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A Systems Thinking Analysis of Institutional Frameworks Governing the Energy–Water Nexus for Productive Agricultural Activities in Rural Tanzania

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Abstract

Sustainable agricultural development in rural sub-Saharan Africa increasingly depends on coordinated governance of energy and water resources. Despite the growing deployment of solar photovoltaic water pumping systems (SPVWPS), little is known about how the institutional framework shapes SPVWPS effectiveness for productive agricultural use in rural Tanzania. Drawing on systems thinking concepts, specifically hierarchy, interaction, and interconnectedness, this study analyses the institutional frameworks governing energy and water provision for irrigation and livestock keeping across three rural Tanzanian communities. A mixed-methods design was employed, with qualitative inquiry as the primary mode; 65 household surveys, nine semi-structured interviews with community leaders, SPV developers, and local officials, and seven focus group discussions with farmers and livestock keepers were conducted across the three study areas. National energy and water policy documents, reports, and strategic plans were also reviewed to contextualise the institutional frameworks governing energy and water delivery in rural areas. Findings reveal limited coordination among stakeholders, particularly between NGOs, government agencies (REA, RUWASA, and NIRC), and local communities in the planning and implementation of SPVWP projects. Top-down delivery mechanisms marginalised community feedback, undermining local ownership and limiting the productive use potential of installed systems. This study proposes an integrated institutional framework that combines systems thinking with bottom-up and top-down approaches, explicitly embedding structured feedback mechanisms and aligning stakeholder roles across all governance levels. The framework was validated through interviews with experts in the rural energy and governance field, confirming its practical relevance and applicability to rural energy–water governance. The framework offers actionable guidance for policymakers and development practitioners seeking to strengthen institutional coordination in rural energy–water–agriculture governance, contributing to progress towards SDG 7 and SDG 2 across sub-Saharan Africa.

Keywords: SPVWP; institutional framework; community participation; productive use; systems thinking; bottom-up and top-down approaches

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Academic Editor: Carlos Vargas-Salgado

Received: 17 April 2026
Revised: 28 May 2026
Accepted: 1 June 2026
Published: 4 June 2026

1. Introduction

Rural areas in sub-Saharan Africa (SSA) have the lowest electrification rates globally, with approximately 43% to 48% of the rural population having access to electricity as of 2024 [1,2]. In this context, electricity access is defined using minimum annual consumption thresholds of 250 kWh for rural households and 500 kWh for urban households [3]. This situation poses a significant barrier to sustainable rural development. To address this challenge and achieve Sustainable Development Goal Seven (SDG 7), which aims to ensure affordable, reliable, sustainable, and modern energy for all, various stakeholders, including local governments, international organisations, public and private sectors, have initiated efforts to expand rural electricity access. Grid extension remains the preferred option for national governments and donor agencies; however, in most rural areas of SSA, centralised grid electricity is uneconomical, making decentralised off-grid electrification solutions essential [4–7]. SPV systems are emerging as the most feasible off-grid option due to their scalability, cost-effectiveness, and suitability for the region's climatic conditions [7]. In rural settings, SPV systems play an important role in supporting productive activities, defined as income-generating and economically beneficial uses of energy, including irrigation, water pumping, livestock keeping, and agricultural processing and storage [8]. These activities depend heavily on reliable and affordable access to energy for water provision, which is essential for improving agricultural productivity, supporting livelihoods, and fostering sustainable rural development [9–12].

The energy–water–agriculture nexus constitutes one of the most critical sustainable development challenges in rural areas of SSA and other arid and semi-arid regions of the global south. Agriculture employs between 50% and 70% of the labour force and accounts for approximately 65% of freshwater withdrawals across SSA [13]. In rural SSA, the primary water sources are rainwater harvesting and groundwater extracted from boreholes or shallow wells, using either manual or electric pumps. The low electrification rate in these areas has driven the adoption of SPVWP for agricultural activities [12,13].

The literature has examined technical performance, financial viability, and farmer-level adoption of SPVWPS [14,15]. However, few studies have examined the institutional arrangements governing cross-sectoral planning and implementation among energy, water, and agricultural agencies in rural settings [16,17]. Energy–water–agriculture nexus research largely focuses on large-scale infrastructure or urban systems, whilst the governance of decentralised off-grid systems in rural areas remains under-researched [18]. Specifically, the key questions remain about how top-down regulatory frameworks and bottom-up participatory processes interact in energy provision, why persistent coordination failures occur across energy and water agencies, and how stakeholders engage meaningfully in project planning, design, implementation, and operation. This institutional governance gap limits both scholarly understanding and practical deployment of solar-powered systems for productive use in rural areas across the global south, including Tanzania, where decentralised SPVWPS are increasingly central to agricultural development, yet their governance remains insufficiently studied.

This article addresses the institutional governance gap by examining how existing institutional frameworks shape the planning and implementation of SPVWPS for productive agricultural activities in rural Tanzania. Employing a qualitative-dominant mixed-methods approach and drawing on systems thinking concepts, specifically hierarchy, interaction, and interconnectedness, the study analyses cross-sectoral coordination, stakeholder interactions, and feedback mechanisms across three rural Tanzanian communities. The following section reviews the relevant literature on energy–water governance, institutional frameworks, and systems thinking as an analytical lens.

2. Literature Review

2.1. Framework for Energy–Water–Agriculture Planning in Rural Areas

Integrated planning for energy, water, and agriculture emerged in the early 2010s as a response to the limitations of sectoral silos in addressing interconnected resource insecurities in the global south [16,19]. Key policy platforms, including the World Economic Forum and the Bonn 2011 Conference, framed energy, water, and agriculture as an integrated system in which interventions in one sector produce cascading effects across the others [20,21]. The literature indicates that integrated resource management sustainably reduces energy and water inputs per unit of agricultural production [22,23].

Despite the growing recognition of the importance of energy for water provision in agriculture, its effective planning and implementation in rural SSA remains constrained by weak institutional frameworks and governance challenges [16,24]. Sectoral silos and fragmented mandates dominate the institutional landscape, whereas the energy, water, and agriculture sectors plan, budget, and regulate independently, with limited or no legal obligation to coordinate [18,25,26]. This fragmentation results in overlapping responsibilities, inconsistent technical standards, and competing subsidy schemes, all of which complicate planning and implementation of SPV energy projects in the rural contexts [25–27].

Furthermore, collaboration between government levels and the absence of a feedback mechanism exacerbate this challenge. Central government authorities and energy implementing agencies commonly adopt a top-down planning approach that often overlooks local needs and priorities, resulting in interventions that are technically viable but socially misaligned [27,28]. Scholars also highlight the absence of feedback mechanisms between rural community actors and local government authorities (LGAs), leading to a persistent mismatch between local energy needs and government-led development interventions [26,27]. This institutional fragmentation weakens the planning and implementation of energy–water projects for agriculture and helps explain why SPV initiatives have yet to deliver systemic agricultural transformation across many rural areas of SSA. Addressing these governance gaps requires a holistic, integrated approach that promotes horizontal coordination between sectors and vertical alignment across governance levels, supported by meaningful community participation mechanisms [26].

2.2. Multi-Level Governance of Energy and Water for Agriculture in Rural Areas

The growing energy demand for agricultural activities, combined with the pressure of climate change, necessitates a shift towards more effective and integrated governance practices that account for the hierarchical interdependencies among stakeholders [29–32]. Two complementary approaches, bottom-up and top-down, characterise the governance levels and structures through which SPV projects are planned and implemented in rural areas, reflecting how governance structures shape the impacts of energy on agriculture. Scholars argue that a bottom-up approach strengthens community participation, ensures alignment with community priorities, and fosters long-term ownership of energy interventions [33–36]. Conversely, the top-down approach enables resource mobilisation, technical sophistication, and institutional coordination, thereby facilitating effective energy project implementation [37–40].

Furthermore, these two governance structures have distinct strengths and weaknesses, and neither approach alone ensures energy sustainability in the rural contexts [41]. These governance challenges are further compounded by weak institutional capacity and limited resource allocation at the local government level, which hinder effective monitoring, maintenance, and stakeholder engagement [26,27]. Recognising the interdependence of these approaches necessitates the adoption of systems thinking perspectives to maximise resource use and ensure long-term sustainability of energy transitions in rural areas [42,43].

https://doi.org/10.3390/su18115736

Scholars further emphasise that multi-level governance in which local, regional, national, and international initiatives operate in parallel, interact, and reinforce one another results in more effective and comprehensive outcomes [41,44]. Therefore, the multi-level governance perspectives prompt an examination of how the existing institutional framework influences the solarisation process for agricultural use in the rural areas. Within this context, the Tanzanian case provides an instructive case through which to examine how institutional arrangements shape practical outcomes in the rural energy–water–agriculture interventions. The following section examines the role of institutional linkages, community involvement, and feedback mechanisms in shaping these outcomes.

2.3. Institutional Linkage, Community Involvement, and Feedback Mechanism in Rural Energy–Water Provision

Effective institutional linkage depends on collaboration between government institutions and agencies through consensus-oriented decision-making processes that bring together diverse stakeholders to address complex, cross-sectoral challenges [45]. Successful institutional linkage requires key enabling conditions, including broad participation, clear institutional design, mutual trust, and facilitative leadership [45]. Cejudo and Michel [46] argue that solving complex, cross-cutting problems demands stronger coordination and policy integration, whereby dedicated decision-making arrangements systematically prioritise the overarching problem over individual sectoral programmes. In the context of energy for water provision in agriculture, collaboration between government institutions and non-governmental organisations forms a critical foundation for strengthening institutional linkages and improving coordination, particularly where service delivery depends on cross-sectoral governance and shared implementation responsibilities [41,45,47]. Furthermore, coordination between institutions and agencies with shared developmental responsibilities involves aligning mandates, information sharing, and synchronising planning and budgeting processes to maximise service delivery outcomes in rural areas [33,40].

