai et al., 2024; KCIC, 2025). Pilot projects across East Africa demonstrate rapid cost recovery: solar MCCs in pastoral regions show 3–5 year payback periods with fee-for-service business models (Cheloti et al., 2024; ACTS, 2025).

Aggregation-stage enterprises present distinct operational complexity relative to production stage. Cooperative-owned solar systems require professional operation and maintenance protocols; governance structures capable of managing shared assets; explicit cost-sharing and revenue-sharing mechanisms; and integration with market linkages to ensure farmers capture value from improved product quality (KCIC, 2025; World Bank, 2022). Success factors include: (1) explicit capacity building addressing cooperative governance, financial management, and technology operation; (2) revenue-generating business models with transparent fee structures ensuring long-term financial sustainability; (3) technical support services ensuring preventive maintenance and rapid fault response; and (4) market linkages connecting improved-quality aggregated product to processors or premium buyers willing to pay for quality (Wangai et al., 2024).

iii. Processing Stage: SME and Micro-Enterprise Opportunities

Processing represents the stage with highest solar energy intensity and greatest potential economic returns from energy cost reduction. Agro-processing operations including milk processing (pasteurization, yogurt production, cheese-making), produce processing (drying, juice extraction, canning, value-added preparation), and oil/grain processing require reliable electricity for refrigeration, heating, mechanical equipment, and product preservation (Wanjala et al., 2024). In Kenya's high-potential agricultural zones, agro-processors experience chronic electricity unreliability and high grid tariffs; solar-diesel hybrid systems increasingly offer economically attractive alternatives even in well-electrified areas (Wanjala et al., 2024; FSD Kenya, 2025).

Processing-stage enterprises include: (1) existing dairy and horticultural processors transitioning to solar-hybrid systems to reduce energy costs and improve reliability; (2) newly-established SME processing operations using solar power as cost advantage enabling entry into value added production; (3) community-based processing operations (often women-led cooperatives) undertaking local-level value addition (fruit drying, juice production, vegetable processing) using solar equipment; and (4) service providers offering processing-as-a-service models where aggregator cooperatives or farmer groups contract with processing SMEs rather than investing in their own equipment (ACTS, 2025; Wanjala et al., 2024).

Processing-stage enterprises are economically attractive because solar energy replaces high-cost inputs: replacing diesel generators or expensive grid electricity with solar power reduces operating costs 40–50%, improving profit margins and competitiveness (FSD Kenya, 2025). However, processing enterprises require substantial capital investment (USD 15,000–50,000+ depending on operation scale) and technical sophistication in system design. Profitability depends on securing reliable raw material supply at competitive prices and accessing markets willing to pay premium prices for processed products (Wanjala et al., 2024). Enterprise development at processing stage therefore requires integrated support: technology supply, finance, technical assistance, and market linkage services.

5.2. Specialized Service Provider Enterprises

Beyond production, aggregation, and processing, a fourth category of solar-agricultural enterprise emerges: specialized service providers supplying equipment, installation, maintenance, financing, and technical support to other value chain actors. Service provider enterprises include: (1) solar retailers and dealers supplying equipment with limited service support; (2) solar installation and system design companies providing system specification, installation, and initial commissioning; (3) maintenance and repair service providers offering preventive and corrective maintenance; (4) solar equipment rental or lease companies providing equipment access without ownership requirements; (5) financing intermediaries offering tailored credit products for agricultural solar systems; and (6) technology aggregators bundling solar equipment with business training, market linkage support, and cooperative strengthening (KCIC, 2025; IFAD, 2024).

Service provider enterprises are particularly critical to scaling adoption in rural areas where integrated demand is insufficient for individual specialist providers. Evidence from pilot projects demonstrates that bundled service delivery combining equipment supply, installation, training, and follow-up maintenance, dramatically improves system performance and farmer satisfaction compared to equipment-only supply (University of Hohenheim, 2020; SelfChill Foundation, 2020). Service provider enterprises operating across multiple value chain actors and geographies achieve economies of scale that reduce per-system costs and improve service quality; conversely, lack of viable service provider businesses is a critical bottleneck constraining adoption scale in many regions (KCIC, 2025).

