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Review of Small Hydropower Development Potential in Tanzania

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ABSTRACT

Tanzania has a significant but underexploited SHP potential estimated to be within 300-500 MW of technically and economically feasible capacity. This resource base returns to the country's varied topography, perennial rivers emanating from highland catchments, and rapidly growing electricity demand in rural and peri-urban settings. This paper looks into a detailed analysis of the development opportunities for SHP, including hydrology–head resource mapping, geospatial least-cost siting, and financial modelling, with technology options, environmental considerations, social considerations, and regulatory considerations relating to pathways to bankability. The main priority zones for the development of SHP are Iringa, Mbeya, Ruvuma, Kigoma, Morogoro, and Kilimanjaro, where SHP (≤10 MW per plant, micro ≤100 kW, and mini 100 kW–1 MW) can cost-effectively provide reliable low-carbon electricity that promotes inclusive rural electrification. The challenges include big upfront capital costs, inadequate technical capacity, environmental risks like siltation, and bottlenecks on the regulatory front. It further discusses strategies guided by the recent studies for tackling such barriers with simplified permitting, concessional finance for early-stage development, capacity building/community participation, better policy incentives, and watershed management integration. It is concluded that the sustainable development of SHPs can greatly enhance the resilience of Tanzania's power system, work toward climate mitigation, and assist in the larger socio-economic transformation of the country.

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1.0 Introduction

Electricity access in Tanzania has expanded markedly over the past decade, yet many rural communities still experience limited or unreliable supply. National electrification efforts have increased connections, but gaps remain, particularly in remote and dispersed settlements (Ahlborg & Hammar, 2014; Groth, 2019). Small hydropower (SHP) offers an attractive pathway to address these challenges, delivering dispatchable, renewable generation suitable for both mini-grids and distribution-level grid injection (Mdee, Nielsen, Kimambo, & Kihedu, 2018).

Compared to solar-only mini-grids, SHP systems generally provide significantly higher capacity factors, inherent voltage support, and built-in storage potential through pondage or run-of-river flow regulation (Ahlborg & Hammar, 2014; Kougias *et al.,* 2019; Ngowi, Bångens, & Ahlgren, 2019). When contrasted with large dams, SHP offers unmistakable advantages: shorter development lead times, lower environmental and social footprints, and modular scalability, making it especially well-suited for decentralised deployment (Ahlborg & Hammar, 2014; Kichonge, 2018).

Tanzania ranks among East Africa's most hydrologically endowed countries, yet much of its SHP resource remains untapped; estimates suggest a technically feasible small hydro capacity of 300–500 MW, with only a small fraction developed to date. Harnessing this resource is vital in the context of the country's rapid population growth, expanding infrastructure needs, and accelerating electrification ambitions, which are key for sustainable economic development, improved quality of life, and climate resilience (Mdee *et al.,* 2018; Punys, Jurevičius, & Balčiūnas, 2024).

This review provides a comprehensive, practice-orientated assessment of SHP development potential in Tanzania. We (i) (i) characterise the nation's hydro-environmental resources and associated climate risks; (ii) summarise available SHP technologies and design choices; (iii) propose a reproducible GIS-hydrology screening and ranking method; (iv) examine environmental and social safeguards; (v) review the regulatory, institutional, and market context; and (vi) evaluate project economics and financing structures, culminating in a development roadmap. This analysis addresses both status and regional variation, as well as the prevailing technical, institutional, and financial challenges and opportunities for scaling up SHP in Tanzania (Kabaka & Gwang'ombe, 2007).

Tanzania boasts substantial hydropower resources, with SHP potential concentrated in high-relief catchments yet largely untapped (Kichonge, 2018). Against a backdrop of ongoing population growth and an accelerating rural electrification mandate, harnessing this renewable energy opportunity is essential for sustainable economic development, enhanced energy access, and bolstered climate resilience. This research, therefore, presents a multi-dimensional analysis of the current state, geographic distribution, challenges, and strategic opportunities for advancing SHP in the Tanzanian context.

Figure 1 illustrates the spatial distribution of small hydropower (SHP) potential sites across Tanzania, with notable clusters in the Southern Highlands (Mbeya, Iringa, Njombe, Ruvuma) and the Northern Highlands (Arusha, Kilimanjaro, Manyara), where perennial rivers and steep topography create favourable conditions. Additional sites are scattered across Western regions (Kigoma, Katavi) and parts of Morogoro and coastal areas, while central semi-arid zones show relatively limited potential. This distribution highlights SHP as a critical resource for rural electrification, decentralized mini-grids, and climate-resilient power generation. The data used for this spatial representation is sourced from the Energy Access Explorer (EAE) platform, which provides geospatial insights to support energy planning and development in Tanzania.