Community participatory approaches in rural energy–water projects represent a shift from top-down (expert-driven) implementation to a bottom-up governance approach that empowers local communities to participate meaningfully in energy projects [40,48–50]. Promoting decentralised governance, co-design, and collaboration between end-users, technical experts, and government agencies is essential to ensure that projects are contextually relevant and locally appropriate [51,52]. Scholars suggest that rural communities play a crucial role in planning and implementation by aligning energy intervention with local priorities and fostering ownership, commitment, and trust factors essential for the long-term adoption and maintenance of SPV systems [53–55]. Evidence from Indonesia shows that local involvement in site selection and operations increased household income by 25% through improved irrigation and livestock watering [56]. Similarly, in the energy sector, community-co-designed solar mini-grids in Kenya achieved 90% uptime, compared with failure rates of 40–60% in top-down projects [57]. These examples demonstrate that community engagement enhances technical reliability, improves economic outcomes, and ensures long-term project sustainability outcomes that remain elusive in many rural Tanzanian communities where top-down delivery continues to dominate [58]. The operationalisation of bottom-up and top-down approaches requires a structured feedback mechanism among stakeholders. Feedback from decision-makers to the community facilitates the smooth implementation of SPV energy projects and contributes to rural development [59]. Establishing a structured feedback mechanism between institutions helps build consensus and align activities toward achieving shared development objectives [41,46]. Scholars argue that development partners often outperform government agencies in mobilising communities, allocating resources, and promoting grassroots participation [47]. Development partners increasingly view solar energy as a climate-smart, cost-effective, and sustainable solution

https://doi.org/10.3390/su18115736

for agricultural use [16]. Taken together, the evidence underscores that meaningful community involvement and robust feedback mechanisms are indispensable for effective rural energy–water governance, a gap that this study empirically investigates in the Tanzanian context, as discussed in the following section [60].

2.4. Systems Thinking and Rural Energy Framework

Systems thinking focuses on a holistic approach to understanding how elements within a system interrelate and integrate [61]. It encompasses analytical approaches that link system structure to performance and performance to structure, with the goal of identifying leverage points for systemic change [62]. Systems thinking offers a powerful lens for understanding the energy–water–agriculture nexus because it treats these domains not as separate sectors, but as a single complex system in which technical components (such as solar pumps and boreholes), stakeholders (including farmers, agencies, and NGOs), institutions (such as policies, subsidies, land-tenure rules), and natural resources continually interact [42].

Beyond its analytical function, systems thinking also informs organisational planning, forecasting, implementation, and a feedback mechanism [63]. It provides an appropriate lens for investigating the planning and implementation of rural energy interventions because it captures the interdependencies, feedback processes, and institutional interactions that shape project outcomes across multiple sectors and governance levels [42]. In the context of SPVWPS for rural agriculture, planning and implementation involve interconnected technical and institutional processes that cannot be understood in isolation [64]. From a systems thinking perspective, these processes are governed by interactions among stakeholders, governance arrangements, and feedback mechanisms that determine how energy and water services are delivered [63,64]. Furthermore, the implementation of the SPV projects involves more than technical deployment; it also depends on how stakeholder roles and responsibilities are defined and coordinated within the institutional framework. Clearly assigning these roles supports more effective governance and helps reduce overlaps, gaps, and inefficiencies in project delivery. Systems thinking also highlights the importance of communication and feedback, as these processes enable stakeholders to assess progress, respond to emerging challenges, and strengthen coordination across actors, institutions, and implementation stages [61,65].

Moreover, systems thinking emphasises the hierarchy within complex systems, which is essential for understanding the structural organisation and interactions across energy–water–agriculture projects [66]. Each hierarchical level possesses unique functions and emergent properties that collectively contribute to the overall system performance. Hierarchies are further characterised by control and communication processes occurring at the interfaces between levels, enabling coordination and integration across the system [42]. In the context of rural SPVWPS for agriculture, hierarchical structures are important for effective decision-making because they support communication among communities, SPV developers, and policymakers. This article specifically employs three systems thinking concepts: hierarchy, interaction, and interconnectedness as analytical tools to examine how institutional arrangements shape the planning and implementation of SPVWPS in rural Tanzania, as elaborated in the methodology section.

Scholars argue that fragmented decision-making hinders the effective use of abundant solar resources in Morocco and Tunisia [67]. Similarly, in SSA, stock-and-flow and participatory modelling approaches help communities and planners visualise trade-offs between short-term food production and long-term aquifer sustainability [68,69]. However, the application of systems thinking to the governance of decentralised renewable energy remains limited and largely conceptual [24]. This article addresses this gap by adopting systems thinking as an analytical lens and a practical framework for examining institutional coordination within Tanzania's rural energy–water–agriculture stakeholder landscape.

Building on the identified gap, this article investigates how existing institutional arrangements shape the planning and implementation of SPVWPS and uses these insights to develop a conceptual institutional framework that strengthens cross-sectoral coordination, integration, and stakeholder participation in rural areas. Tanzania serves as a representative case, reflecting broader patterns of institutional fragmentation across SSA, characterised by overlapping sectoral mandates, weak intersectoral coordination, and limited community participation in development project design and implementation [27,28,69]. The article further analyses how top-down and bottom-up approaches interact and identifies the systemic coordination barriers that constrain the productive use of SPVWPS in agriculture. Drawing on interviews, focus group discussions, household surveys, and a systems thinking framework, the study proposes an integrated institutional framework to strengthen intersectoral coordination, stakeholder participation, and feedback mechanisms in rural energy–water governance. Specifically, the study answers three interrelated research questions: (1) How do existing institutional frameworks shape the planning and implementation of SPVWPS for agriculture in rural areas, using Tanzania as an empirical case? (2) What systemic coordination barriers limit the effectiveness of top-down and bottom-up approaches in SPVWPS planning and implementation, and how do these barriers manifest across hierarchical governance levels in rural Tanzania? (3) How can institutional linkages, feedback mechanisms, and community engagement be strengthened to improve the planning and implementation of SPVWPS for productive agricultural activities in rural Tanzania? Understanding these governance interactions is essential for advancing SDG 7 (Affordable and Clean Energy) and SDG 2 (Zero Hunger) in rural contexts.

The remainder of the article is structured as follows: Section 3 describes the methodology; Section 4 analyses the existing framework for energy delivery for water pumping in rural agriculture; Section 5 presents the proposed improved institutional framework for SPVWP delivery in rural agricultural activities; and Sections 6 and 7 present the discussion and conclusions, respectively.

3. Materials and Methods

3.1. Study Context

The study adopts a multiple-case study approach to develop a comprehensive understanding of the institutional arrangements governing SPVWPS in rural Tanzania. Examining multiple cases enables comparison across diverse contexts, revealing consistent patterns and contextual variations [69]. This enhances analytical depth, robustness, and credibility, as insights from each case complement one another [68,69]. Such an approach also supports meaningful conclusions about the institutional and contextual dynamics shaping SPVWPS deployment and governance in rural Tanzania [69–71].

The study covers two irrigation-focused regions, Iringa and Dodoma, and one livestock-based region, Manyara, as shown in Figure 1, which illustrates the geographical distribution of the three study sites across Tanzania. These cases were selected based on the following criteria: confirmed installation and operation of solar-powered water-pumping systems for agricultural purposes and evidence of active community use of those systems in irrigation or livestock activities. With the assistance of Energy and Water Utilities Regulatory Authority (EWURA) and Tanzania Renewable Energy Association (TAREA), a list of registered rural SPV projects was obtained, from which three projects were purposively selected to encompass diverse agricultural context, including both irrigation and livestock activities, and to reflect variation in implementing actors government, NGOs, and development foundations thereby enabling examination of different institutional arrangements as shown in List of Abbreviations.

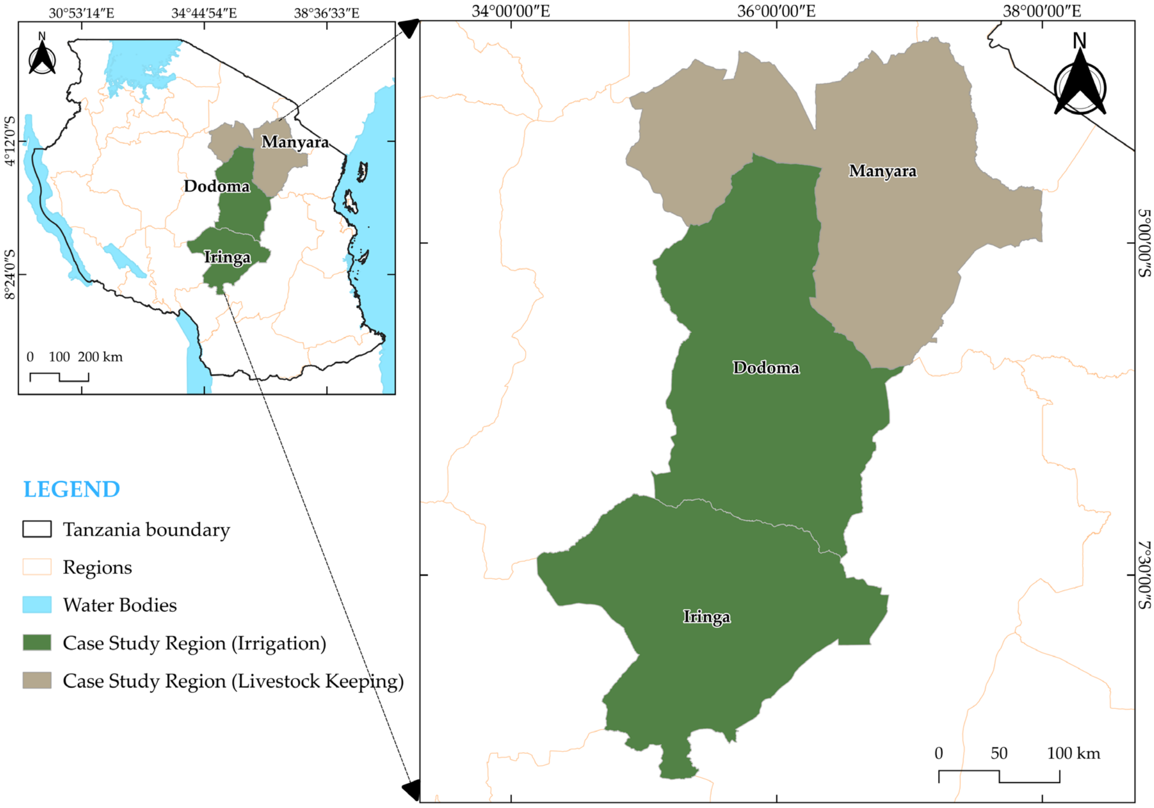

Figure 1. Case study areas. Source: Adapted from the Tanzania ad{ministrative map, National Bureau of Statistics [72].