5.3. Support Requirements Enabling Enterprise Scale

Identifying viable enterprise opportunities is insufficient; scaling adoption requires targeted support addressing distinct barriers confronting each enterprise type and value chain stage.

i. Access to Appropriate Financing Instruments

Financing represents the most fundamental constraint on enterprise scale. Production-stage smallholder enterprises and aggregation-stage cooperative investments require USD 5,000–15,000 system costs substantially exceeding enterprise capital and borrowing capacity. Processing-stage SME investments may require USD 20,000–50,000+ exceeding conventional commercial financing availability in rural areas (KCIC, 2025; World Bank, 2022).

Conventional commercial bank lending is poorly suited to agricultural solar investment: high interest rates (14–20% annually) make solar system payback unaffordable; short loan terms (1–3 years) mismatch 5–7 year technology payback periods; inflexible monthly payment schedules conflict with seasonal agricultural cash flows; collateral requirements exclude smallholders lacking land titles or productive assets (KCIC, 2025; World Bank, 2022).

Evidence-based financing solutions demonstrated in pilot implementations include: (1) **concessional term financing** with 8–10% interest rates, 5–7 year terms, and seasonal payment schedules matched to agricultural income patterns; (2) **green credit guarantee schemes** where partial credit guarantees from development finance institutions reduce lender risk, enabling commercial banks to offer better terms at lower costs; (3) **equipment-secured lending** where solar systems themselves serve as collateral rather than requiring land or productive asset pledges; (4) **cooperative refinancing** where development finance institutions provide capital to cooperatives for on-lending to member farmers; (5) **pay-as-you-go (PAYG) models** integrated with mobile money enabling weekly/bi-weekly payments (USD 5–20) reducing upfront barriers; and (6) **lease-to-own models** where users build equity through service fee payments eventually owning equipment (SelfChill Foundation, 2020; IFAD, 2024; World Bank, 2022).

Development finance institutions and concessional lenders have piloted these mechanisms with demonstrated impact: solar-powered dairy cooling systems financed through concessional 8–10% 6-year term loans show 80%+ repayment rates with borrower satisfaction substantially exceeding conventional bank experiences (Wangai et al., 2024; Cheloti et al., 2024). PAYG models piloted in Kenya demonstrate strong uptake when payment amounts are modest (USD 5–10 weekly) and products are reliable; pilot participants show 86% willingness to transition to recurring payments once income improves (Shell Foundation, 2024).

Scaling appropriate financing requires: (1) dedicated green financing funds capitalized by development finance institutions and impact investors with mandates for agricultural solar lending; (2) capacity building of microfinance institutions and commercial banks in agricultural solar product design; (3) technical assistance helping enterprises develop bankable business plans and financial projections supporting loan applications; and (4) credit guarantee mechanisms de-risking lender concerns about unfamiliar agricultural solar lending.

ii. Technical Assistance and Business Development Support

Beyond financing, enterprises require business development support and technical assistance to operate profitably and scale operations. Production and aggregation-stage enterprises need: (1) participatory system design ensuring technology specifications match operational requirements; (2) installation quality assurance and supervision; (3) operator training and ongoing technical support; (4) preventive maintenance protocols and spare parts supply chains; and (5) business planning and financial management support (University of Hohenheim, 2020; KCIC, 2025).

Processing-stage enterprises and service provider enterprises require more intensive business support: (1) technical feasibility assessment and system design optimization for processing operations; (2) business plan development and financial projections; (3) market assessment and market linkage facilitation; (4) operational efficiency advice; and (5) business governance and organizational development support (Wanjala et al., 2024; FSD Kenya, 2025).

Technical assistance providers include government extension services (where solar capacity exists), development implementing partners, private sector consultants, and technology companies. The limiting factor constraining technical assistance delivery is institutional capacity: most government agricultural extension services have minimal solar energy expertise; development partner technical assistance is typically time-limited; and private consultant services are expensive and concentrated in urban areas (KCIC, 2025). Scaling technical assistance requires: (1) strengthening existing institutions (government extension, cooperative development agents) with solar energy and business training; (2) developing cadres of local technical service providers or para-professionals capable of delivering routine technical assistance at lower cost; and (3) technology support platforms (mobile-based systems, online guidance) extending professional advice to resource-constrained enterprises (IFAD, 2024).

iii. Market Linkages and Demand Aggregation

Enterprise profitability and sustainability depend on market linkages enabling value chain integration. Enterprises adopting solar technology without corresponding market access improvements gain energy cost reductions but miss revenue opportunities from improved product quality or volume. Dairy enterprises using solar cooling produce higher-quality milk commanding price premiums; horticultural enterprises reducing post-harvest losses capture higher volumes and quality premiums. Realizing these benefits requires market linkages connecting improved products to buyers willing to pay quality/consistency premiums (Cheloti et al., 2024; Wangai et al., 2024).

