Feasibility Report for the Solar for Climate Resilience and Productive Uses (S4CRPU) in Kazungula District Southern Province, Zambia.

April 2025

This report has been jointly prepared by the Zambia Renewable Energy Association (ZARENA) and the University of Strathclyde, under the Global Renewables Center (GRC) initiative, to assess the feasibility of implementing a renewable energy-powered agricultural demonstration site in Kazungula District, Zambia.

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ACRONYMS

Acronym	Full Meaning
S4CRPU	Solar for climate resilience and productive uses
ZARENA	Zambia Renewable Energy Association
GRC	Global Renewables Centre
SPIS	Solar-Powered Irrigation Systems
EMP	Environmental Management Plan
EIA	Environmental Impact Assessment
M&E	Monitoring and Evaluation
FAO	Food and Agriculture Organization
$kWh/m^2/day$	Kilowatt-hours per square meter per day
PV	Photovoltaic
O&M	Operation and Maintenance
IRR	Internal Rate of Return
NPV	Net Present Value
CO_2	Carbon Dioxide
AdIP	Adaptive Investment Pathways
Ha	Hectare
m^3	Cubic meters
DC	Direct Current
kWp	Kilowatt-peak
ZMW	Zambian Kwacha
NGO	Non-Governmental Organization
WB	World Bank
SOPs	Standard Operating Procedures
8NDP	Eighth National Development Plan
NDC	Nationally Determined Contributions

Executive Summary

This report presents a comprehensive feasibility study for the *Solar for Climate Resilience and Productive Uses (S4CRPU)* initiative, led by the Zambia Renewable Energy Association (ZARENA) in partnership with the Global Renewable Centre (GRC) at Strathclyde University and funded by the Scottish Government. The study investigates the deployment of solar-powered irrigation systems to enhance agricultural productivity, water access, and climate resilience in Kazungula District, Southern Province of Zambia.

The S4CRPU project proposes the establishment of agricultural demonstration sites in three rural villages namely Sichombe, Silimbana, and Mukuni selected based on critical needs, solar potential, water availability, and community engagement. Following detailed technical and socio-economic assessments, Sichombe and Silimbana were prioritized for Phase I implementation.

The proposed interventions include the drilling of boreholes, installation of submersible solar pumps and development of drip irrigation systems. Supporting measures encompass cooperative governance structures, community training, and sustainable financing models. The initiative aims to supply reliable water for domestic use, livestock, and year-round crop cultivation.

Using the FAO-endorsed SPIS (Solar Powered Irrigation Systems) toolbox, the study analyzed water demand, solar potential, financial viability, environmental impacts, and community readiness. Findings indicate that the solar systems are technically feasible, economically sound, and socially beneficial. Projected outcomes include improved food security, economic empowerment, gender equity, and reduced pressure on natural resources.

The S4CRPU project aligns with Zambia's Eighth National Development Plan (8NDP), National Energy Policy (2019), Climate Change Policy (2016), and the Updated Nationally Determined Contributions (2021). By integrating renewable energy into rural agricultural systems, the initiative offers a replicable, climate-smart model for sustainable development in drought-prone areas of Zambia.