In Lupembe-Lwasenga Village, Iringa, annual rainfall averages 700–800 mm [72]. A 14.8 kWp SPVWPS, implemented by the Elico Foundation with support from the Mott Foundation, replaced a diesel generator to support irrigation activities. In Ilolo-Kikombo Village, Dodoma, where the average annual rainfall is approximately 500–600 mm, a 7.41 kWp SPVWPS was installed by the Municipal through the Agriculture Sector Development Programme (ASDP) to improve irrigation activities. In Loswaki Village, Manyara, known for its high livestock population and annual rainfall of 450–700 mm, NGOs including OMASI/SMART Village and OIKOS installed a 7.5 kWp SPVWPS to replace a diesel generator, providing water for livestock keeping, domestic use, and home vegetable farming. Across the study regions, solar energy adoption exceeds grid connections: in Iringa, 31.9% solar versus 43.1% grid connections; in Dodoma, 34.0% solar versus 28.9% grid connections; and in Manyara, 35.1% solar versus 23.1% grid connections [72]. Nationally, only 13.8% of rural households rely on grid electricity for lighting, reflecting the growing prominence of decentralised solar systems that meet both household and productive energy needs [72].

3.2. Study Methods

This study employs a concurrent mixed-methods design to analyse the institutional framework governing energy provision for agricultural water supply. Qualitative inquiry constitutes the primary mode of investigation, and quantitative survey data have a nested function. The mixed-methods design leverages the strengths of each method whilst mitigating their individual limitations, thereby providing a more comprehensive understanding of the phenomenon [73,74]. The justification for using the mixed-methods approach in this study is as follows: first, it enables triangulation, whereby findings from different methods corroborate each other in examining the same phenomenon; second, complementarity ensures that one method enhances, elaborates on, or clarifies the results of the other [74,75]. It is appropriate for this study because the institutional framework governing SPVWPS involves both measurable patterns of stakeholder participation and coordination, and qualitative insights into the processes, relationships, and challenges shaping planning and implementation. The interview guide and questionnaire were developed drawing on constructs from the literature on rural energy governance and community participation, with selected items adapted from comparable studies and others designed specifically for the Tanzanian context.

An empirical review of academic and grey literature was conducted, encompassing policy documents and government reports, including the Energy Report for Sustainable Agricultural Innovative International [76,77], the National Water Sector Development Strategy and the Water Sector Development Programme [78], the National Irrigation Commission (Medium Term Strategic Plan 2023/2024–2027/2028) [79], and the Building a Better Tomorrow-Youth Initiative for Agribusiness (BBT-YIA) (2022–2030) [80]. The empirical review situates the study within the existing policy and institutional context, and provides a basis for understanding how governance arrangements shape SPVWPS planning and implementation in rural areas [81].

To gain deeper insights into key issues regarding SPVWPS's institutional framework for agriculture, nine semi-structured interviews with key informants and seven focus group discussions (FGD) with farmers were conducted to understand the solarisation processes across the three selected cases in Iringa, Dodoma, and Manyara regions. Key informants were selected because they play central roles in the decision-making, planning, and implementation of SPVWP projects. Also, the semi-structured interviews offer flexibility to explore issues in depth whilst ensuring consistency across interviews, enabling the collection of rich, valid insights from respondents' experiences and perceptions of institutional processes and project outcomes [82]. The FGDs provided an interactive platform that complemented survey data by revealing group dynamics, shared challenges, and collective perspectives whilst generating rich qualitative insights [83].

Moreover, 65 questionnaire surveys were administered to capture demographic information, respondents' perceptions, and satisfaction levels. This method was selected to obtain standardised and comparable data from a relatively large number of respondents, enabling the study to capture general perceptions, user experiences, satisfaction levels, and perceived benefits of SPVWPS in agricultural activities [84]. Group-administered surveys proved effective in this setting, enabling simultaneous data collection from multiple respondents [84]. Although group-administered surveys are labour-intensive, they are well-suited for studies in remote rural settings where travel costs are high, and access to individual respondents may be limited [74,84]. This integrated methodological approach enables a detailed examination of institutional relationships, policy contexts, and governance processes relevant to the study's objectives.

3.3. Study Set-Up

The study population is divided into three main groups. The first group comprises users of SPVWPS for irrigation and livestock keeping. The second group comprised SPV developers involved in the design and implementation of solar projects, registered with TAREA. The third group comprised local government representatives, including village chairpersons, village executive officers (VEOs), district agriculture, irrigation, and cooperative officers (DAICOs), and regional irrigation officers. A purposive sampling approach was employed to select participants from each group, ensuring that respondents possessed relevant experience and knowledge of the SPV water systems under study.

https://doi.org/10.3390/su18115736

Key informants were directly contacted based on their involvement in SPVWPS planning and implementation, from project inception through commissioning. FGDs were pre-arranged with the assistance of village chairpersons, farmers' group leaders, and VEOs, who facilitated participant mobilisation within each community.

A group-administered questionnaire survey was conducted with irrigators and livestock keepers (Group 1). The questionnaires were distributed, completed, and returned in a single session during community meetings convened at each site. The survey encompassed respondents' demographic information, the SPVWPS installation process, and respondents' perceptions of the benefits. Respondents were asked to rate the level of agreement using a 5-point Likert scale (5 = strongly agree, 4 = agree, 3 = neither agree nor disagree, 2 = disagree, and 1 = strongly disagree). The researcher remained present throughout to clarify any queries from survey respondents. A total of 22, 20, and 23 questionnaires were administered in Iringa, Dodoma, and Manyara, respectively.

In-depth semi-structured interviews were conducted with representatives of SPV project developers (Group 2) and local administrative leaders (Group 3). These participants served as key informants because of their direct involvement in policy interpretation, project planning and implementation, and community coordination. They provided valuable insights into the institutional framework and solarisation processes in rural areas. In addition, FGDs comprising six to ten participants were conducted with farmers and livestock keepers (Group 1) to capture their perceptions, needs, priorities, and experiences of SPVWPS installed in their areas.

Nine interviews and seven FGDs were conducted across the case study areas. The researcher facilitated the semi-structured interviews and FGDs using a topic guide organised into three sections. The first covered demographic information of respondents; the second explored perceptions and understanding of how the solarisation process was organised; and the third examined views on the benefits of SPVWPS for irrigators and livestock keepers. Interviews lasted 40 to 70 min, whilst FGDs lasted 30 to 90 min. All data collection activities, including surveys, interviews, and FGDs, were carried out between March and July 2023. The discussions were conducted in Swahili to ensure clarity and meaningful insights relevant to the research topic.

Quantitative data were analysed descriptively using SAS software version 9.4 to generate mean values and frequency distributions. Mean values were used to interpret general trends and levels of agreement among respondents. Interview and FGD participants provided consent for audio recording, after which the data were transcribed verbatim, translated from Swahili into English, and imported into NVivo 12 Plus for qualitative analysis. The transcripts were edited, segmented, and summarised to reduce volume, then coded to identify emerging themes, clusters, and patterns. This analytical process ensured that findings were systematically organised and interpreted in relation to the study's three research questions. This study involved human participants who provided informed consent prior to data collection. Participants were assured of anonymity and confidentiality, and their participation was entirely voluntary. No personal identifying information was recorded or disclosed.

4. Analysis of Existing Framework for Energy Delivery for Water Pumping in Rural Agriculture

This section analyses the institutional governance of SPVWPS for rural agricultural activities. Findings regarding sectoral coordination, administrative mandates, and stakeholders' participation are presented. Attention is given to interactions and interconnections among the energy and water sectors, and their alignment with agricultural development objectives. The analysis identifies planning and implementation gaps in the governance of SPV systems for agricultural water delivery.

4.1. The Current Framework for Planning of Energy and Water for Agriculture

Findings from the empirical review of scholarly works and grey literature, including policy documents and government reports, reveal that the framework for planning and implementing rural energy projects for water provision in Tanzania involves several key stakeholders. These include the Ministry of Energy (MoE), which sets policy and legal frameworks, the Tanzanian Electric Supply Company Ltd. (TANESCO), which monitors electricity generation, transmission, and distribution, and the Rural Energy Agency (REA), which promotes access to electricity in rural areas [28,85,86]. REA recognises the productive use of energy (PUE) within its broader rural electrification and renewable energy support instruments. However, based on the reviewed REA documents, a fully operational PUE framework targeting rural agricultural applications is not yet institutionalised [87].

Furthermore, the review reveals that the Ministry of Water (MoW) collaborates with the Rural Water Supply and Sanitation Agency (RUWASA) to develop rural water supply systems and oversees rural water projects that are managed by Community-Based Water Supply Organisations (CBWSOs) under district council supervision [88,89]. EWURA regulates technical and economic performance across both the energy and water sectors [71]. Agriculture, particularly irrigation and livestock, falls under two separate ministries: the Ministry of Agriculture (MoA) and the Ministry of Livestock and Fisheries (MLF) [90,91]. The National Irrigation Commission (NIRC), under MoA, oversees irrigation development and efficiency, whilst the Directorate of Livestock Development (DLD), under MLF, oversees livestock development and farmer extension support [90].

Figure 2 illustrates the existing public service delivery structure in Tanzania's rural areas, showing the hierarchical organisation and communication channels from the central to the local government, integrating the MoE, MoW, MoA, MLF, and their agencies. The structure spans administrative levels from the national to the village level. The red-dotted lines indicate weak sectoral linkages and miscommunication in the planning and implementation of development programmes. The four ministries are responsible for energy, water, agriculture, and livestock development, and maintain limited horizontal coordination, which often leads to fragmented and uneven service delivery in rural areas. Scholars argue that the institutional framework fails to support effective service delivery in rural areas. From a systems thinking perspective, this represents a failure of horizontal interconnectedness and cross-level feedback, two dynamics central to effective institutional governance. The literature contends that the institutional framework for service delivery in rural areas remains complex and fragmented, with overlapping mandates and limited cross-sectoral communication [27,92]. Coordination challenges often stem from sector-specific policies and funding streams that prioritise institutional objectives rather than shared outcomes [8,28,93]. Tanzania's sector ministries maintain a vertically integrated administrative structure (region to district to ward to village) but operate through horizontally disconnected governance systems, reinforcing institutional silos and undermining integrated rural development planning for sustainable livelihoods improvement.