Market linkage support includes: (1) buyer identification and contract negotiation support; (2) quality standard development and compliance support; (3) aggregation and bulking of product volumes meeting buyer requirements; (4) supply chain coordination ensuring consistent supply; and (5) price information systems reducing information asymmetries between buyers and suppliers (World Bank, 2022). Evidence demonstrates these market linkage elements are critical to enterprise success: dairy cooperative cold storage infrastructure without corresponding market linkage support frequently fails to achieve financial sustainability as milk volumes remain limited and price premiums fail to materialize (KCIC, 2025). Cooperative-based solar infrastructure pilot projects incorporating explicit market linkage components show substantially higher profitability and sustainability compared to technology-only interventions (Wangai et al., 2024; ACTS, 2025).

iv. Enabling Policy and Regulatory Environment

Enterprise development and scaling are constrained by policy gaps and regulatory uncertainty. Specific policy support requirements include: (1) **tariff harmonization and zero-rating** of all agricultural solar equipment components (currently only partial zero-rating creates import price uncertainty); (2) **simplified licensing pathways** for agricultural solar installers distinct from general electrician licensing, reducing compliance burdens while maintaining safety standards; (3) **quality standards and enforcement** for agricultural solar installations, providing customer confidence and installer quality incentives; (4) **tax incentives** (VAT exemption, accelerated depreciation) reducing cost barriers for processing and cooperative-scale investments; (5) **grid interconnection and net metering regulations** enabling grid-connected solar systems to export excess generation, reducing system sizes and costs; and (6) **concessional financing mechanisms** through government or development finance institution channels (Mutai et al., 2025; Energy and Petroleum Regulatory Authority, 2024).

Current policy implementation creates enterprise uncertainty: import duty reductions announced in 2024 remain inconsistently implemented; net metering regulations adopted in 2024 lack implementation protocols; quality standards for agricultural solar installations are absent. This uncertainty discourages enterprise investment and reduces investor confidence in agricultural solar markets (KCIC, 2025).

Supporting policy implementation requires: (1) institutional coordination mechanisms linking energy, agriculture, and finance sectors to align policies toward shared objectives; (2) dedicated government staffing for agricultural solar implementation ensuring consistent application; and (3) private sector engagement in standards development and regulatory design ensuring requirements are technically feasible and commercially viable (Mutai et al., 2025).

5.4. Cross-Cutting Constraints and Success Factors

While enterprise opportunities and support requirements are specific to value chain stage and enterprise type, several cross-cutting patterns emerge as critical to enterprise scale.

i. Bundled Service Delivery as Essential to Enterprise Performance

Single-element interventions, providing equipment only, financing only, or training only, show limited impact on sustainable adoption and enterprise scale. Successful enterprise models bundle multiple service elements: technology supply, installation quality assurance, operator training, maintenance support, financing, and market linkages (University of Hohenheim, 2020; Shell Foundation, 2024; Wangai et al., 2024). Evidence from SEFFA program across Ethiopia, Kenya, and Uganda demonstrates bundled models supporting 5,375 smallholder farmers with solar technology combined with finance, training, and market access show adoption sustainability and productivity impact substantially exceeding equipment-only programs (Programme for Sustainable Energy and Development, 2024).

This bundling principle applies across enterprise types: individual farmer adoption succeeds when combined with cooperative strengthening and market linkages; cooperative-scale infrastructure investments require bundling with business training and technical support; processing-scale SME investments require simultaneous financing, technical assistance, and market linkage support (ACTS, 2025; Wanjala et al., 2024).

ii. Women's Enterprise Leadership and Inclusive Business Models

Gender inclusion in solar enterprises is not incidental to equity but fundamental to enterprise success and scale. Women constitute a large share of agricultural labor and decision-making regarding household and community energy use; yet women are substantially underrepresented in solar technology supply enterprises and technical professions (Ashoka East Africa, 2025). Gender-responsive enterprise development explicitly recruits women as entrepreneurs, technicians, and cooperative leaders; incorporates women in household decision-making for technology adoption; ensures women benefit from income opportunities created by solar enterprises; and tailors financing and business support to address women's specific constraints (Bryan & Garner, 2022; Winther et al., 2018).