1. INTRODUCTION

1.1. Project Background

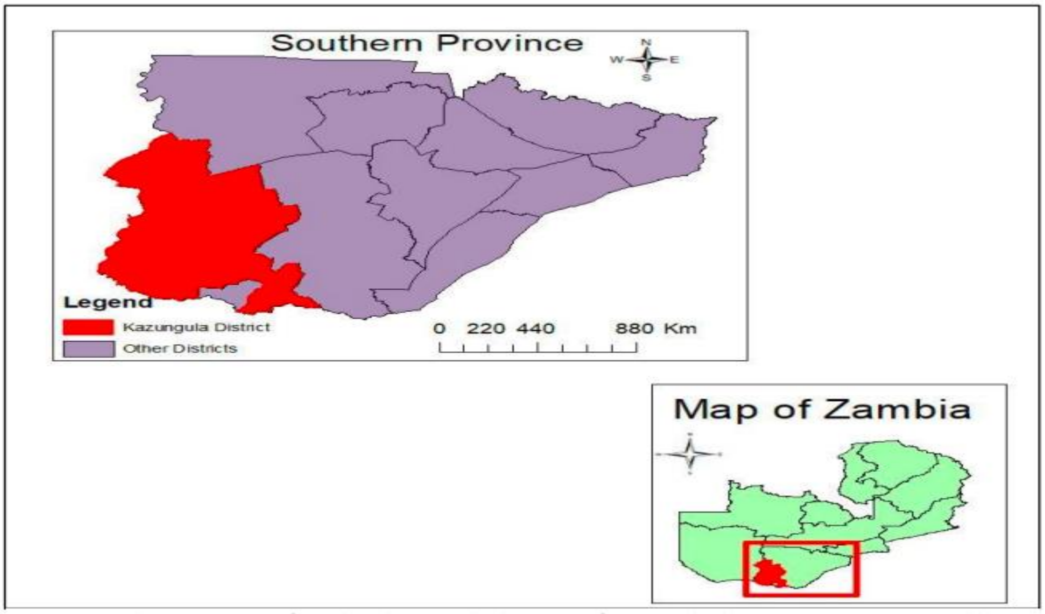
The Zambia Renewable Energy Association (ZARENA), under the Global Renewables Centre (GRC) [1] initiative supported by the Scottish Government, conducted a feasibility study to assess the potential for implementing a solar powered agriculture demonstration site in Kazungula District, Southern Province. Kazungula borders Botswana, Namibia, and Zimbabwe. It lies approximately 234 kilometers (km) from Livingstone and covers 18,055 square kilometers (km^2), with a population of 173,002 as of the 2022 census. The district is situated between latitudes -17.6°S and longitudes 25.08°–26.4°E [2] as shown on the map in Figure 1.

Kazungula falls within Agroecological[1] Region I, which is characterized by low and erratic rainfall, typically below 800 millimeters (mm) annually, and high summer temperatures. The district is historically drought-prone, with sandy soils limiting conventional agriculture. [2] Climate projections estimate temperature increases of 1–3°C by 2060, posing risks of intensified droughts, floods, and reduced agricultural productivity. [3]

The local economy is heavily reliant on small-scale agriculture, livestock, fishing, and cross-border trade. However, limited infrastructure, reliance on biomass for energy, and poor water access further constrain livelihoods. As forests are cleared for firewood and charcoal, the district is experiencing notable tree cover loss, contributing to rising greenhouse gas emissions and degrading environmental resilience.

Kazungula District faces interconnected challenges—climate-induced droughts, food insecurity, and limited access to modern energy services. These conditions have weakened agricultural productivity and increased reliance on unsustainable energy sources.

[1] Agroecology refers to farming that works with nature to protect the environment and support communities.



Source: A Case Study of Cross-Border Traders in Kazungula District

Figure 1: Southern Province of Zambia showing the location of Kazungula district

This feasibility study was undertaken to assess how solar-powered irrigation could address these gaps, developing a practical, climate-smart model for integrating renewable energy into rural agriculture, one that can be adapted and replicated in similar communities across Zambia.

The selected sites, Sichombe, Mukuni, and Silimbana, were chosen for both their urgent development needs and their potential to serve as future demonstration hubs. With the right support, they could showcase how clean energy and agriculture can be effectively combined to drive sustainable rural development.

The feasibility study was initially structured as a three-stage process, reflecting a logical progression aligned with the project cycle approach:

- Stage I: Project Planning—The phase focused on the foundational design of the project, including stakeholder identification, initial consultations, and site reconnaissance visits.
- Stage II: Technical Analysis—The stage involved detailed assessments conducted by subject-matter experts, covering hydrological, renewable energy, and agricultural components to inform technical feasibility.
- Stage III: Development Planning— The final stage centered on consolidating findings to guide project implementation. It included sustainability modeling—standard operating procedures (SOPs), risk

analysis, timeline development, and the establishment of a monitoring and evaluation (M&E) plan.

The subsequent chapters of this feasibility study highlight the specific outputs under each stage and provide a roadmap for advancing the project to implementation.