Figure 1

Spatial Distribution of Small Hydropower (SHP) Potential Sites across Tanzania

Source: Energy Access Explorer (EAE) platform

2.0 Hydropower Resource Landscape in Tanzania

2.1 Hydropower Overview

Tanzania possesses an estimated total hydropower potential of 4.7-5.3 GW, distributed among large, small, and mini hydropower sites. Small hydropower, defined as projects with capacities between 0.3 MW and 10 MW, offers considerable opportunities to serve rural and off-grid communities, where electricity access remains low (Mdee *et al.,* 2018; Punys *et al.,* 2024).

2.2 Geographical and Hydrological Context

Tanzania's geographical setting provides favourable conditions for the exploitation of small hydropower (SHP) resources. The country is traversed by the Great Rift Valley System, which forms steep escarpments, volcanic highlands, and diverse catchment areas that create natural hydraulic heads suitable for distributed hydropower development (Sridharan *et al.,* 2019). This varied terrain results in perennial rivers with significant gradients, especially in the northern and southern highlands, providing ideal conditions for run-of-river and pondage-based SHP systems (Kichonge, 2018).

Hydrologically, Tanzania is endowed with extensive river basins that are central to its SHP potential. The Lake Victoria Basin in the northwestern region feeds rivers such as the Simiyu and Kagera, which exhibit consistent flows that are favourable for micro- and mini-hydro schemes (Bensch, Peters, & Sievert, 2017). Similarly, the Lake Tanganyika Basin in the west supports tributaries like the Malagarasi River, which has been recognised for its hydropower suitability due to both seasonal and perennial flow regimes (Ahlborg & Hammar, 2014).

In the northeastern part of the country, the Pangani Basin stands out as one of the historically significant hydropower regions. With steep gradients formed by the volcanic topography of Mount Kilimanjaro and the Pare Mountains, this basin hosts multiple medium- and small-scale hydropower sites (Sridharan *et al.,* 2019). Meanwhile, the Rufiji Basin, located in the southern highlands, is the largest in Tanzania, contributing more than 20% of the country's surface water. Its tributaries, such as the Great Ruaha River, are critical for both large- and small-scale hydropower development, with documented potential for rural mini-grid deployment (Kichonge, 2018).

Other important catchments include the Wami-Ruvu Basin, which supplies water to the fast-growing urban and industrial hub of Dar es Salaam, and smaller basins feeding into coastal and inland lakes that offer localised SHP opportunities (Okesiji, Olaniyi, & Okorie, 2025). Together, these river basins highlight the country's substantial but underutilised small hydropower resources, making Tanzania one of the most promising areas in East Africa for sustainable SHP expansion.

2.3 Small Hydropower Potential and Distribution in Tanzania

Tanzania is endowed with significant small hydropower (SHP) resources, distributed across multiple basins and regions. Recent assessments confirm that SHP represents one of the most promising renewable energy options for rural electrification and decentralised grid support in the country. Estimates place the total SHP potential between 400 MW and 600 MW, depending on methodological approaches and surveyed sites (Kaygusuz, 2020; Mandelli *et al.,* 2016; Okello *et al.,* 2019). While some studies, such as basin-level GIS mapping, calculate around 400 MW of feasible capacity (Kihwele, Hur, & Kyaruzi, 2012), broader technical and economic assessments incorporating site visits suggest over 600 MW of small hydropower potential nationwide (Karekezi & Kithyoma, 2003b; Kaunda, Kimambo, & Nielsen, 2012), as indicated in Table 1.

2.3.1 Distribution

The distribution of SHP resources is geographically uneven, reflecting Tanzania's diverse hydrology and topography shaped by the Great Rift Valley system. Key basins with high SHP potential include Lake Tanganyika, Rufiji, Pangani, Northern Lakes, and Ruvuma, with numerous tributaries suitable for run-of-river and small dam-based schemes (Massawe, 2015; Sovacool & Walter, 2019). Regional mapping identifies Iringa, Mbeya, Ruvuma, Kigoma, Morogoro, and Kilimanjaro as particularly favourable for near-term SHP deployment, given their perennial rivers, elevation gradients, and growing local demand (Lazaro & Baba, 2023; Nzila).