As shown in Figure 2, SPV for water availability in agricultural activities is undertaken by four separate institutions, with limited integration into rural infrastructure planning, resulting in parallel interventions without linkages. This highlights that weak cross-sectoral coordination constrains productive activities such as irrigation and livestock development and reduces the impact of SPVWP intervention [5,6].

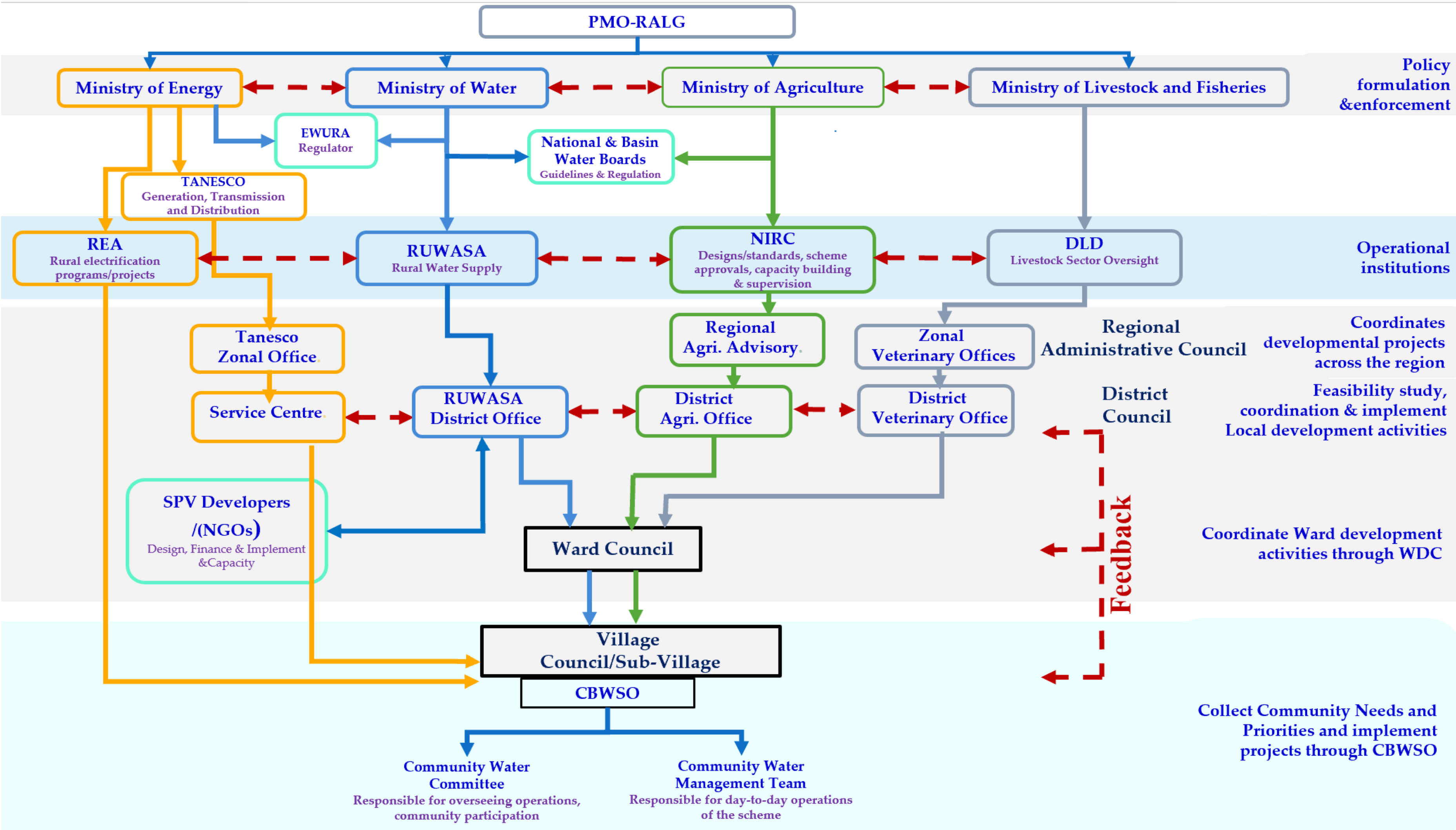

Figure 2. The existing framework for energy, water, and agriculture service delivery in rural areas shows hierarchical linkages and areas requiring stronger coordination. Sources: Adapted from Gudaga et al. [94], Sustainable energy for all [91], and the United Republic of Tanzania (Local Authority Act) [93].

4.2. Insights from the Field Work

This section presents the demographic characteristics and educational profiles of participants across the three case study areas, contextualising the study population within rural solar energy initiatives. Demographic information of the study population across the three study areas is presented in Appendix B (Table A1). The in-depth interviews (n = 9) primarily involved male participants aged 30–49, most of whom held diplomas or certificates reflecting their roles as technical and administrative decision-makers. The survey (n = 65) had balanced gender representation (and participants were predominantly engaged in full-time agriculture, with a primary education level and an average age of 37–43 years across the three sites. The FGDs (n = 7) primarily included female participants aged 30–49, most of whom were full-time agricultural workers with a primary-level education. The predominance of primary-educated participants among community members underscores the importance of accessible, participatory engagement approaches over technically complex top-down implementation processes, a finding that recurs throughout the analysis in subsequent sections.

4.2.1. Institutional Coordination and Procedural Delays

An interview with an SPV developer in Manyara revealed that procedural and coordination challenges delay the implementation of SPV projects. Delays stem from fragmented communication among local government authorities (LGAs), developers, and RUWASA, particularly during the approval phase. The interviewee explained that project implementation was often delayed because the community, the developer, and RUWASA must reach a common understanding before work could begin. The respondents further clarified that although villagers communicate their SPV needs and their agreement with the developer to RUWASA, the lengthy approval process, legal review, and administrative verifications extended the timelines before project activities could commence. An interviewee narrates:

> *"… . The procedure involved extensive paperwork and back-and-forth communication more than we expected." (IDI 4, Manyara)*

Similarly, in Dodoma, FGDs with farmers revealed that the Kikombo irrigation project experienced limited feedback from the LGA during the operational phase. Farmers reported that although challenges are communicated to leaders, responses remain low, resulting in inefficiencies and farmer frustration. One FGD respondent states:

> *"We have reported the challenges we are facing to our leader, but nothing has been done until now. All local leaders and those at the district level know our problem, but no action has been taken to date". (FGD 1, Dodoma)*

These findings demonstrate that coordination challenges exist from project initiation through implementation and operation. Limited feedback between governance levels reduces accountability, slows decision-making, and undermines the performance of the SPV system. These lifecycle governance gaps highlight the need for clearer communication and stronger coordination among stakeholders across all project phases. Findings suggest that planners and implementers overlook opportunities for synergies between energy, water, and agriculture initiatives. From a systems thinking perspective, these coordination failures reflect the absence of effective feedback mechanisms and weak interconnectedness across hierarchical governance levels. Stronger coordination among agencies, particularly REA, NIRC, and RUWASA within national planning frameworks, would bridge this gap and unlock the productive potential of rural energy for water in rural agriculture. Establishing joint planning mechanisms, harmonising policy instruments, and promoting shared data systems could facilitate this integration.

4.2.2. Governance and Stakeholders' Interactions

An interview with a key informant in Iringa revealed that the main stakeholders in the solar-powered irrigation initiative include the crop buyer, SPV developer, villagers, and VEOs. The crop buyer linked the farmers in Lupembe-Lwasenga with development partners supporting the transition from diesel-powered to SPV irrigation pumps. Communication began between the crop buyer and the farmers before formal information and procedures were sent to VEO and the District Council. One interviewee explains:

> *"Farmers in Lupembe-Lwasenga village, who supplied vegetables to markets in the United Kingdom and the United States through a crop buyer, face high irrigation costs due to their reliance on fuel-powered pumps. To address this challenge, the MOTT Foundation, introduced by the crop buyer, proposed transitioning to solar energy for irrigation. After several discussions with the villagers and the VEO, the Iringa District Council received formal notification through the Municipal Irrigation Engineer that Elico Foundation will implement the SPVWPS". (IDI 7, Iringa)*

In Dodoma, the interview reveals that the solarisation initiative involved collaboration between the District Council, development partners, and the local community. The respondent explained that the African Development Bank (AfDB) funded the project as part of its support for agricultural activities in the district. The interviewee also describes how the flow of information begins with villagers presenting their needs through village assemblies and councils, which then submit these priorities to the District Council. After the District Council conducts a feasibility study, the SPV project is implemented using allocated LGA funds, supplemented by contributions from development partners such as FAO. An interviewee notes:

> *"The Kikombo irrigation project was implemented and operated by the Council using funds from the DADPs plan, which forms part of the Agricultural Sector Development Programme (ASDP). Initially, the villagers submitted their needs and priorities to the District Council through the Ward Development Committee, and after the feasibility study, the Council implemented the project". (IDI 8, Dodoma)*

In Manyara, an interviewee explained that the SPV developer initiated the project by identifying the energy challenges faced by villagers in the Terat Ward and proposed a SPV solution. The respondent further explained that the community accepted the proposal following extensive discussions among villagers, the District Council, and a representative from RUWASA. The SPV developer implemented the solar-powered pump PV system after reaching a payment agreement with the villagers, coordinated by the local water committee under RUWASA's supervision. An interviewee narrates:

> *"When the milk processing system was established at Terat (2008–2010), a large generator was installed, but it was supplemented with plant-based biodiesel. However, the generator was damaged, most likely due to the use of unrefined biodiesel. In 2019, SMARTVILLAGE Research Group partnered with OMASI under the Smart Integrated Community Energy in Tanzania initiative, working with local communities to identify challenges and design renewable energy solutions, such as SPV, to meet their needs". (IDI 7, Iringa)*

Furthermore, the interviewee noted that NGOs have played a crucial role in financing SPVWP systems. However, community contributions remain necessary to demonstrate commitment, enhance ownership, and ensure readiness to participate in the solarisation process. The interviewee stated that in Manyara, the community contributed to the installation cost through several instalment payments. The unpaid balance was granted by OIKOS. An interviewee explains:

"We had a contract because they wanted it to be that way; they would not give us the solar panels for free. Instead, they lent them to us with the expectation that we would repay through the sale of water to the community. Therefore, we entered a three-year contract, which included a grant of 30 million Tanzanian shillings. The repayment process is ongoing. Once the loan is fully repaid, all profits generated will be used to benefit and improve our water supply infrastructure". (IDI 7, Iringa)

FGDs with pastoralists in Manyara further revealed that payment arrangements were managed through the Local Water User Committee (Kamati ya Watumia Maji), which coordinates the collection of contributions from community members based on the agreed amount. This arrangement involves a formal three-year repayment contract under which the NGO provides the solar system as a loan rather than a donation. Respondents explained that repayment is made from revenues generated through water sales. Once the loan is cleared, management of the solar system is transferred to the Water User Committee, which collects revenues and reinvests them in improving local water infrastructure. One FGD respondent narrates:

"OMASI and OIKOS collaborated with RUWASA, and we were connected and supplied with a solar PV system. We agreed to pay for it; it was not free. We are paying in instalments over a three-year period". (FGD 1, Manyara)

4.2.3. Local Community Participation and Social Structures in the Solarisation Process

Survey findings reveal that the local community is involved in the planning and implementation of the solarisation process. Table 1 summarises respondents' views on community participation in planning and implementing SPVWPS for agriculture across the three case study areas. A total of 89% of respondents reported that the community was involved in the solarisation process through several village meetings, whilst 70% noted that all villagers were invited. However, 30% of respondents thought that only some were invited. Additionally, 75% of respondents reported participating in fundraising meetings, and 78% reported being involved in identifying project locations. However, in Dodoma, only 42% participated in fundraising activities, whilst 58% reported not participating. This is because information regarding fundraising arrangements was not effectively communicated to all community members. These findings show that local communities are being engaged in the solarisation process through village meetings and contribute to decision-making on the solar PV water-pumping projects for agricultural use. Overall, whilst community participation is robust, its depth and consistency vary by region and activity, depending on how information was disseminated to the community. This suggests the need to strengthen inclusiveness and communication mechanisms among stakeholders involved in the solarisation process.

Table 1. Local community involvement in the planning and implementation of SPVWPS.

Regions	Several Village Meetings		Everyone Invited		Identify Location		Fundraising Meetings	
	Yes	No	Yes	No	Yes	No	Yes	No
Dodoma	15	4	8	11	16	3	8	11
Iringa	19	3	14	8	19	2	12	5
Manyara	23	0	23	0	14	9	23	0
Total	57	7	45	19	49	14	44	15
Total%	89%	11%	70%	30%	78%	22%	75%	25%

Source: Field, 2023.

Furthermore, FGDs with farmers in Iringa support the survey findings. In contrast, they explained that they participated in manual work associated with SPV installation, such as excavating, loading, and unloading materials for the construction of a water storage tank. A FGD respondent explains:

> *"We participated in digging trenches from the pump house to the tank and preparing the area for the construction of the storage tank. We also loaded and unloaded materials during the construction of the water storage tank". (FGD 1, Iringa)*

Similar observations have been reported in Malawi, where villagers contribute unskilled labour during the construction of water projects, demonstrating community support for local infrastructure development [95]. Likewise, Ahmar et al. [95] suggest that active community participation in the planning and implementation phases enhances the adoption and productive use of SPV technologies. Such engagement may enhance acceptance and long-term security of SPVWPS, promoting a sense of ownership that enhances project acceptability and sustainability [96–98].

Moreover, interviews with the SPV developer in Iringa revealed that the formation of farming groups, the election of water committees, and the strengthening of existing community groups were important during the planning and implementation of the SPV project. The respondent reported that bylaws govern the formation of these groups, with leaders elected during village assembly meetings. They also emphasise that the existence of organised farming groups in an area is a key factor for SPV developers, particularly NGOs, when selecting villages for solarisation. A respondent narrates:

> *"Ideally, we did not go to Lupembe-Lwasenga village to start something new; the people were already engaged in irrigation schemes and had initiated a process to form farming groups, although they were not yet formalised (i.e., not registered or did not have a bank account). The crop buyer introduced us and began working with the community". (IDI 7, Iringa)*

Further interview with the VEO in Lupembe village indicates that informal groups are encouraged to formalise by registering with local authorities, opening a group bank account, and appointing designated signatories. The respondent noted that villagers were required to contribute an agreed amount to the account to support the maintenance of the SPV system. In contrast, an interview with the RUWASA representative in Manyara revealed that the water committee makes an advance payment directly to the project developers. In contrast, in Iringa and Dodoma, individual group members contribute to the group account monthly.

Furthermore, an interview with a key informant from Manyara District Council highlights the important role of traditional leaders, particularly elders, in influencing community acceptance of SPVWPS. In this context, project developers often begin the implementation process by engaging with traditional leaders, recognising their cultural and social influence on their community. The respondent explained that among the Maasai, traditional leaders known as *Laigwanan* play a central role in shaping community acceptance of the solarisation process. The interviewee further explained that SPV developers begin by engaging and educating these elders about the technology and its potential benefits. Once the *Laigwanan* understand and endorse the initiative, they act as trusted intermediaries, communicating information to the wider community in culturally appropriate ways. This approach fosters smoother communication and enhances community buy-in. The interviewee elaborates:

> *"Sometimes we use elders (Laigwanans) because of how our society is culturally constructed. If the elder is educated and understands, then he returns and communicates to his society, and they understand him very well. If the elderly leader understands and communicates with them (the villagers), the likelihood is that they will accept the project". (IDI 1, Manyara)*

The involvement of local leaders (elders) underscores the value of culturally embedded stakeholder engagement, where leveraging traditional authority helps bridge the gap between external actors such as NGOs or SPV developers and rural communities. This culturally grounded approach enhances trust, communication, and community acceptance of SPVWPS. However, despite the strengths at the local level, gaps emerge when decisions are forwarded to higher tiers of governance, where community influence tends to diminish.

Findings from FGDs revealed that, whilst villagers initially identify and communicate their needs through village meetings, subsequent decisions are often made at district or regional levels without further consultation. Once priorities are submitted, local government authorities (LGAs) revise them during council meetings and determine which projects to implement first. Community involvement in this stage is limited, so that villagers may be unaware of the final decisions made at higher levels. A FGD participant in Dodoma explains:

> *"Since launching the Kikombo irrigation project in this village to date, the project has been formally handed to us. Government officials sometimes visit us, accompanied by development partners, to gather information on the project's challenges and opportunities. However, they rarely follow up or give us feedback". (FGD1, Dodoma)*

In addition, the FGD respondents revealed that several village meetings play a crucial role in awareness creation and deliberating on the introduction of SPV systems for agriculture. Focus group respondents noted that they were invited to meetings through public announcements and that village leaders encouraged them to attend. A respondent narrates:

> *"I heard about the solarisation from the village leader as I gave him a ride to somewhere on my motorbike". (FGD 1, Dodoma)*

These findings align with previous studies suggesting that local governments often implement centrally determined plans based on budgetary guidelines rather than community priorities [27]. Although District Councils nominally delegate planning responsibilities to lower administrative levels, real decision-making power remains at the central level, thereby limiting participatory governance [52]. This disconnect highlights a persistent tension between top-down administrative structures and the principles of bottom-up rural development. Also, studies suggest that village meetings serve as an important platform for community participation in decision-making [26].

Interactions among the three key stakeholders, namely SPV developers, decision-makers, and the community, reflect a mix of top-down and bottom-up approaches; however, weak coordination of the SPVWP project for agriculture remains evident. The absence of feedback creates communication gaps that undermine project efficiency and trust among beneficiaries. Strengthening feedback mechanisms, particularly during feasibility assessments and project evaluations, is essential for ensuring that SPVWP projects remain responsive to community needs and contribute to long-term sustainability.

4.3. Bottom-Up and Top-Down Approaches as Drivers of Change in Rural Areas

Building on the hierarchical levels of stakeholder engagement identified above, this study categorises stakeholders into three key groups: community, policymakers, and developers. Each group performs a distinct role at different stages of the solarisation process. Insights from the three study areas are illustrated in Figure 3a–d. The Figure shows that interactions among these actors shape the SPVWPS demand, availability, and operational efficiency, highlighting the systemic interdependence of bottom-up and top-down approaches in planning and implementing SPVWPs in rural areas. The figures also illustrate how these dual approaches shape technological performance, governance structures, and overall project outcomes. These four governance models reflect varying degrees of hierarchical coordination, stakeholder interconnectedness, and feedback integration.

Figure 3a illustrates the bottom-up approach, in which rural communities communicate their needs and priorities to policymakers after discussion at village meetings and through the Ward Development Council. Following an evaluation and feasibility assessment, the LGA collaborates with SPV developers to implement projects within the community. In contrast, Figure 3b demonstrates the top-down approach, which aligns with government development objectives, strategic plans, and budget allocations for rural initiatives. Whilst this approach ensures that SPV interventions address urgent rural energy needs, it often faces challenges related to community acceptance, operational efficiency, and long-term sustainability.

Furthermore, Figure 3c illustrates a hybrid model that integrates both bottom-up and top-down approaches. In this arrangement, community needs and priorities are first identified through participatory processes, as shown in Figure 3a, whilst project implementation depends on the outcomes of feasibility studies and the availability of funding. The bottom-up approach supports local needs assessment, whilst the top-down strategy guides the overall implementation and resource allocation. Figure 3d presents a developer or partner-driven model, in which SPV developers, NGOs, or development partners identify specific community challenges, propose technical solutions and a financial model, and facilitate stakeholder consultations. Once a consensus is reached, stakeholders submit the energy demand to the LGA for approval, coordination, and integration into local plans and policies. Collectively, these governance pathways demonstrate that sustainable SPV development in rural areas depends on the effective interaction between community-driven demand, institutional coordination, and developer engagement. Balancing these approaches enhances both the responsiveness and efficiency of solarisation initiatives for agricultural development.

Overall findings indicate that effective solarisation in rural areas depends on the coordinated interaction of all three stakeholder groups: communities, policymakers, and developers. Integrating bottom-up and top-down approaches in planning and implementation enhances alignment between local needs whilst upholding institutional accountability. Such a hybrid approach enhances implementation efficiency and promotes community ownership of SPVWP systems for agricultural activities in rural areas.