Table 1: Three-Stage Feasibility Study Framework

KEY FEASIBILITY OUTPUT		
STAGE	**PROJECT PHASE**	**KEY DELIVERABLES**
Stage I	**Project Planning & Development Analysis**	• Stakeholder mapping and engagement • Site visitation and preliminary selection • Contextual analysis
Stage II	**Technical Feasibility Analysis**	• Soil sampling and analysis • Water resource and hydrological assessments • Irrigation system design
Stage III	**Development Planning**	• Project implementation timeline • Financial sustainability analysis • Project monitoring and evaluation plan • Risk identification and mitigation strategy

1.2. Project Rationale

The current dependence on rain-fed agriculture, combined with increasingly unpredictable weather and poor infrastructure, continues to limit smallholder farmers and slow down rural development. These challenges have led to low agricultural productivity, water shortages, energy poverty, and environmental degradation in some selected areas across the country.

The solar-powered irrigation systems offer a practical and sustainable solution for rural communities and will help improve access to water and support farming all year round. By using clean energy, the project will also boost food production and household income while protecting the environment. This is especially important in the chosen sites, which are off the national power grid but have strong sunlight throughout the year.

The project supports Zambia's national goals, including those in the Eighth National Development Plan (8NDP), which focuses on growing the economy, building rural infrastructure, and adapting to climate change. It also aligns with the National Energy Policy (2019), which encourages the use of renewable energy; the National Climate Change Policy (2016), which promotes climate-friendly solutions; and Zambia's Updated Nationally Determined Contributions (2021), which outline the country's climate action commitments and improvements to rural livelihoods in Zambia.

The selected sites; Sichombe, Mukuni, and Silimbana were chosen based on need, technical readiness, and potential of replicability to other areas. With the right support and investment, these sites can become models for how clean energy and smart farming practices can work together to transform rural communities.

2. METHODOLOGY

2.1. Project Sites

The project sites are located in Kazungula District of Zambia's Southern Province, specifically in Sichombe and Silimbana villages under the Katombola Constituency, as shown in Figure 1. Kazungula is the largest district in the province, spanning approximately 16,835 km². It borders Zimbabwe, Botswana, and Namibia and surrounds Livingstone District, with the Zambezi River forming part of its hydrological network. The district lies between Longitude 25°00′ to 26°25′ East and Latitude 18°00′ to 16°05′ South, at elevations ranging from 850 to 1,150 meters above sea level. Kazungula Township, located in the district's southern region, sits at approximately 921 to 1,012 meters above sea level [4].

The district is home to about 161,645 people, with 81% aged between 0 and 35 years. It is sparsely populated with a density of 6.2 persons/km² and experiences a 4.0% annual growth rate. Climate-wise, Kazungula follows a subtropical summer rainfall pattern, with average temperatures ranging from 10°C (cold season) to 29.6°C (hot season) and annual precipitation between 600 and 1000 mm. Soils are predominantly sandy to clay loamy, with a pH between 3.8 and 7, while vegetation spans savanna grasslands, Miombo, Mopane woodlands, and species like Mukwa and Zambezi Teak. The region's geology is dominated by the Batoka Basalt of the Karoo Supergroup. [4]

Kazungula's economy is largely based on agriculture, livestock rearing, tourism, and cross-border trade. While hydrological resources include the Zambezi, Kasaya, and Ngwezi rivers along with 22 man-made dams, water and energy infrastructure remains underdeveloped, particularly in rural areas like Sichombe and Silimbana. These communities face compounded challenges of drought, limited access to grid electricity, and over-reliance on rainfall-based agriculture.

2.2. Site Visitation and Pre-selection Assessment

Field assessments in Sichombe, Silimbana, and Mukuni were conducted through guided focus group discussions, technical surveys, and informal interviews with key community groups, including women and youth representatives. These visits evaluated the socioeconomic, environmental, and technical readiness of the villages for implementing solar-powered water pumping and agriculture systems. The assessment informed a multi-criteria site selection approach.

2.2.1. Sichombe Village

Sichombe, located in Katombola Ward, represents a community experiencing severe water scarcity due to prolonged droughts. Water is currently sourced from a 16-meter open well and a mono pump serving over 200 households across a 1.5 km radius. The mono pump is over a decade old, prone to breakdowns, and suffers from a slow recharge rate, causing long queues starting as early as 4:00 AM. Water contamination during dry periods is common due to reliance on makeshift wells. Livelihoods, especially cattle farming, are compromised, as livestock must walk up to 5 km to find water. Despite these constraints, the village demonstrates high enthusiasm for agricultural development, particularly among women and youth.