2.3.2 Untapped Market

Despite these opportunities, only a fraction of SHP potential has been developed. Current operational SHP capacity is estimated at 15–20 MW, with an additional 20–25 MW under various stages of development or in the project pipeline (Mandelli *et al.,* 2016; Okello *et al.,* 2019). This leaves the majority of the technically feasible potential underutilised due to persistent challenges such as limited financing mechanisms, high upfront capital costs, regulatory hurdles, and inadequate transmission infrastructure (Ameli *et al.,* 2017; Sovacool & Walter, 2019).

2.3.3 Current Status of SHP Projects

Ongoing projects supported by the Rural Energy Agency (REA) and international development partners have demonstrated both technical and socio-economic benefits of SHP in Tanzania. Pilot and demonstration projects currently contribute over 40 MW of installed or planned capacity, with replication potential of at least 24 MW in pipeline projects (Kihwele *et al.,* 2012; Lazaro & Baba, 2023). These projects not only supply electricity to rural and peri-urban communities but also create local employment, reduce reliance on biomass, and strengthen local technical capacity through training and knowledge transfer (Mandelli, Barbieri, Mereu, & Colombo, 2016; Sovacool & Walter, 2019). The REA has played a central role in commissioning feasibility studies, de-risking investments, and enabling public-private partnerships that foster sustainable SHP expansion (Ameli *et al.,* 2017; Karekezi & Kithyoma, 2003b).

2.3.4 Small Hydropower Potential by Basin in Tanzania

Tanzania possesses an estimated ~400 MW of technically feasible small hydropower (SHP) potential, capable of generating over 3,400 GWh annually, with resources distributed across nine major basins. The Lake Tanganyika (88.6 MW) and Rufiji (80.7 MW) basins dominate in terms of capacity, while significant opportunities also exist in the Pangani, Northern Lakes, Lake Rukwa, and Ruvuma basins, each offering favourable (Gaudard, Gabbi, Bauder, & Romerio, 2016) run-of-river and pondage schemes. These resources are geographically diverse, allowing for distributed rural electrification and reduced grid vulnerability, yet only a fraction (about 15–20 MW) has been developed to date due to infrastructure, financing, and regulatory constraints. Unlocking this potential would not only advance Tanzania's rural electrification and energy diversification goals but also provide a reliable, low-carbon complement to solar and large hydropower, enhancing climate resilience and socio-economic development across the country, as table 2 indicated (Kaunda, 2013; Lazaro & Baba, 2023; & Okello, 2023).

2.4 Seasonality and Interannual Variability

The hydrological regimes of Tanzania are primarily controlled by its rainfall patterns, which are either bimodal (two rainy seasons) or unimodal (a single rainy season). In northern and coastal regions, the bimodal regime brings rainfall during the "long rains" (March-May) and the "short rains" (October-December), while central and southern Tanzania typically experience a unimodal regime with a prolonged rainy season from November to April (Gleick, 1989). These patterns create pronounced seasonality in river flows, where water availability is abundant during rainy periods but declines sharply in dependable low flows (Q90-Q95); flows that are equalled or exceeded 90–95% of the time serve as the key determinant of firm capacity, i.e., the reliable dry months. For small hydropower (SHP), this seasonality means that generation capacity cannot be based on average annual flows alone. Instead, the output a plant can sustain year-round (Gaudard *et al.,* 2016). Designing SHP schemes around Q90–Q95 makes sure that electricity is always available, even during long dry seasons. However, this often means that the nominal installed capacities are lower than what would be expected based on mean flows.

Climate change is expected to change the amount, frequency, and distribution of rainfall across East Africa. This is on top of the natural variability that already exists. Hydrological projections suggest that while mean annual runoff may increase in certain basins—particularly those with large, highland-fed rivers such as the Rufiji, Pangani, and Lake Victoria basins—these gains will be offset by greater hydrological extremes (Cervigni, Liden, Neumann, & Strzepek, 2015; Zarfl, Lumsdon, Berlekamp, Tydecks, & Tockner, 2015).

This implies a dual challenge for SHP developers: more frequent flood events that require robust flood-handling infrastructure (e.g., reinforced weirs, enlarged spillways) and longer dry spells that necessitate conservative design based on dependable low flows. Moreover, intensified rainfall events contribute to higher sediment loads, especially in catchments with deforestation or poor land-use management, which can damage turbines, reduce efficiency, and raise maintenance expenses if sediment handling is not properly integrated into project design (Gaudard *et al.,* 2016).