Evidence demonstrates gender-inclusive solar enterprises are more profitable and sustainable: women-led dairy cooperatives with solar infrastructure show higher fee payment rates and greater revenue diversification than male-dominated cooperatives; women operators of solar equipment show reliable maintenance and operation protocols; women solar entrepreneurs in pilot programs demonstrate comparable business performance to male operators while accessing previously unavailable economic opportunities (Ashoka East Africa, 2025; Njuki et al., 2014).

iii. Institutional Coordination and Inter-Agency Alignment

Agricultural solar is inherently cross-sectoral, requiring coordination across energy, agriculture, water, and finance sectors. However, institutional fragmentation remains common: energy policies lack agricultural focus; agricultural policies omit energy considerations; cooperatives development operates separately from energy deployment; rural finance institutions lack solar sector knowledge (KCIC, 2025). This fragmentation creates implementation gaps: agricultural extension services are not trained in solar energy; energy agencies lack agricultural expertise; cooperatives development agents do not address energy infrastructure; financial institutions lack tailored agricultural solar products.

Success factors include establishment of formal coordination mechanisms (inter-ministerial working groups, joint planning processes) defining shared objectives for agricultural energy transitions; designation of lead agencies responsible for implementation accountability; joint staff deployment combining agricultural and energy expertise; and integrated program design ensuring energy, technology, financing, and market linkage components are synchronized (Mutai et al., 2025; ACTS, 2025).

iv. Local Institutional Capacity Development and Private Sector Engagement

Sustainable enterprise development depends on local institutional capacity government agencies, cooperatives, private service providers capable of operating programs independently after external support concludes. However, institutional capacity for agricultural solar is limited: most government agricultural agencies have minimal energy expertise; cooperative development capacity is weak in many counties; private sector solar service providers are few in number and concentrated in urban areas (KCIC, 2025).

Sustainable scaling requires deliberate capacity development: government extension service training in solar technology and agricultural energy planning; cooperative development agent strengthening to support cooperative-scale solar infrastructure; private service provider enterprise development programs building local technician and entrepreneur capacity; and knowledge management systems documenting lessons and scaling-up experience across programs (IFAD, 2024; University of Hohenheim, 2020). This local capacity development is time-intensive and resource-demanding but essential to transition from external support-dependent models to locally-sustainable systems.

5.5. Synthesis: Enabling Pathway to Enterprise-Driven Scale

Solar enterprise opportunities across dairy and horticulture value chains are substantial and increasingly demonstrated at pilot scale. Production-stage smallholder adoption enabled through group-based financing and market linkages; aggregation-stage cooperative infrastructure generating revenue-based business models; processing-stage SME investments realizing energy cost reductions; and service provider enterprises aggregating demand and reducing transaction costs all represent viable pathways to scaled solar adoption (ACTS, 2025; Wangai et al., 2024; Wanjala et al., 2024). However, scaling from pilot demonstration to economy-wide adoption requires systematic support addressing financial, technical, institutional, and policy dimensions. Access to appropriate financing instruments is the most fundamental requirement—concessional term lending, credit guarantees, and innovative financing mechanisms enabling enterprises to undertake capital investments while maintaining financial sustainability. Technical assistance and business development support ensure enterprises operate profitably; market linkages enable enterprises to capture full value of technology adoption. Enabling policy creates the regulatory certainty and incentive structures encouraging enterprise investment and private sector engagement.

Most critically, success depends on bundled service delivery recognizing that technology adoption, financing, business development, and market access are interdependent rather than substitutable. Individual enterprises cannot simultaneously navigate technical specification, financing sourcing, operator training, and market linkage development independently; programmatic support bundling these elements dramatically improves enterprise performance and sustainability.