Site Coordinates & Access:

- Distance to Main Road: 1 km
- Distance to Kazungula Town: 13 km
- Distance to Kazungula Border: 15 km
- Distance to Livingstone Town: 44 km

Table 2: Preselection Justification Summary-Sichombe:

Criterion	Assessment
Aging/inefficient infrastructure	Mono pump over 10 years old, frequent failures
Community demand	High with strong interest in irrigation
Renewable energy viability	Good solar potential, space for PV
Social vulnerability	Disproportionate impact on women, children
Institutional readiness	Active local water committee

2.2.2. Silimbana Village

Silimbana, located in Sekute Ward comprised of 656 households and depends on a single 50m deep borehole drilled by WaterAid in 2004. Though functional, the borehole often struggled to meet demand during dry seasons. A local committee oversees its maintenance, collecting monthly fees (K5 per household). The village lacks any grid or solar energy infrastructure and relies entirely on firewood. The community has expressed strong interest in solar technologies to support irrigation and improve food security. Mobile network coverage is stable, aiding communication.

Subsistence farming dominates, with maize, sorghum, and pumpkins being common, though crop yields are declining due to shifting rainfall patterns. Past agricultural interventions failed largely due to water scarcity.

Site Coordinates & Access:

- Distance to Main Road: 1 km
- Distance to Kazungula Town: 23 km
- Distance to Kazungula Border: 25 km
- Distance to Livingstone Town: 39 km

Table 3: Preselection Justification Summary-Silimbana:

Criterion	Assessment
Water infrastructure strain	Single borehole under pressure
Community readiness	Strong water committee and fee system
Energy gap	No access to electricity or solar systems
Agricultural vulnerability	Declining yields due to climate shifts
Potential for solar use	High potential for food security interventions

2.2.3. Mukuni Village

Though not selected for immediate implementation, Mukuni village is predominately situated in an agricultural zone and showed notable readiness for the project. It had relatively better infrastructure, multiple boreholes, and some solar irrigation systems. However, agriculture remains primarily rainfed, and 10,000ha of potentially arable land remain underutilized. The village experienced crop losses from wildlife such as elephants and to mitigate this, fencing was highly recommended.

Table 4: Preselection Justification Summary-Mukuni:

Criterion	Assessment
Agricultural zone	Predominantly agricultural
Water challenges	Despite boreholes, farming is seasonal
Irrigation methods	Outdated, rainfall-based
Community engagement	High readiness for solar solutions
Infrastructure	Stronger relative to other villages

2.3. Final Selection and Implementation Justification

A multi-criteria scoring framework (scale 1–5) was applied to rank sites based on water availability, energy infrastructure, agricultural potential, soil quality, and community mobilization.

- Silimbana (Score: 3.25): Reliable borehole and functional governance, though with limited energy services.
- Sichombe (Score: 3.20): Broad impact and high community interest but constrained by extreme water scarcity.

Based on the alignment with the project's objectives, Sichombe and Silimbana were selected for implementation in Phase 1. Both villages demonstrated strong community engagement, high need, and good geographic proximity to key markets in Kazungula and Livingstone. Mukuni was recommended for future scale-up due to its superior land and infrastructure capacity but would require critical consideration on resolving wildlife and irrigation challenges.

The selection approach ensured that technical, environmental, and social factors were comprehensively considered, laying the foundation for a scalable, climate-resilient, solar-powered agriculture model.

2.4. Feasibility Study

The feasibility study relied on an open-source tool "Solar-Powered Irrigation Systems (SPIS) [1]" toolbox, originally designed for small-scale irrigation. Where appropriate, the toolbox was adapted and populated with site-specific data for the Solar for climate resilience and productive uses project. It comprises a handbook divided into modules and a set of Excel and Word-based tools. For this study, the following modules were applied: Impact Assessment, Water Requirements, Market Assessment, Farm Analysis, Payback, Finance Deployment and Pump Sizing.

The Impact Assessment Tool used a structured questionnaire that assigned scores and weights to environmental and socio-economic impacts. Inputs were drawn from long-term research in Kazungula District and feedback gathered during stakeholder field visits.