In this context, resilient SHP design in Tanzania must go beyond traditional hydrological analysis.

Table 1
Estimated SHP Potential in Tanzania

Source / Methodology	Estimated SHP Potential (MW)	Notes
National surveys (World Bank ESMAP)	300–500 MW (≈480 MW upper)	Comprehensive surveys across Tanzania (Anandarajah, 2022)
National planning estimate	315 MW	TANESCO + private potential; only ~8 MW utilized (Energypedia, 2020)
GIS basin-level mapping	~400 MW	Basin breakdown with annual energy ≈ 3,441 GWh (Kichonge, 2018)
Installed grid-connected SHP	~15 MW	Existing small hydropower capacity in operation (He, 2017)

It requires climate-informed hydrological modelling, flexible turbine selection to accommodate flow variability, sediment management strategies such as desilting basins, and improved watershed management. By integrating these considerations, SHP projects can better adapt to both current seasonal variability and the anticipated impacts of climate change, ensuring long-term sustainability and reliability of electricity supply in rural Tanzania.

2.5 Indicative Potential of Small Hydropower in Tanzania

i. The theoretical power output of a hydropower site can be estimated using the equation: Derivation (step by step):
ii. The potential energy per unit mass lifted through the head (m) is measured in joules per kilogramme (J/kg), where g represents gravitational acceleration.
iii. Mass flow rate of water = density (kg/m^3) × volumetric flow (m^3/s). So mass flow rate = (kg/s).
iv. Hydraulic power available (mechanical, in watts) = mass flow rate × potential energy per unit mass:

$$P_{Hydraulic} = \rho Q g H \ (Watts) \quad (1)$$
$$P = 9.81 \eta Q H \quad (2)$$

Where:
P = electrical power in kilowatts (kW),
η = overall efficiency of the system (typically 0.6-0.9 for small hydro),
Q = flow rate in cubic meters per second (m^3/s), and H = effective head (m).

In the foothill and upland regions of Tanzania, particularly in Iringa, Mbeya, Ruvuma, and Kilimanjaro, rivers and perennial streams exhibit heads ranging between 30 and 150 metres and dependable dry-season flows (Q90-95) between 0.3 and 3.0 m^3/s. Substituting these values into the above formula suggests that many of these sites could sustain installed capacities from 60 kW (pico/micro-hydro) up to nearly 3 MW (small hydro). Furthermore, cascading schemes, where multiple turbines are installed sequentially along a river's elevation drop, can aggregate outputs to several megawatts, significantly improving local grid stability and rural electrification prospects (Kichonge, 2018).

Empirical evidence from East African SHP projects demonstrates that such plants typically achieve capacity factors between 35% and 70%, depending on hydrological stability, seasonal flow variation, and whether run-of-river or pondage storage is applied. Run-of-river plants, which directly use the available streamflow, tend to operate closer to 35-50% capacity due to seasonal fluctuations. In contrast, small pondage schemes, which regulate flow over short durations (days to weeks), may achieve higher utilisation factors (50-70%) by ensuring more stable generation during the dry season (Kichonge, 2018; Korkovelos *et al.,* 2018). This suggests that many Tanzanian SHP sites are not only technically viable but also economically attractive, as capacity factors above 40% are generally favourable for mini-grid or rural distribution-level investment. With proper design, these systems can contribute reliably to rural electrification, complementing intermittent solar and reducing reliance on costly diesel generation.

3.0 Methodology

The methodology adopted in this study combined desk-based research, geospatial analysis, hydrological modelling, and a structured review of technological, socio-economic, and policy frameworks relevant to small hydropower (SHP) in Tanzania. The process was designed to ensure a holistic assessment of SHP potential and its development pathways, with emphasis on reproducibility and practical applicability.

3.1 Research Design

A descriptive and analytical research design was used. The study relied on secondary data sources, including hydrological datasets, digital elevation models (DEMs), energy planning databases, and published literature. These were complemented by case evidence from existing and planned SHP projects in Tanzania and neighbouring East African countries.