The evidence base increasingly demonstrates that deliberately enterprise-focused approaches to solar-agricultural deployment achieve both greater adoption scale and greater economic efficiency than technology-oriented or infrastructure-only approaches (KCIC, 2025; IFAD, 2024; World Bank, 2022). Realizing this potential requires moving beyond pilot initiatives toward systematic enterprise development programming at scale, over sustained timeframes, with corresponding investment in institutional and policy enabling environments.

6.0. CONCLUSION AND RECOMMENDATIONS

Scaling solar-agricultural deployment requires coordinated action across five stakeholder groups: government (national and county), financial institutions, development partners, cooperatives and producer organizations, and KCIC/implementing partners. This section synthesizes findings into actionable recommendations for each stakeholder group, organized thematically around the most critical leverage points for achieving scale.

3.1. Recommendations for Government (National and County Levels)

Figure 2. Illustration showing government recommendations ranging from policy reforms to financing mechanisms.

Policy and Regulatory Harmonization

1. **Implement consistent tariff policies for agricultural solar equipment.** The current patchwork of zero-rating for some agricultural components while maintaining 25% tariffs on others creates price uncertainty and discourages investment. Government should enact full zero-rating for all photovoltaic modules, inverters, charge controllers, mounting structures, and other balance-of-system components used in agricultural applications. This single-action policy intervention could reduce effective system costs 8–12%, providing meaningful demand stimulus for smallholder and cooperative adoption. Implementation should include clear registry of eligible agricultural applications (irrigation pumping, cooling, processing) and simplified customs clearance protocols for zero-rated items.

2. **Streamline licensing pathways for agricultural solar installers.** Current requirements force agricultural solar technicians through full electrician licensing (expensive, time-consuming, location-dependent), creating compliance barriers for rural service providers. Alternative approach: establish specialized "Agricultural Solar Technician" licensing tier

combining abbreviated training (3–6 months, focused on agricultural solar safety and technical standards) with supervised field experience. This creates a viable pathway for rural technician credentialing without imposing full electrician licensing burden. Licensing should be county-devolved to enable local relevance.

3. **Establish mandatory quality standards for agricultural solar installations.** The absence of design standards (irrigation sizing, cooling adequacy, drying performance, structural robustness) creates a market for poor-quality installations undermining user confidence. Government, in coordination with private sector solar companies and technical institutes, should develop and publish standards for common agricultural solar applications (milk cooling systems, irrigation pumping, cold storage, processing-scale systems). Standards should address: technical specifications for application-specific performance; installation safety and electrical compliance; warranty and after-sales service requirements; and certification protocols. Implementation should combine voluntary industry standards with consumer awareness of certification marks enabling informed purchasing.

4. **Establish inter-ministerial coordination mechanism for agricultural energy.** The current silos between Ministry of Energy, Ministry of Agriculture, Ministry of Water, and national/county authorities create implementation gaps and missed opportunities. Establish a formal Agricultural Energy Taskforce (convened by Energy Ministry, including Agriculture, Water, Finance, and devolved county representatives) meeting quarterly to: align policy across sectors; coordinate extension and technical support; streamline licensing and permitting; monitor implementation of energy policies across county jurisdictions. Designate the Ministry of Energy as the lead agency responsible for agricultural energy outcomes, with quarterly accountability reporting to Cabinet.

Financing Mechanism Development

5. **Establish government-backed credit guarantee facility for agricultural solar lending.** Development finance institutions (DFIs) have demonstrated that partial credit guarantees covering 30–50% of loan default risk enable commercial banks to offer favorable terms on agricultural solar lending. Establish a Government-backed guarantee facility (capitalized through Treasury or concessional DFI lending, managed by an existing development bank such as KDA or CDC) that: provides partial guarantees to commercial banks and microfinance institutions extending agricultural solar loans; covers loans for production-stage smallholder adoption, aggregation-stage cooperative infrastructure, and processing-stage SME investments; accepts credit guarantees as partial security enabling lower overall collateral requirements; operates with transparent pricing (guarantee premiums of 1–2% of loan value) ensuring commercial viability. This mechanism should be capitalized with initial KES 500M–1B, sufficient to catalyze KES 2–5B in guaranteed agricultural solar lending.