The Water Requirements Tool calculates crop, and livestock demands and therefore underpins pump-system design. It implements the Food and Agriculture Organization (FAO) methodology [2] to estimate crop evapotranspiration. A representative 1ha planting schedule was modelled for maize, beans, groundnut and rape, each on 0.25 ha, run with sowing dates on 1 June, 1 September, 1 December, and 1 March, respectively. These four food-security crops complete a production cycle in 90–120 days [3], enabling two to three harvests per year under drip irrigation (assumed efficiency: 90%). Weather records for 2015–2023 from Kazungula's station supplied temperature and rainfall data to calculate reference evapotranspiration (ETo) and effective precipitation [4]. Livestock demand was added based on 200 adult dry cattle, following District Agricultural Office guidance. For domestic needs at the case study sites, requirements were set at 20 L $person^{-1}$ day^{-1} in line with Zambian norms.

The Market Assessment Tool defines the prevailing business environment. Key parameters were selected via drop-down menus, and supplemental data were retrieved from the linked global databases. Relevance ratings (inconsequential to critical) remained at default weighting.

The Farm Analysis Tool evaluates enterprise profitability. Fixed and variable cost spreadsheets were populated with price and yield data obtained from small-holder farmers and extension officers, allowing a realistic profit-and-loss projection for a typical holding.

The Payback Tool analysed the financial viability of the solar pumping system. Capital and O&M costs were entered using current market quotations and manufacturer specifications. The model outputs Internal Rate of Return (IRR), Net Present Value (NPV), cumulative 25-year cash flow, life-cycle cost, simple payback period, annual loan obligations (where applicable) and yearly CO_2-emission savings.

The Finance Deployment Tool screened the potential funding mechanisms for the project through a Yes/No questionnaire. Responses based on stakeholder interviews and local financial-service mapping determine which products and services are retained for further consideration.

Finally, the Pump Sizing Tool was employed to configure solar-powered groundwater systems for the two demonstration sites. It calculated total dynamic head from measured static water levels and required lift to storage reservoirs, then specified pump type, peak power demand and photovoltaic array area accordingly.

Together, these modules provided a coherent framework for assessing technical feasibility, economic performance and sustainability of the proposed Solar for Agriculture installation in Kazungula District.

2.5. Feasibility Assessment

A socio-economic and environmental impact assessment of the study area was carried out with the SPIS Impact Assessment Tool [1]. Figure 2 shows the resulting output graph. Population change and migration, women's roles, and minority and Indigenous groups were only partially evaluated, using data obtained from the district offices. Even so, the introduction of the S4CRPU project will undoubtedly expand employment and economic opportunities, which should slow outward migration and elevate women's social standing by improving access to water, markets, resources, and training while freeing time for education and leisure. Minority and Indigenous groups are expected to benefit in the same way. Income and amenities score particularly well (Figure 2) because the project diversifies production, stimulates technical services and markets, creates jobs, and supports new infrastructure. Given its local footprint, the intervention is not expected to affect national politics, social harmony, or regional development. Although food security gains are aimed at local communities, surplus produce may reach markets in Livingstone, other provinces, and neighboring Botswana, thereby strengthening transport, marketing, and processing links. User involvement also scores highly thanks to stakeholder engagement, public consultations on credit and marketing, attention to community needs, and end-user training.

Natural-resource impacts are manageable (Figure 2). Increased groundwater abstraction will alter the water balance (evapotranspiration, storage, baseflow), but sustainable withdrawal limits can be enforced by automatically shutting off pumps once groundwater reaches a preset level. Groundwater-quality risks from irrigation return flows are minimal because smallholder plots are dispersed. Salinization, acidification, alkalinization, and waterlogging are unlikely in the short term but will be monitored over time. Land degradation through sheet and gully erosion and sub-soil compaction remains a major concern, and fertilizer and pesticide use will require close supervision.