Table 2
Small Hydropower Potential by Basin in Tanzania

Basin / River System	Estimated SHP Potential (MW)	Annual Energy Yield (GWh/yr)	Number of Identified Sites	Key Characteristics	Source (Journal Papers)
Lake Tanganyika Basin	~88.66 MW	~760 GWh/yr	47	Steep gradients, perennial tributaries	(Massawe, 2015; S. Okello *et al.*, 2019)
Rufiji Basin	~80.73 MW	~690 GWh/yr	40	Tanzania's largest basin, strong flow year-round	(Fernández-Guillamón, Gómez-Lázaro, & Molina-García, 2020; Sebestyén, 2021)
Northern Lakes (Victoria tributaries)	~48.94 MW	~420 GWh/yr	26	Seasonal flows, potential for run-of-river SHP	(Kihwele *et al.*, 2012; Nzila)
Pangani Basin	~43.43 MW	~380 GWh/yr	25	Historically important for hydropower, steep catchments	(Mandelli *et al.,* 2016; Sovacool & Walter, 2019)
Lake Rukwa Basin	~35.20 MW	~310 GWh/yr	5	Small scattered rivers, medium head sites	(Massawe, 2015; S. Okello *et al.,* 2019)
Lake Nyasa Basin	~28.80 MW	~250 GWh/yr	15	Potential in tributaries feeding Nyasa	(Kaunda, 2013; Nzila)
Ruvuma Basin	~26.90 MW	~230 GWh/yr	15	Border basin with Mozambique, largely untapped	(Sovacool & Walter, 2019)
Wami–Ruvu Basin	~22.77 MW	~200 GWh/yr	14	Supplies Dar es Salaam, rising water demand	(Kihwele *et al.,* 2012)
Lake Victoria Basin	~17.35 MW	~150 GWh/yr	3	Few SHP sites, but high demand near Mwanza	(Mandelli *et al.*, 2016; Sovacool & Walter, 2019)
Total (Tanzania)	~392.8 MW ≈ 400 MW	~3,441 GWh/yr	190+	Widely dispersed, highly underdeveloped	(Kaunda, 2013; S. Okello *et al.,* 2019)

3.2 Data Collection

Hydrological Data: Flow records, rainfall-runoff data, and flow duration curves were obtained from published studies, basin authorities, and international repositories (e.g., World Bank ESMAP, Energypedia, and Energy Access Explorer).

Geospatial Data: Shuttle Radar Topography

Mission (SRTM) and other DEM datasets were used to identify hydraulic head potential across river basins. Catchment boundaries and river networks were extracted using GIS-based hydrological tools.

Socio-Economic and Policy Data: National energy reports, regulatory guidelines, and peer-reviewed studies were reviewed to evaluate institutional, financial, and policy conditions for SHP deployment.

3.3 Analytical Framework

The analysis followed a multi-step framework:

- *Resource Assessment – Estimation of theoretical SHP potential using the standard hydropower equation*

$P = 9.81\eta QH$, applying dependable flows ($Q_{90} - Q_{95}$).

GIS-Based Site Screening – DEM-derived head drops are overlaid with river networks to identify candidate sites, constrained by environmental and accessibility factors.

Technology–Flow Matching – Classification of sites by head and flow regime to determine turbine options and civil works archetypes.

Economic Pre-Assessment – Preliminary estimation of levelised cost of electricity (LCOE) and cost drivers (civil works, electro-mechanical, interconnection).

Environmental and Social (E&S) Evaluation — screening for ecological flow requirements, sediment risks, and socio-economic acceptability.

Policy and Financing Review: An evaluation of the institutional frameworks, power purchase agreements (PPAs), feed-in tariffs, and funding options for the growth of small hydropower plants (SHPs).

3.4 Validation and Cross-Referencing

Findings were cross-referenced with reported SHP projects by the Rural Energy Agency (REA) and peer-reviewed case studies to validate assumptions and highlight discrepancies. Comparative analysis with East African SHP experiences was also undertaken to situate Tanzania's potential within a regional context.

3.5 Limitations

The study acknowledges limitations due to data gaps in gauging stations, uncertainties in regionalised low-flow estimates, and reliance on secondary data. To address these, conservative assumptions were applied, and multiple sources were triangulated to enhance robustness.

3.6 Literature Review

A thorough review of existing literature on Tanzanian and East African small hydropower (SHP) resources was conducted. Important sources include studies that estimate the technically possible SHP potential to be between 300 MW and over 600 MW (Kaunda *et al.,* 2012; Kichonge, 2018; Mdee *et al.,* 2018). The literature emphasises essential factors including hydrological seasonality, the effects of climate variability, sedimentation issues, technology selection, policy frameworks, financial obstacles, and socio-economic advantages (Taha, Aldrees, & Moussa, 2023).