Interviews' evidence from key informants supports the interaction illustrated in Figure 3, emphasising that district-level irrigation projects depend on community readiness, a supportive environment, and an informed understanding of local priorities. The interviewee explains:

> *"The implementation of irrigation projects at the district level depends on community readiness, a supportive environment, and the identification of local needs and priorities. Village and ward authorities initiate development projects, and the District Council subsequently evaluates them and allocates funds based on community priorities and government guidelines. Implementation follows the established LGA procedures".* (IDI 8, Dodoma)

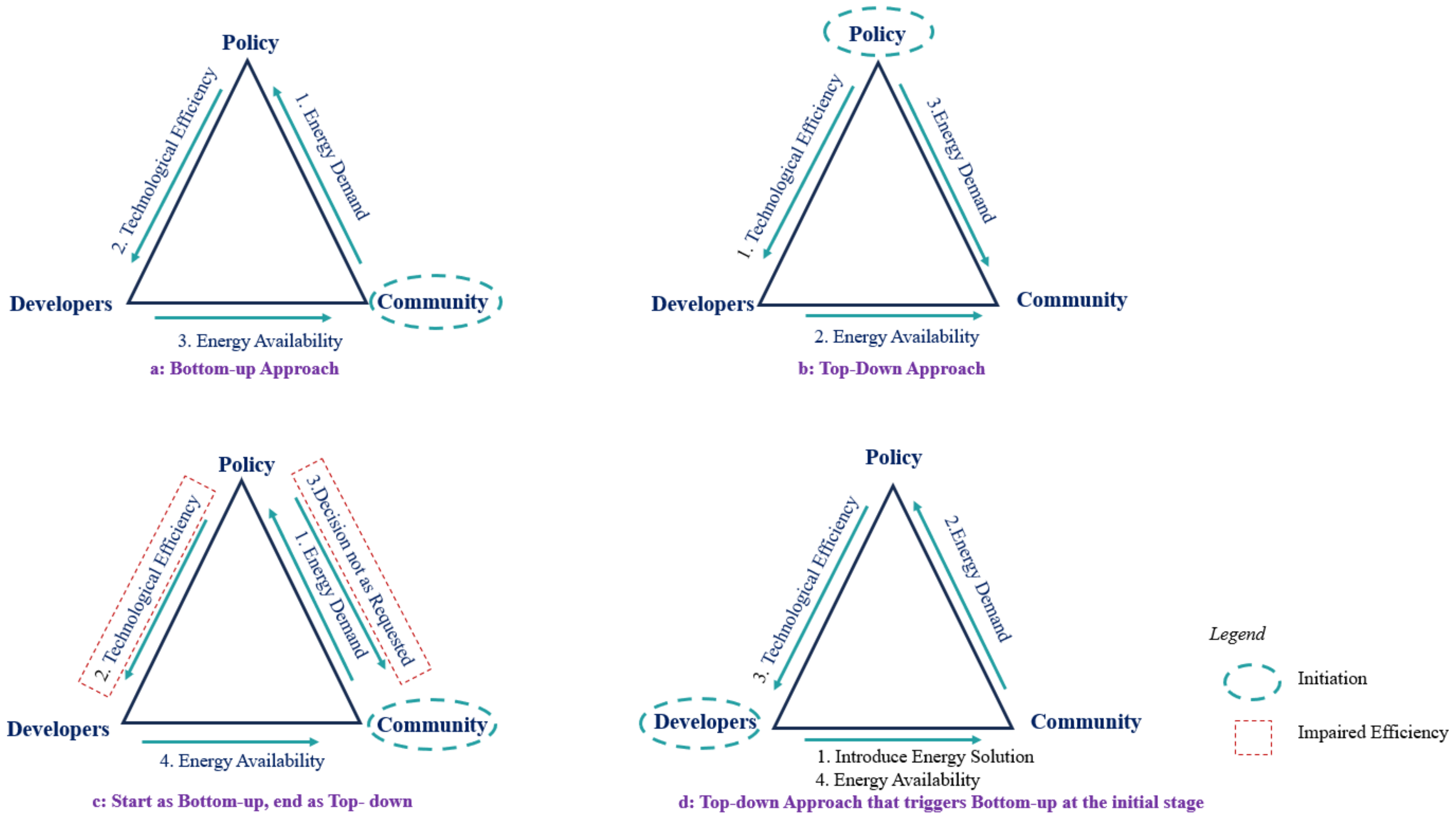

Figure 3. Categorisation of stakeholders and interaction between bottom-up and top-down approaches in the solarisation process.

Despite this structured process, several systemic challenges persist, including financial constraints, limited technical knowledge and skills, community acceptance, and sustainability concerns. From a systems thinking perspective, these challenges reflect breakdowns in feedback mechanisms and weak interconnectedness across hierarchical governance levels, precisely the dynamics that undermine effective SPVWPS delivery in rural Tanzania. Studies suggest that strategic and inclusive electrification programmes should be tailored to local contexts by combining customised SPV systems with targeted appliances, training, and capacity-building initiatives delivered collaboratively by developers and government agencies [99]. Such integration enhances the productive use of electricity in the agricultural sector. The World Bank [100] notes that bottom-up approaches provide more accurate local demand forecasts, whilst top-down strategies offer financial and institutional support for large-scale implementation. However, an overreliance on top-down decision-making risks overlooking local contexts and misaligning interventions with community needs [101]. Integrating both approaches is therefore vital for effective planning, inclusive participation, and sustainable rural energy delivery [40].

5. Development of an Improved Framework for SPVWP Delivery in Rural Agricultural Activities

Drawing insights from the preceding analysis of institutional coordination, community participation, governance, and stakeholder interactions, this section develops a conceptual framework to guide the planning and implementation of SPVWPS for agricultural activities in rural areas. The framework combines systems thinking, specifically the concepts of hierarchy, interconnectedness, and feedback, with bottom-up and top-down approaches to support a more integrated strategy for SPVWP delivery in rural areas. Figure 4 presents the proposed framework depicting key stakeholders and their roles and responsibilities. The framework proposes stronger coordination to support more effective planning and implementation of SPVWPS across the study areas. It also emphasises that strong horizontal communication, coordination, and feedback among stakeholders are essential for improving SPVWP delivery and improving water access for agricultural use in rural areas.

The proposed framework adopts a systems-thinking perspective to illustrate the interconnection and interdependence among stakeholders involved in the solarisation process. Arrows illustrate communication between different levels and stakeholders within the framework. Solid red arrows show the proposed interactions and essential linkages that require strengthening among institutions and their respective offices at the regional and district levels. Coordination among these key stakeholders responsible for energy, water, and agricultural activities is important for delivering solar energy for productive use in the rural areas. Similarly, red arrows within LGAs indicate limited feedback from District Councils to villagers during SPV implementation, a gap that requires strengthening. In addition, poor inter-agency communication leads to the independent provision of solar energy and water services, undermining the PUE in agriculture and reinforcing scholarly arguments that energy access alone cannot improve rural socio-economic well-being [69,101].

Therefore, the proposed framework calls for stronger coordination and interrelationships between REA NIRC, DLD, and RUWASA to ensure coherent planning, resource allocation, and shared progress toward rural development objectives. Establishing feedback mechanisms between these institutions and LGAs promotes alignment and integrated service delivery. Furthermore, regulatory bodies such as the National Water Board and Basin Water Boards play a crucial role in ensuring equitable and sustainable water use [79,89]. Ultimately, systematic coordination across all stakeholders, including government agencies, the private sector, NGOs, and community-based organisations, is essential to reduce duplication, enhance accountability, and deliver sustainable energy–water services that support agricultural productivity and rural livelihoods [102].

Moreover, the proposed framework illustrates a streamlined implementation process in which SPV developers engage directly with community administrative leaders and village representatives, reducing procedural delays whilst maintaining the oversight role of ward and village councils. This approach strengthens stakeholder communication and supports transparent, responsive implementation. However, overlapping mandates and responsibilities within the local government structure continue to prolong SPV project implementation in Tanzania [26,69].

The feasibility study conducted by the government authority at the district level is a prerequisite for project implementation, providing a foundation for informed decision-making and effective resource allocation. As reported by the interviewee, after gathering community needs and priorities, District or Regional Councils assess project costs, economic viability, and potential environmental impacts to ensure that SPVWPS benefit the majority. Conversely, interviews revealed that private SPV developers and NGOs conduct embedded feasibility studies or risk assessments to evaluate community readiness and the long-term sustainability of projects. These actors often leverage the local potential, such as organised farming groups, reliable water sources, and community willingness to participate, as decisive factors in site selection. This approach aligns with Bhattacharyya and Srivastava [103], who emphasise that local energy needs, resource availability, economic conditions, and socio-cultural contexts shape rural operational frameworks. Similarly, Szabó et al. [104] highlight that aligning technological choices with agricultural practices enhances project success, whilst Pueyo and Maestre [105] stress that embedding community priorities into feasibility assessments strengthens ownership and sustainability. Moner-Girona et al. [106] further note that integrating socio-economic and environmental dimensions into planning increases the resilience of SPV projects in rural agricultural settings.

Prior to finalisation, the proposed framework underwent structured expert validation. Three purposively selected experts, a local SPV developer, a representative from the MoE, and a representative from TAREA independently evaluated the framework against criteria including clarity, completeness, logical consistency, policy relevance, and practical applicability. The validation exercise confirmed the framework's relevance and applicability to rural energy–water–agriculture governance in Tanzania.

Given the limited resources available for rural development, integrating the energy, water, and agriculture sectors is crucial for achieving sustainable development outcomes. Such integration creates a unified roadmap for planning and implementing rural energy projects to improve agricultural productivity and socio-economic well-being [107]. Tanzania's Integrated Rural Electrification Planning (IREP) approach, outlined in the National Electrification Program Prospectus, introduced a geospatial, impact-driven methodology that prioritises areas with the highest development potential [108], thereby offering a strategic basis for aligning electrification with broader agricultural development goals. However, weak coordination among REA, RUWASA, and NIRC has hindered the effective integration of grid and off-grid planning for agricultural development. Strengthening collaboration and feedback mechanisms between these agencies and LGAs can improve planning coherence and ensure that SPVWP projects meet community agricultural needs. Evidence from other developing countries indicates that poor institutional coordination hinders long-term sustainability, whilst integrated governance frameworks promote adoption and lasting success [109,110]. Therefore, strengthening the energy–water nexus for agricultural activities in rural Tanzania is pivotal to realising the full potential of SPVWPS and advancing progress towards SDG 7 (Affordable and Clean Energy) and SDG 2 (Zero Hunger) in rural sub-Saharan Africa.