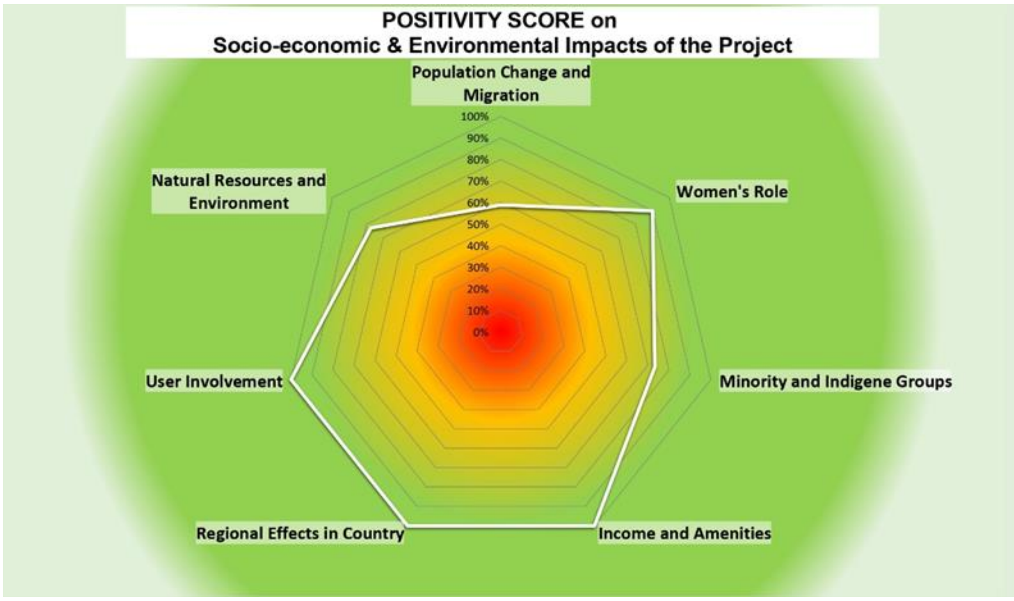


Figure 2: Screen-print of SPIS impact scores for solar-powered groundwater pumping in the study area. High scores indicate positive impacts; low scores indicate negative impacts.

Water requirements for the case study farms (Table 5) were calculated with the SPIS Water Requirements Tool [1], and the outputs appear in Table 6. Monthly crop demand depends on season, atmospheric evaporation, effective rainfall, and overlapping planting schedules. Peak demand is recorded from July to October (24.4 m^3/d per 0.25 ha in October), with the minimum in January (11 m^3/d per ha). Livestock demand is negligible by comparison, so total site demand mirrors crop demand, peaking at 24.9 m^3/d per 0.25 ha in October. A daily volume of 8 m^3 would supply roughly 400 people at 20 L/d each. The pump utilization rate is 78 percent because the unit must meet peak-month demand and is underused during the rest of the year. Alternative crop mixes—beans, maize, rape, groundnuts, and staggered planting can be modeled to optimise both demand and utilisation.

Table 5: Daily water crop irrigation requirements generated by the SPIS Water Requirements Tool

Crop	Area (ha)	Daily Water Need (L)	Irrigation Duration (hrs)	Drip Line Configuration
Maize	0.25	14,400	3 hrs @ 0.6 L/hr	50 m lines, 100 cm spacing, 30 cm emitter spacing
Beans	0.25	9,600	2 hrs @ 0.6 L/hr	Same as above
Groundnuts	0.25	9,600	2 hrs @ 0.6 L/hr	Same as above
Rape	0.25	9,600	2 hrs @ 0.6 L/hr	Same as above

Table 6: Daily water domestic and livestock requirements generated by the SPIS Water Requirements Tool

Use Case	Units	Daily Rate per Unit (L)	Total (L/day)
Domestic	100 hh	80	8,000
Livestock	200 heads	10	2,000
Total			**11,000**

The SPIS Market Assessment Tool [1] returned an overall score of 62.0 percent for Kazungula District. Climatic and geophysical conditions, supportive government policies, and active development partners all indicate high potential. Financing options, the presence of alternative power sources, and logistics infrastructure contribute moderate potential, while technical capacity scores remain low because formal training in solar technology is limited. Nevertheless, awareness is growing, suppliers are present, and agriculture dominates the local economy, reinforcing the market case. Land-tenure arrangements are favorable, while transport and communications, though good, were judged inconsequential in the scoring.

The Farm Analysis Tool [1] was used to evaluate a hypothetical one-hectare demonstration plot donated by community leaders. Four cropping seasons are assumed, and the village herd numbers 100–200 cattle. Under these conditions, the annual gross income is ZMW 248,093 and total costs is ZMW 114,600, yielding a gross profit of ZMW 133,493. These figures feed into the Payback Tool. Assuming 30 percent of profit is available for loan repayment and 16 percent annual inflation, the solar pumping system—sized at 2–3 kW, producing 3.5 m^3/h for eight hours a day across 180 irrigation days—pays back in four years. Net present value is high, life-cycle cost is lowest over 25 years, and cumulative savings surpass diesel from year 7 onward. Panel replacement in year 25 triggers a cost spike but remains financially acceptable. Expanding the irrigated area would boost profits but also require safeguards against groundwater over-abstraction.