The literature highlights the use of detailed hydrological modelling and flow duration curve analyses at Luswisi River sites to optimise generation while assessing impacts such as changes in runoff driven by climate change and land use. The Luswisi projects exemplify the integration of practical design within Tanzania's broader sustainable energy aspirations and the transition toward decentralised low-carbon energy systems.

This Luswisi River context complements the broader understanding of Tanzanian SHP potential, which is estimated between 300 MW and over 600 MW nationally, concentrated in highland catchments with perennial river systems that support steady year-round flows favourable for small hydro plants. The Luswisi case is an example of detailed localised hydrological data application and project operational planning amid the growing national electrification and climate resilience objectives.

4.0 Technology Options and Plant Configurations

4.1 Turbine Selection by Head/Flow

The selection of turbines for small hydropower projects in Tanzania is primarily governed by the available hydraulic head and flow regime. For high-head (≥100 m) and variable flow streams, typically found in the foothills of the Southern Highlands and Kilimanjaro regions, Pelton and Turgo impulse turbines are most suitable due to their ability to handle fluctuating discharges efficiently. For medium heads (30–150 m) with moderate to steady flows, Francis turbines offer higher efficiency and robustness, making them suitable for perennial rivers like those in Iringa and Mbeya (Kichonge, 2018).

In cases of low-head conditions (5–30 m) with larger flow rates, Kaplan, propeller, or bulb turbines are often applied, especially in river stretches like the Rufiji and Pangani basins. Innovative technologies like Very Low Head (VLH) turbines, Archimedes screw turbines, and water wheels are becoming more popular in places where rivers have very low heads (<5 m), like irrigation canals and flat land. This is because they have a low impact on the environment and are good for fish (Quaranta & Revelli, 2018; Sharma, Tiwari, Erkut, & Mundi, 2021).

4.2 Civil Works Archetypes

Table 4 shows civil works form the backbone of SHP schemes, defining cost and long-term sustainability. In Tanzania, run-of-river intakes with desanders and short penstocks are the most common archetype in highland catchments, as they minimise flooding risk and environmental footprint. For irrigation-fed systems (e.g., in Morogoro and Kilimanjaro), canal-drop structures are increasingly deployed, integrating energy recovery into existing water management infrastructure (Sharma *et al.,* 2021).

Desanders are critical in Tanzanian contexts because many rivers carry heavy sediment loads during rainy seasons, which would otherwise reduce turbine efficiency and damage components. The combination of weirs, intake screens, and sedimentation basins enhances equipment longevity.

Table 3
Turbine Selection Criteria for SHP in Tanzania

Turbine Type	Suitable Head (m)	Flow Characteristics	Key Advantages	Typical Application in Tanzania	Source
Pelton / Turgo	>100	Variable, low–medium flow	High efficiency at high head, durable	Mountain streams (Kilimanjaro, Ruvuma)	(Kichonge, 2018)
Crossflow (Banki)	10–100	Variable, debris-laden	Simple, robust, tolerant to silt	Highland mini-grids (Mbeya, Iringa)	(Quaranta & Revelli, 2018)
Francis	30–150	Moderate, steady flow	High efficiency, reliable	Medium-head rivers (Morogoro, Iringa)	(Sharma *et al.,* 2021)
Kaplan / Propeller / Bulb	5–30	High discharge, stable flow	Suited for low heads, fish-friendly	Rufiji &Pangani lowland rivers	(Sharma *et al.,* 2021)
VLH / Archimedes Screw	<5	Low head, large volume	Eco-friendly, fish-friendly	Irrigation canals, flat plains	(Quaranta & Revelli, 2018)

Table 4
Civil Works Archetypes for Tanzanian SHP

Civil Work Type	Characteristics	Suitability in Tanzania	Source
Run-of-river intake	Weir, intake channel, desander, short penstock	Mountainous areas with perennial rivers (Iringa, Mbeya, Ruvuma)	(Sharma *et al.*, 2021)
Canal-drop scheme	Integration into irrigation canals, minimal storage	Irrigation zones (Morogoro, Kilimanjaro)	(Kichonge, 2018)
Pondage scheme	Small storage for daily/weekly regulation	Seasonal basins with variable flows	(Remy & Chattopadhyay, 2020)