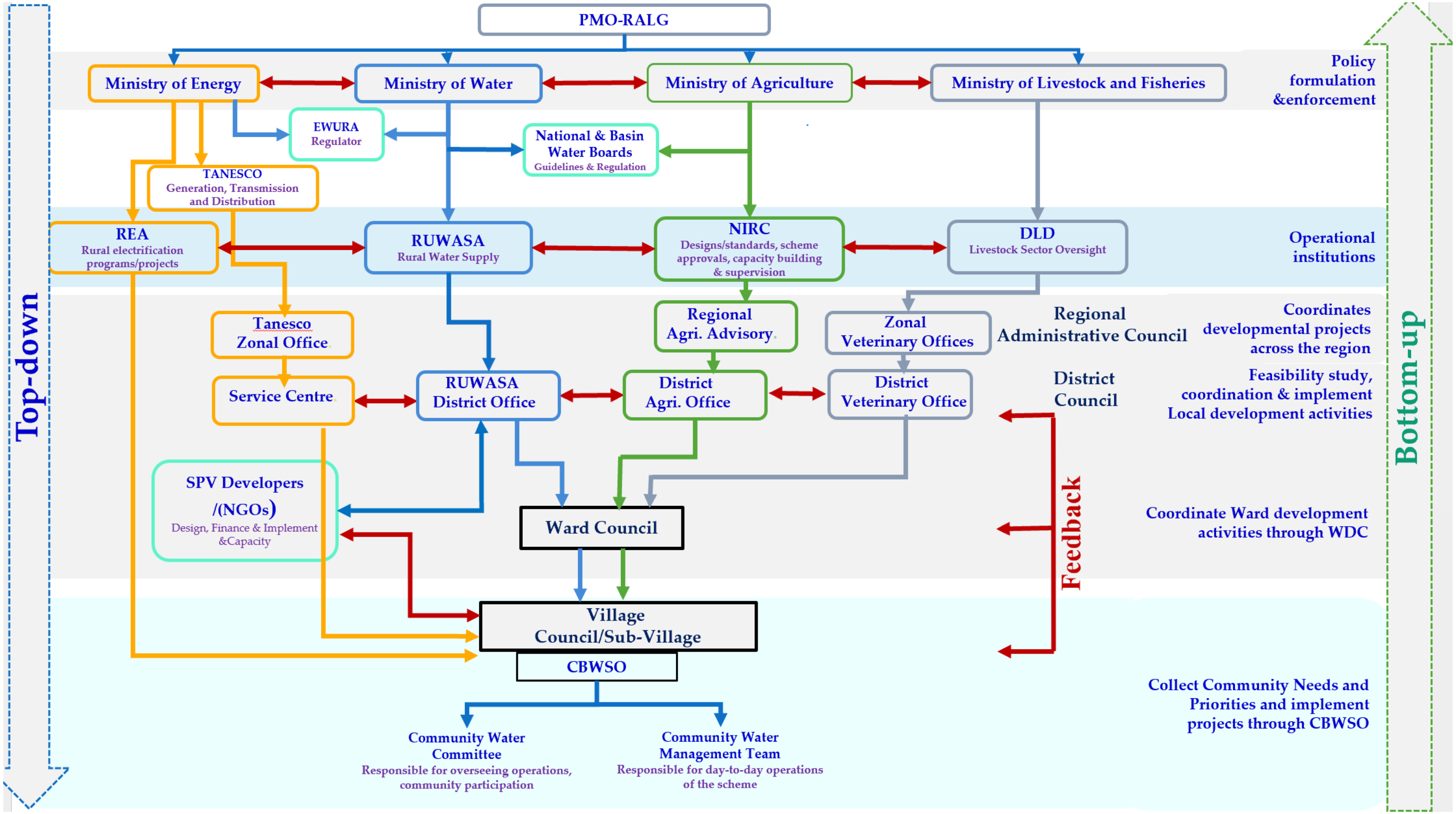

Figure 4. Proposed conceptual framework for SPVWPS planning and implementation in rural areas. Solid red arrows indicate the key institutional interactions and linkages that require strengthening at the regional and district levels.

6. Discussion

The study findings indicate that the SPVWP projects promoting agricultural activities in rural Tanzania are hindered by fragmented institutional coordination and limited feedback among stakeholders. This study did not evaluate the full technical or economic efficiency of SPVWPS; instead, it focused on institutional frameworks, stakeholder interactions, planning, and implementation processes that shape outcomes. Within this scope, the results suggest that limited coordination and fragmented communication among stakeholders constrain the effective integration of solar energy and water systems for productive use in agricultural activities in rural areas.

The identified gaps in communication and coordination among institutions responsible for rural electrification, water service provision, and irrigation and livestock activities, including REA, RUWASA, NIRC, and DLD, show how sectoral silos undermine the integrated planning and implementation of rural development projects. Similarly, governance challenges have been widely documented in the decentralised renewable energy and water–energy–food nexus literature, where weak inter-agency collaboration limits the PUE despite available resources [16,24]. Evidence from Tanzania and other sub-Saharan African contexts suggests that misalignment between sectoral mandates frequently results in projects that achieve electrification targets without delivering sustained agricultural or water-related benefits [45–47,111]. These findings align with broader analyses that identify institutional fragmentation, rather than technological limitations, as a critical constraint to rural development outcomes [51,112].

The findings further indicate that the effectiveness of bottom-up planning diminishes when feedback mechanisms remain weak or absent, resulting in limited community visibility into how locally articulated priorities influence final development decisions. This suggests that community participation alone does not guarantee meaningful inclusion unless it is supported by a feedback mechanism across governance levels. This observation aligns with previous studies showing that weak feedback processes reduce the effectiveness of participatory planning and limit accountability across governance levels [27,40,113]. Further empirical evidence from East Africa and South Asia shows that hybrid governance arrangements perform more effectively than exclusively centralised models in sustaining decentralised renewable energy interventions [114,115]. Similarly, integrating bottom-up and top-down approaches fosters inclusivity, accountability, and adaptive learning within decentralised energy governance frameworks [38,40,116]. Community involvement in decision-making strengthens local ownership and system reliability, ultimately improving the long-term sustainability of SPVWPS in rural contexts.

Furthermore, the findings show that local government planning frameworks in Tanzania are formally designed to operate through participatory and community-based processes, whereby project initiatives originate at the local level and move upward through administrative structures. However, this formal design does not necessarily translate into meaningful participation in practice, as communication often weakens once communities submit their priorities to higher levels. As a result, the credibility and practical value of community involvement diminish during later stages of planning and implementation. This pattern is consistent with findings from the decentralisation and rural development literature, which show that central government priorities frequently override locally endorsed plans, thereby reducing implementation effectiveness [26,102,116]. This dynamic, in which community-level priorities lose influence as decisions move from the local to district, regional, and national levels, emerges as a critical governance challenge for energy and water interventions aimed at productive use in rural agricultural activities. The integrated framework proposed in Section 5 directly addresses this challenge by embedding structured feedback mechanisms and joint planning processes across all governance levels.

From a systems thinking perspective, energy and water provision for agricultural activities constitutes an interconnected socio-economic system in which stakeholders, institutions, and resources interact dynamically. Systems thinking emphasises interdependencies, interconnectedness, and feedback loops across institutional levels as key determinants of system performance [42,60]. The study shares findings that corroborate those of previous studies: weak feedback mechanisms do not necessarily undermine immediate project functionality but pose substantial risks to long-term sustainability, particularly with respect to system maintenance and stakeholder ownership [63,109]. This dimension is relevant for SPVWPS, where initial operational success may obscure deeper governance-related vulnerabilities.

Although governance, coordination, and stakeholder interaction factors are central to the findings, alternative explanations warrant consideration. Technical system design, financing mechanisms, and post-installation support arrangements also influence SPVWPS performance as documented in studies from other contexts [10,12,117]. These factors fall outside the scope of the present institutional analysis but remain important determinants of system outcomes. The findings from the rural districts of Manyara, Dodoma, and Iringa reflect Tanzania's specific institutional governance context, as manifested in the solarisation process. However, challenges such as sectoral fragmentation, inadequate feedback mechanisms, limited community involvement, and poor coordination between the energy, water, and agriculture sectors mirror trends observed across other SSA settings [64,110]. Therefore, the study offers insights applicable to comparable rural settings where decentralised renewable energy systems support productive agricultural activities, subject to variations in institutional and policy frameworks.

7. Conclusions

This study examines how institutional frameworks shape the planning and implementation of SPVWPS for agricultural activities in rural Tanzania. The study found that the existing institutional arrangement limits SPVWPS outcomes through fragmented mandates, overlapping administrative structures, and weak intersectoral coordination, resulting in incoherent planning and implementation of SPVWP projects for agriculture. Limited collaboration among the rural electrification, water, and agricultural sectors constrains the effective integration of solar energy and water systems for productive use in rural contexts. Although decentralised governance structures exist in principle, their operationalisation remains constrained by inadequate inter-agency communication and overlapping roles and responsibilities, undermining coherent planning and resource allocation. Strengthening these institutional linkages is therefore fundamental to achieving coherent, integrated cross-sectoral delivery of energy and water solutions that enhance agricultural productivity.

The study further concludes that systemic coordination barriers limit the effectiveness of both bottom-up and top-down approaches in planning and implementation of SPV projects. Whilst the community articulates their priorities through a participatory planning framework, their influence diminishes during implementation due to limited feedback mechanisms, centralised financial control, and misaligned budgeting decisions. This shortcoming reduces the responsiveness of solarisation initiatives to community agricultural needs. Bridging this disconnect requires institutionalising iterative feedback systems that link local priorities with district, regional, and national planning, thereby promoting adaptive governance capable of learning and responding to community needs.