6. **Support development finance institution (DFI) products for agricultural solar.** Current DFI lending to agriculture focuses on working capital and seasonal inputs; long-term productive-asset financing for solar equipment is nascent. Government should convene DFIs (World Bank (KOSAP), AfDB, bilateral development banks) to jointly develop standardized agricultural solar lending products with: 8–10% interest rates (vs. 14–20% commercial rates); 5–7 year terms matching technology payback; seasonal

payment schedules aligned to agricultural cash flows; equipment-secured lending accepting solar systems as collateral; and bundled business development services. This product standardization reduces DFI development costs and enables inter-lender coordination facilitating customer access.

County-Level Implementation

7. **Develop county renewable energy strategies with explicit agricultural focus.** Many county Integrated Development Plans mention renewable energy generically; few address agricultural solar specifically. County governments should develop Agricultural Energy Strategies (as part of broader county renewable energy frameworks) addressing: county-specific energy needs and demand hotspots (e.g., irrigation in Makueni, dairy cooling in pastoral ASAL); mapping of existing energy infrastructure (grid coverage, mini-grids, diesel supply); identification of priority value chain nodes for solar investment; coordination mechanisms across county departments; financing and investment facilitation strategies; and workforce development plans. These strategies should be informed by participatory needs assessment with farmers, processors, and cooperatives ensuring county plans reflect actual beneficiary priorities.
8. **Establish county-level solar installation and maintenance registries.** Counties should maintain publicly-accessible registries of: licensed/certified solar installers operating within the county; equipment dealers and suppliers; spare parts availability and suppliers; repair and maintenance service providers. This transparency improves customer confidence (ability to verify technician credentials), facilitates geographic matching of service providers to customers, and creates accountability mechanisms (complaints against registered technicians have institutional response pathways). Integration with county websites enables online access; periodic registry updates (quarterly) maintain current information.

3.2. Recommendations for Financial Institutions

Product Development and Risk Mitigation

9. **Develop specialized agricultural solar lending products.** Commercial banks and microfinance institutions possess the distribution networks and credit management capacity for scaled lending but currently lack products suited to agricultural solar investing. Specific recommendations: (1) create 5–7 year solar equipment financing products with seasonal payment schedules matching agricultural income patterns; (2) accept solar systems as collateral through equipment-secured lending, reducing collateral requirements; (3) partner with insurance providers offering production insurance (protecting against yield/income losses) reducing lender default risk; (4) integrate with government credit guarantees reducing net default risk to acceptable commercial levels; (5) develop risk-based pricing enabling specialized lenders (accepting higher risk) through higher interest rates while maintaining affordability for lower-risk customers.
10. **Pilot innovative financing mechanisms with technical assistance.** Evidence from case studies demonstrates that lease-to-own, pay-per-use, and group-based lending models achieve higher adoption and lower default rates than conventional individual purchase financing. Financial institutions should pilot: (1) lease-based financing where equipment

ownership transitions to customer after successful payment of lease payments; (2) group-based lending where smallholder groups access larger loan amounts through group liability, enabling shared equipment investment; (3) PAYG models integrated with mobile money enabling small, frequent payments reducing upfront barriers and default risk; (4) bundled financing packages combining equipment, installation, training, and 12–24 month technical support, recognizing that financing alone is insufficient without corresponding capability building. Initial pilots should be conducted at scale (500+ farmers or 20+ SMEs) with rigorous performance monitoring enabling scaling of successful models.

Market Development Support

11. **Conduct value chain finance assessments identifying capital gaps and opportunities.** Financial institutions should commission or conduct dairy and horticulture value chain finance assessments addressing: current sources and costs of capital for production, aggregation, and processing actors; unmet financing demand (how many farmers/processors seek financing but cannot access it); gaps between available financing terms and actual needs (term lengths, payment schedules, collateral requirements); high-return investment opportunities (which value chain nodes offer highest financial returns, enabling higher interest rates while remaining user-affordable). These assessments should be conducted county-by-county or value chain cluster-by-cluster enabling targeted product development meeting specific market needs rather than generic approaches.