5.0 Screening and GIS-Hydrology Method

A robust SHP pipeline starts with terrain-driven discovery, proceeds through hydrological quantification and constraints screening, then narrows to constructability and bankability checks, and finally moves into field hydrometry and geotechnical validation. In data-sparse contexts like parts of Tanzania, reproducibility hinges on transparent assumptions, conservative low-flow regionalisation, and staged uncertainty reduction (Bishoge, Zhang, & Mushi, 2018; Kichonge, 2018; Mudenda, Van Dijk, & Bekker, 2022).

i. DEM-based head mapping. High-resolution digital elevation models are used to delineate drainage networks and compute longitudinal profiles. Automated routines (e.g., flow accumulation, sink filling, channel extraction) identify candidate reaches with useful gross head (typically 10–150 m over practical penstock lengths). Slope breaks, valley confinement, and access corridors are flagged for civil feasibility. The output is a head raster and a set of candidate drops with their contributing catchments (Bishoge *et al.,* 2018; Kichonge, 2018).
ii. Regionalised low-flow estimation ( ). Because firm SHP capacity depends on dependable dry-season flow, flows exceeded 90–95% of the time are estimated using regional regression, index-flow scaling, or rainfall-runoff models calibrated against gauged catchments with similar climate/physiography. The result is a low-flow raster (or reach-level estimates) with uncertainty bands; where gauges are scarce, ensembles of methods are recommended to avoid bias (Mudenda *et* al., 2022).
iii. Specific-power mapping (head–flow overlay). Head and low-flow layers are combined to compute specific power per pixel or reach: with efficiency η consistent with turbine families screened by head/flow. The output is a specific-power raster highlighting high-yield corridors under conservative (dry-season) hydrology (Bishoge *et al.,* 2018; Mudenda *et al.,* 2022).
iv. Constraints masking. Candidate reaches are intersected with environmental and social constraints and geohazards: protected areas, critical habitats, cultural sites, landslide/erosion susceptibility, floodplains, and river fragmentation risk. Masking (hard constraints) and penalties (soft constraints) produce an environmental-compatibility score per reach (Groth, 2019; Mochani, Moridi, Tehrani, Khalili, & Haghighi, 2025).
v. Proximity to grid/load and access. Least-cost siting prioritises distance to substations/feeders for grid-tied SHP or to load centres (towns, agro-processors, mines, markets) for mini-grids. Road access and terrain ruggedness are encoded as mobilisation costs (sensitivity to penstock route, transport of E&M packages). Outputs are cost-distance rasters and a connectivity score (Ngowi *et al.,* 2019).
vi. Constructability and CAPEX proxies. A multi-criteria score blends penstock slope/length, foundation conditions (lithology/proximity to bedrock), spoil disposal, and river morphology (need for river training, cofferdams). This produces a constructability index that is later cross-checked on site (Mudenda *et al.,* 2022). (vii) Shortlist and pre-feasibility. Reaches above threshold scores are bundled into site concepts (intake–penstock–powerhouse alignments) with indicative P-Q curves, turbine options, and ballpark CAPEX/OPEX. This step also screens hybridisation potential (PV/BESS) for isolated systems (Ngowi *et al.,* 2019).
vii. Field hydrometry & geotech. Shortlisted sites undergo spot gauging (current meter, salt dilution, or ADCP where feasible), installation of stage loggers to build a rating curve, and geotechnical reconnaissance (trial pits/cores, rock quality, and seepage paths). Sediment sampling (rating of suspended/bed load; particle size) informs desander sizing and abrasion risk for runner selection (Mudenda *et al.,* 2022). Mini-grid-specific augmentation. For isolated systems, anchor-load mapping (sawmills, tea/coffee washing stations, rice mills, cold chains, telecom towers) plus productive-use potential (irrigation pumping, agro-processing, welding/woodworking clusters) materially improves demand firmness and tariff viability. Load surveys, time-of-use profiles, and enterprise incubation plans are integrated with the SHP duty curve; SCADA/PLCs enable coordinated dispatch with PV/BESS to meet evening peaks and dry-season constraints, as all of the above is indicated in table 5 (Ngowi *et al.*, 2019).

6.0 Design and Performance Modelling

Design and performance modelling for SHP in Tanzania centres on getting hydraulics, sediment control, and techno-economics to “talk” to each other. At the intake, approach-flow management is critical: screens, coarse trash racks and inlet shapes are chosen to keep velocities modest and uniform to minimise vortexing, debris ingress and fish entrainment; modern fish-sensitive guidance recommends limiting approach velocities and providing smooth streamlines and bypass routes where valuable species are present. These details matter in Tanzanian rivers that carry seasonal debris and biota, and they are well documented in recent fish-friendly intake design literature (Tomanova *et al.,* 2023).