The study proposes an integrated framework that combines systems thinking with bottom-up and top-down approaches as a practical pathway for improving institutional coordination and communication among stakeholders in rural solarisation. Unlike existing frameworks that treat governance and technology as separate concerns, the proposed framework explicitly embeds a feedback mechanism, aligns stakeholder roles and responsibilities, and integrates community participation across all planning and implementation stages. The framework suggests that solarisation for productive use depends on aligning roles and responsibilities, embedding structured feedback mechanisms, and strengthening local capacity for operation and maintenance. Improving collaboration among government agencies, particularly REA, RUWASA, and NIRC, development partners, and the rural community can unlock the productive use potential of decentralised solar energy systems for agricultural activities. This holistic approach supports SPVWP project sustainability and broader social–economic initiatives in rural areas.

Whilst this study primarily focuses on institutional and governance dimensions, it recognises that technical design, financing, and post-installation management also shape SPVWPS outcomes; these issues warrant further empirical attention. The case study evidence from rural districts in Manyara, Dodoma, and Iringa limits direct generalisation; however, the institutional challenges identified, particularly fragmented institutional mandates, weak inter-agency collaboration, and limited community feedback during planning and implementation, are characteristic of decentralised renewable energy initiatives in many rural settings across SSA and Asian contexts. Consequently, the insights generated are analytically transferable to similar decentralised renewable energy settings, provided institutional and policy variations are considered.

The analytical framework combining systems thinking and bottom-up/top-down approaches proves relevant in explaining these findings. Applying systems thinking perspectives, the study captures the interdependencies among the energy, water, and agriculture sectors and highlights how weak feedback mechanisms and fragmented mandates create planning and implementation delays. The integration of bottom-up and top-down approaches enables a clear understanding of vertical and horizontal coordination gaps across administrative levels. Therefore, the framework shapes the analysis beyond descriptive cases and provides a structured explanation of the institutional dynamics shaping rural solarisation outcomes.

Overall, the study underscores that improving planning and implementation of SPVWPS for agricultural productivity extends beyond technological deployment. Strengthening institutional coordination, reinforcing feedback mechanisms, and aligning bottom-up and top-down planning processes are essential for ensuring that energy–water initiatives deliver sustained socio-economic benefits in rural areas.

Author Contributions: Conceptualization, O.G.; methodology, O.G.; software, O.G.; validation, O.G.; formal analysis, O.G.; investigation, O.G.; writing—original draft preparation, O.G.; writing—review and editing, O.G., W.D., S.P., W.K. and G.V.; supervision, W.D., S.P., W.K. and G.V.; project administration, G.V. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by special research fund of Hasselt University, Belgium and Ardhi University, Tanzania.

Institutional Review Board Statement: Ethical review and approval were waived for this study due to the use of anonymous data that does not involve personal identifiers, in accordance with the National Health Research Ethics Committee (NatHREC) Standard Operating Procedures (SOPs), Version 3.0, April 2023 (p. 77), which explicitly exempts the analysis of de-identified, publicly available data from ethics review.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study are available on request from the corresponding author due to confidentiality requirements since the results are part of the ongoing PhD thesis.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

CBWSO	Community-Based Water Supply Organisation
DAICO	District Agriculture, Irrigation, and Cooperative Officer
DLD	Directorate of Livestock Development
FGD	Focus Group Discussion
IREP	Integrated Rural Electrification Planning
LGA	Local Government Authority
MLF	Ministry of Livestock and Fisheries
MoA	Ministry of Agriculture
MoE	Ministry of Energy
MoW	Ministry of Water
NIRC	National Irrigation Commission
PO-RALG	President's Office–Regional Administration and Local Government
PUE	Productive Use of Energy
REA	Rural Energy Agency
RUWASA	Rural Water Supply and Sanitation Agency
SD	System Dynamics
SPV	Solar Photovoltaic
SPVWPS	Solar Photovoltaic Water Pumping System
TANESCO	Tanzania Electric Supply Company Limited
VEO	Village Executive Officer

Appendix A

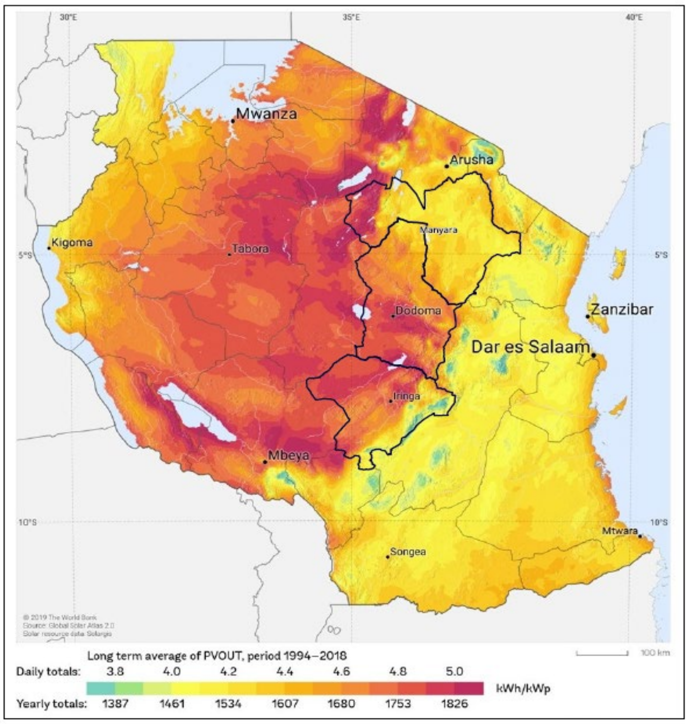

Figure A1. Map of solar power potential in Tanzania obtained from the Global Solar Atlas 2.0, a free, web-based application developed and operated by Solargis s.r.o. on behalf of the World Bank Group (ESMAP). Additional information can be found at https://globalsolaratlas.info (accessed on 12 March 2026). Source: ESMAP (2020).

Appendix B

Table A1. Demographic information of respondents.

In-Depth Interviews			**Sex**		**Education**				**Age Group**				
Respondents	Region		F	M	None	PL	OL	D/C	20–29	30–39	40–49	50–59	60+
IDI 9	Dodoma		✓			✓						✓	
IDI 8	Dodoma			✓				✓		✓			
IDI 5	Iringa		✓				✓			✓			
IDI 6	Iringa			✓				✓			✓		
IDI 7	Iringa			✓				✓		✓			
IDI 1	Manyara			✓				✓			✓		
IDI 2	Manyara			✓			✓				✓		
IDI 3	Manyara			✓		✓					✓		
IDI 4	Manyara			✓				✓		✓			
Focus Group Discussion			Sex		Education				Age Group				
Group	Region	No. of participants	F	M	None	PL	OL	D/C	20–29	30–39	40–49	50–59	60+
FGD1	Dodoma	6	2	4	0	4	2	0	2	3	1	1	0
FGD2	Dodoma	7	3	4	1	6	0	0	0	1	2	3	1
FGD1	Iringa	6	3	3	0	3	3	0	3	1	0	1	0
FGD2	Iringa	6	1	5	0	5	1	0	3	1	1	1	0
FGD3	Iringa	10	10	0	1	8	0	1	0	4	3	2	1
FDG1	Manyara	7	4	3	0	6	1	0	0	1	5	1	0
FDG2	Manyara	6	3	3	1	5	0	0	0	1	5	0	0
Total			26	22	3	37	7	1	8	12	17	9	2
Questionnaire Surveys													
Regions			Sex		Education				Employment		Age		Total
			F	M	None	PL	OL	D/C	FT	CL	(Mean)	Std Dev.	
Dodoma			8	12	7	10	2	1	18	2	39	37	20
Iringa			14	8	1	15	5	1	22	0	37	37	22
Manyara			10	13	8	14	1	0	23	0	43	43	23
Total			32	33	16	39	8	2	63	2			65

Notes: F = female, M = male, None = did not attend formal training, PL = primary level, OL = ordinary level, D/C= diploma or certificate, FT = full-time, CL = casual labourer.

Appendix C

Table A2. Selection of case study areas/projects.

Case	Project Area	Region	Type of Renewable	Generation Capacity (kWp)	Customer Served	Customer Usage	Registration Date	Remarks	Case Study
1	Itaswi Village, Chemba District	Dodoma	Solar PV	6.39	64	Distribution and sales to users located in the off-grid household use	2017	Operational	Disqualified
2	London Village, Manyoni District	Singida	Hybrid mini-grid (Solar PV & Diesel Genset)	16	210	Household use and water pumping for Household	2018	Low operational due to new tariff directives	Disqualified during pilot study
3	Ilolo-Kikombo village, Chamwino District	Dodoma	Solar PV	7.41	32	Borehole; Solar-powered pump for irrigation use	2020	Operational	Qualified
4	Kwa Mtoro Village, Kondoa District	Dodoma	Solar PV	9.5	87	Distribution and sales to users located in the off-grid household use	2017	Operational	Disqualified
5	Ololosokwan Village, Ngorongoro District	Arusha	Solar PV	6	94	Distribution and sales to users located in the off-grid household use	2017	Not operational during data collection	Disqualified
6	Soitsambu Village, Ngorongoro District	Arusha	Solar PV	6	67	Distribution and sales to users located in the off-grid household use	2017	Not operational during data collection	Disqualified
7	Loswaki village, Terat ward, Simanjiro District	Manyara	Solar PV	7.5	Estimated 2000	Borehole; Solar-powered pump for Livestock and Home gardens	2018	Operational	Qualified
8	Dongo kiteto	Manyara	Solar PV	3.5	Estimated 200	Distribution and sales to users located in the off-grid household use and small business such as barbers hops, tailoring and charging phones	2016	Low operational due to new tariff directives	Disqualified during pilot study

Case	Project Area	Region	Type of Renewable	Generation Capacity (kWp)	Customer Served	Customer Usage	Registration Date	Remarks	Case Study
9	Orkejuloongishu Village, Ketumbeine Ward, Longido District	Arusha	Solar PV	15.6	81	Distribution and sales to users located in the off-grid household use	2016	Low operational due to new tariff directives	Disqualified
10	Lupembe Lwasenga Village, Iringa District Council	Iringa	Solar PV	14.8	36	Rivers and Borehole; Solar-powered pumps for irrigation	2020	Operational	Qualified
11	Lukuba/Etaro Village, Musoma District	Musoma	Solar PV	10	155	Distribution and sales to users located in the off-grid household use	2020	Low operational due to imposed tariffs	Disqualified
12	Msolwa - Kilosa District	Morogoro	Hydro	995	1	Individual farm	2019	Operational	Disqualified

https://doi.org/10.3390/su18115736

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https://doi.org/10.3390/su18115736