3.3. Recommendations for Cooperatives and Producer Organizations

Governance and Capacity Strengthening

12. **Establish solar infrastructure governance protocols for cooperatives and producer groups.** Solar infrastructure investments (milk collection centers, packhouses, processing facilities) represent significant capital requiring transparent, accountable management. Producer organizations should establish explicit governance protocols addressing: cost-sharing mechanisms (how are equipment and operational costs allocated among members); revenue-sharing procedures (how are fee-for-service revenues allocated back to members or reinvested in cooperative operations); decision-making procedures (member participation in equipment acquisition, maintenance, and operational decisions); dispute-resolution mechanisms (procedures when members disagree about infrastructure operation or cost allocation); and succession/sustainability planning (procedures ensuring infrastructure operation and maintenance continue as cooperative membership changes). Governance protocols should be documented in writing, disseminated to members, and reviewed annually with member input.

13. **Invest in technical and business management training for cooperative leaders.** Successful solar infrastructure operation depends on cooperative leaders possessing technical knowledge (equipment operation and maintenance), financial management expertise (revenue collection, cost tracking, equipment lifecycle budgeting), and organizational development skills (member communication, conflict resolution, delegation). Cooperatives should conduct annual training for leadership teams addressing: solar technology fundamentals (how systems operate, basic troubleshooting); preventive maintenance protocols and spare parts management; financial record-keeping and revenue

tracking; cooperative governance and member engagement; and linkages between energy infrastructure investment and market development. Training should be conducted by county agricultural extension services (with solar energy training support from county energy or KCIC), development partners, or private solar companies, with incentive structures ensuring regular attendance and skill application.

Market Development and Value Chain Integration

14. **Prioritize market linkage development in conjunction with solar infrastructure investment.** Evidence demonstrates that solar infrastructure without corresponding market linkages frequently fails to achieve financial sustainability and farmer value capture. Producer organizations should invest equivalent resources in market linkage development as in infrastructure investment. Specific actions: (1) invest in buyer identification and relationship development (market research identifying processors, exporters, institutional buyers interested in member product supply); (2) establish or strengthen collective marketing platforms enabling aggregated supply to buyers; (3) develop quality standards and certification protocols (e.g., organic certification, quality assurance) enabling product differentiation and price premiums; (4) establish supply chain coordination mechanisms ensuring consistent, reliable supply meeting buyer requirements; (5) integrate price information systems reducing information asymmetries with buyers. This market linkage investment recognizes that improved product quality (through solar cooling/preservation) only translates to farmer income gain if markets are structured to value that quality through higher prices.

3.4. Recommendations for Development Partners and Implementing Organizations (Including KCIC)

Enterprise Development and Innovation Support

15. **Support enterprise-focused solar-agricultural programming as a scaling lever.** Evidence from case studies (Savanna Circuit, Baridi, SokoFresh) demonstrates that viable business models and social enterprises achieve greater adoption scale and sustainability than standalone technology deployment. Development partners should explicitly prioritize enterprise development support including: (1) business model innovation and refinement (working with entrepreneurs to develop financially sustainable business models matching user context); (2) product-market fit assessment (rigorous testing ensuring products address actual user needs at price points users can afford); (3) financing strategy development (working with entrepreneurs to identify appropriate financing mechanisms, structure loan applications, prepare financial projections); (4) operational scaling support (helping proven models scale from 100s to 1000s of customers); (5) network facilitation connecting entrepreneurs across geographies enabling learning and collaboration. This enterprise-focused approach recognizes that scaling depends on viable, profitable businesses delivering services reliably rather than project-based deployments ending when donor funding concludes.

16. **Establish technology validation and certification protocols for agricultural solar equipment.** The market currently includes poor-quality equipment, unreliable suppliers, and underperforming systems. Development partners should support establishment of

independent technology validation and certification protocols addressing: equipment performance testing (reliability under field conditions, durability, efficiency); safety standards compliance; and warranty/after-sales service requirements. KCIC and partner institutions should: (1) conduct performance testing of solar equipment under Kenyan field conditions (e.g., dust accumulation impacts, temperature extremes, humidity effects); (2) publish results transparently enabling informed customer choice; (3) develop certification marks enabling end-users to identify equipment meeting standards; (4) coordinate with quality assurance bodies (Kenya Bureau of Standards) ensuring governmental backing for standards; (5) establish certification for installation companies ensuring quality installation standards. This validation infrastructure reduces information asymmetries and improves customer confidence in technology and suppliers.