The Finance Deployment Tool [1] recommends a cooperative model. Capital costs will be covered initially by donor funds channeled through the Zambia Renewable Energy Association. A community cooperative will then manage operations, fund maintenance from agribusiness revenues, and collect a one-time membership fee to build commitment. Members' access to mobile banking and their strong sense of collective responsibility makes cooperatives, informal savings groups, and pay-per-use arrangements the most viable long-term financing mechanisms. These align with the project's goals of shared ownership and equitable access.

Finally, the Pump Sizing Tool [1] sized each scheme using 8 sun-hours d^{-1} and an average irradiation of 6.4 kWh m^{-2} d^{-1} from the Kazungula weather station. A 25 percent system-loss factor and fixed-tilt array were assumed. Sustainable borehole yield is set at 1 L s^{-1} (28.8 m^3

d^{-1} at 50 percent abstraction). Peak demand of 24.4 m^3 d^{-1} at both sites translates to 2.8–3.4 kWp and 18.7–22.3 m^2 of PV. Total dynamic head is 50 m at Silimbana and 65 m at Sichombe, both within the capabilities of standard submersible DC pumps.

3. DISCUSSION

The novelty of this feasibility study lies in the tailored application of the Solar for Climate Resilience and Productive Uses (S4CRPU) project to highly site-specific environmental, socioeconomic, economic, and infrastructural conditions. While similar technologies exist, their successful deployment requires context-driven adaptation to ensure technical, social, and economic viability. In the Zambian setting, particularly in Kazungula District's Sichombe and Silimbana villages. The key challenges include the impacts of climate change (notably, recurrent droughts and water scarcity), widespread poverty and unemployment, limited water infrastructure, the absence of grid electricity, and a national energy crisis. Solar-for-agriculture initiatives are proposed as adaptive strategies to address these interconnected issues. Comparable research has been conducted in Morocco's Youssoufia Province through the IMAGINE project [5], which implemented water–energy–food nexus solutions to empower impoverished rural populations. This methodology aligns with the Adaptive Investment Pathways (AdIP) model for irrigation in Sub-Saharan Africa [6], which suggests that smaller, decentralized irrigation systems are often more effective and compatible with smallholder farming and solar energy availability than large-scale infrastructure.

In this study, solar-powered boreholes will be installed in both communities. These boreholes are intended to supply drinking water for humans and livestock, as well as support small-scale agricultural production aimed at local and regional markets. Currently, these areas rely almost entirely on rainfall; however, frequent droughts leave farmers with minimal or no yield after the rainy season [7]. The villages' distance from the national electricity grid is about 1 km from the nearest 220 kV transmission line, which makes grid connection prohibitively expensive. Diesel generators, while technically feasible, are economically unsustainable due to rising fuel costs, particularly during periods of increased irrigation demand. Most households cannot manage these recurring energy expenses, and government support through grid expansion, diesel subsidies, or infrastructure investment is inconsistent at best. This situation underscores the need for alternative, cost-effective energy sources. Solar water pumps offer a viable solution for rural settings, proving more affordable than diesel or conventional electricity in the long run.

Community engagement and consent are essential before implementing any project. The social dynamics of transitioning to solar-powered systems are critical, as local populations will need to take on greater roles in managing, maintaining, and securing these systems roles less emphasized in conventional bulk-supply models. At present, the two villages lack reliable boreholes, water storage, and basic distribution networks, necessitating a full infrastructure build-out. Given the impracticality of grid extension and the unsustainability of diesel options, this feasibility study prioritizes a completely solar-powered system that can meet local needs without exposing residents to volatile fuel costs. The infrastructure development must align with regulatory requirements for water abstraction, environmental approvals, and land use, in consultation with traditional leaders. If implemented, a solar-based water system would represent the most feasible path to achieving year-round water security at a cost manageable for end-users.

From a geotechnical standpoint, the area is moderately suitable for solar energy development, receiving an average of 6.4 $kWh/m^2/day$ and abundant daily sunshine. This creates the potential for intensified agricultural production and value-added processing, with access to informal and formal markets in nearby Kazungula town (~8 km) and Livingstone (~40 km). Additional economic opportunities could arise from ancillary businesses. The current water scarcity highlights the substantial benefits that S4CRPU could deliver for livelihoods, public health, sanitation, and cultural practices. While no formal waste management systems exist, particularly for e-waste, plastics, and batteries, the small volume of waste from solar pumps can be locally managed without posing significant environmental risks.