Knowledge Management and Learning Facilitation

17. **Document and disseminate case study evidence from implemented solar-agricultural systems.** Evidence from documented implementations (Kaptabuk, SokoFresh, Baridi, Savanna Circuit) proves invaluable for demonstrating feasibility, identifying success factors, and building investor confidence. KCIC and partners should systematically: (1) conduct rigorous impact evaluations of implemented systems documenting productivity impacts, income effects, employment outcomes, gender benefits, and sustainability indicators; (2) document implementation processes identifying critical success factors and common failure modes; (3) disseminate case study evidence through accessible formats (policy briefs, case study summaries, video documentation) reaching policymakers, practitioners, and potential entrepreneurs; (4) establish learning communities bringing together implementers across geographies for peer exchange and cross-learning; (5) feed lessons learned into updated technical guidance and programming strategies. This knowledge documentation and dissemination accelerates learning from pilot experiences, reducing inefficiencies in scaled programming.

18. **Develop and deploy just-in-time training and decision-support tools for solar-agricultural adoption.** Smallholders and cooperatives often lack information at critical decision points (should we invest in solar?, which technology is appropriate?, how do we finance?, where do we find technicians?). KCIC should develop: (1) decision-support tools (online or phone-based) guiding farmers through system selection based on their energy needs, production scale, and financial capacity; (2) supplier and technician directories enabling farmers to identify nearby qualified providers; (3) financing options comparators enabling farmers to evaluate available financing products and identify best-fit options; (4) technical troubleshooting guides (printed or video) enabling users to diagnose common system problems and perform basic maintenance; (5) market linkage databases connecting farmer groups to potential processors, exporters, and institutional buyers. These tools should be available in local languages through multiple channels (online, SMS, voice-based phone services) ensuring accessibility across literacy and technology-access levels.

Gender Integration and Inclusive Programming

19. **Mainstream gender analysis and inclusive programming across all KCIC solar-agricultural initiatives.** Evidence demonstrates that gender-intentional programming (not treating gender as add-on) achieves both greater equity and greater economic impact. KCIC

should: (1) conduct gender analysis as baseline for all programming identifying how gender relations shape energy needs, technology adoption, and benefit capture in target communities; (2) implement household-level engagement ensuring both men and women participate in technology discussions, needs assessment, and adoption decisions; (3) prioritize women's organizations (all-women producer groups, cooperatives) for financing and technical support allocation; (4) establish gender-targeted entrepreneur and technician development programs recruiting women into solar technician training (targeting 40%+ women representation) and providing mentoring/business support for women entrepreneurs; (5) develop gender-responsive financing products addressing women's specific constraints (smaller loan sizes, flexible repayment, reduced collateral); (6) track gender-disaggregated impacts documenting whether women benefit equally from solar deployment and identifying barriers to equal benefit where not achieved.

3.5. Recommendations for Private Sector (Equipment Suppliers, Installers, Service Providers)

Quality and Service Standards

20. **Establish and maintain professional standards for solar installation and maintenance.** Professional credentialing and transparent performance standards improve customer confidence and market quality. Private sector actors should: (1) advocate for government establishment of agricultural solar technician licensing (recommendation 2 above); (2) establish industry associations coordinating quality standards, professional development, and peer accountability; (3) develop clear warranty and service standards (e.g., 2-year equipment warranty, 24-hour response time for system failures) enabling customer comparison and market differentiation; (4) invest in technician training and professional development ensuring workforce capacity keeps pace with market growth; (5) establish customer feedback mechanisms and complaint resolution procedures improving service quality based on user experience.

Business Model Innovation and Market Expansion

21. **Develop diverse financing and business models expanding access to solar technology across market segments.** Case study evidence demonstrates that no single business model serves all customer types; successful scaling combines lease-based, pay-per-use, equipment financing, and direct purchase models. Private sector companies should: (1) pilot and refine lease-to-own models enabling customers without capital to access technology through monthly payments; (2) develop equipment rental or short-term lease options enabling seasonal or temporary technology access; (3) establish regional distribution networks improving geographic access for rural customers; (4) invest in local manufacturing and assembly reducing equipment costs and supply chain complexity; (5) bundle technology with business development services (training, market linkage support) improving customer sustainability and creating differentiated market positioning. Competition among diverse business models serves customers better than single dominant model.

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