Solar-powered groundwater pumping has the potential to enhance water security, agricultural yields, community participation, and gender equity. However, risks such as groundwater over-abstraction must be carefully managed. Sustainable groundwater use depends on maintaining adequate reserves during drought periods, supported by periodic recharge from floods. While shallow groundwater yields in the area are moderately high, long-term sustainability and resource conservation remain critical concerns.

The cost-effectiveness of solar energy was evaluated relative to conventional power sources. Over a 25-year lifecycle, solar systems could save over ZMW 400,000 compared to grid electricity. Diesel systems, however, are not financially sustainable [12]. The main challenge for solar adoption remains the high upfront investment cost, likely requiring subsidies from government or donor agencies. Community-led operation and maintenance under the guidance of ZARENA should be promoted. Local engagement and ownership are vital to ensure long-term functionality. Cooperative farming activities were identified as feasible financial models to sustain operations. A comprehensive evaluation of financial and operational frameworks is necessary.

The system's design is highly site-specific and was developed using the SPIS tool, which incorporates biophysical parameters, borehole yields, aquifer characteristics, pressure requirements, and water needs. The scale of the installations is consistent with other systems of similar scope. Design flexibility allows for modifications to solar arrays, pipe layouts, tank sizes, and the inclusion of booster pumps, depending on equipment availability and implementation conditions. Numerous configurations can be modeled, including variations in water usage (drinking vs. irrigation), crop types, population demands, hydrogeological contexts, and financial inputs. The case studies serve as strong reference points for assessing the practical feasibility of solar-powered groundwater systems.

Ultimately, these systems are not intended to replace bulk water infrastructure but to serve as emergency interventions and climate adaptation strategies. They can alleviate health burdens, improve school attendance, and reduce the physical strain on women and girls traditionally tasked with water collection. Viewed as "no-regret" interventions, solar groundwater systems can augment water access during droughts and build climate resilience.

4. CONCLUSIONS

The feasibility assessment concludes that implementing solar-powered shallow groundwater pumping and the S4CRPU initiative is viable in Kazungula District, considering factors like solar energy potential, cost efficiency, agricultural yield, market access, and groundwater availability. These systems can improve water security, support community-driven enterprises, and advance gender equity. Regular monitoring of groundwater levels can ideally be monthly and is strongly advised to prevent unsustainable depletion.

Typical case studies suggest daily peak water needs ranging from 24.4 to 31.9 m^3, with corresponding peak power demands of 1.2 to 3.4 kWp and solar panel surface areas between 8.0 and 22.3 m^2. Ensuring adequate water quality, especially for irrigation, will necessitate filtration, thereby increasing both capital and operational costs. Cooperative farming models have been identified as a viable financial mechanism. Nonetheless, external funding from donors or government bodies will likely be required at least during the pilot phase of the project to cover initial investments and operational support. However, the active participation of local authorities and communities remains crucial for sustaining the systems long-term.

In the next phase, emphasis should be placed on mobilising financial resources, initiating detailed design and construction activities at prioritised sites, and building technical and governance capacities within communities. Periodic monitoring, evaluations and adaptive management approaches will ensure that the project continues to meet its development and sustainability goals effectively.

The S4CRPU project supports multiple national and international development frameworks:

- SDG 2: Zero Hunger through improved food production, diversified agriculture, and year-round irrigation.
- SDG 6: Clean Water and Sanitation by providing reliable access to clean water for domestic use, livestock, and farming.
- SDG 7: Affordable and Clean Energy by implementing decentralized solar energy systems in off-grid rural communities.
- SDG 13: Climate Action by enhancing community resilience to climate-induced droughts and reducing dependence on fossil fuels.

S4CRPU advances Zambia's Eighth National Development Plan by promoting rural infrastructure, sustainable agriculture, and renewable energy integration. It aligns with the National Energy Policy (2019) and National Climate Change Policy (2016), ensuring cohesion with national climate and energy transition strategies. Implementation of the project will curb the dependency on rainfed agriculture as well as seasonal income in the community.

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