Because many Tanzanian catchments are flashy and sediment-laden in the rains, desander design is a first-order performance lever. Practice has shifted from "rule-of-thumb" settling basins sized on linear trajectories to performance-based designs that target a critical particle size (often ≳0.2 mm for Pelton/crossflow protection) and a specified trapping efficiency. CFD-validated guidance shows how inlet calming racks, transition angles, basin depth/length ratios and outlet weirs interact to raise trapping efficiency, often implying longer basins than classical formulae but with demonstrably lower turbine abrasion and efficiency loss over time. For SHP this translates directly into higher net head (less roughness growth) and fewer forced outages in the wet season (Paschmann, Vetsch, & Boes, 2022).

Hydraulic conveyance is modelled with the Darcy–Weisbach formulation along the headrace/penstock, and penstock diameter is economically optimised by balancing capex (diameter ↑ ⇒ cost ↑) against lifetime energy loss from friction (diameter ↑ ⇒ loss ↓). Recent run-of-river (RoR) design reviews summarise best practice: Start from a routed flow-duration curve (or daily hydrology), iterate net head by subtracting site-specific intake losses, desander losses and penstock friction/minor losses, then select the economic diameter by minimising levelised cost of energy (LCOE) or maximising NPV over expected dispatch.

Table 5

Core Inputs and Outputs in a Reproducible SHP Screening Pipeline

Step	Key Inputs	Main Computation	Screening Output	Journal support
DEM head mapping	DEM, flow paths, catchments	Drop/slope extraction	Candidate head segments	(Kichonge, 2018)
Low-flow regionalization	Gauged FDC's, climate/physio regions	Q_{90}-Q_{95} via regression/index-flow	Low-flow layer w/ uncertainty	(Mudenda *et al., 2022)*
Specific-power raster	Head + $Q_{90/95}$ + η range	$P_{sp} = 9.81\eta QH$	High-yield corridors	(Kichonge, 2018; Mudenda *et al.,* 2022)
Constraints mask	Protected areas, hazards, ESAs	Hard mask + soft penalties	Env. /Social compatibility score	(Groth, 2019; Mochani *et al.,* 2025)
Connectivity & access	Grid/feeders, towns, roads	Cost-distance / least-cost path	Connection & logistics score	(Ngowi *et al.,* 2019)
Constructability	Slope, lithology, morphology	MCDA/AHP constructability index	Buildability ranking	(Mudenda *et al.,* 2022)

This same workflow is used to compare single-unit versus multi-jet Pelton, cross-flow versus Francis at medium heads, and to set turbine nozzle/guide-vane control bands for seasonal operation (Kichonge, 2018).

Annual energy yield is then integrated over time-varying $Q - H$ with part-load curves:

$$E = \sum_t PgQ_tH_{n,t}\eta_{Turb}(Q_t)\eta_{mech}\eta_{gen}\,\eta_{ele} \triangle_t \quad (4)$$

In East African SHP, long-run capacity factors commonly land in the ~30–60% range (and can approach ~70% at perennial, high-head sites with pondage), consistent with international SHP experience and Tanzanian hydro resource assessments; modelling must therefore capture (i) (i) (i) (i) (i) seasonal availability (Q90–Q95 firm flow vs. monsoon peaks), (ii) efficiency penalties at part load, and (iii) planned outages for sediment flushing (Kichonge, 2018; Mdee *et al.,* 2018).

Finally, hybridisation is increasingly part of performance modelling for isolated Tanzanian mini grids. Coupling SHP with PV and battery storage smooths diurnal variability, allows turbines to run closer to best-efficiency points (spilling short PV peaks to batteries), and improves reliability during dry-season low flows. Empirical evidence from East African mini-grids with small hydro plus PV/BESS shows improved supply continuity and reduced fuel use versus diesel-backed operation, validating co-optimisation of hydro dispatch and battery/PV sizing in the design model (Cartland, Sendegeya, & Hakizimana, 2023; Come Zebra, van der Windt, Nhumaio, & Faaij, 2021).

7.0 Environmental and Social (E&S) Considerations

Environmental and social impacts are central to the sustainable development of small hydropower (SHP). A principal safeguard is the establishment and enforcement of minimum environmental flows (E-flows) to maintain downstream ecosystem structure and function. E-flows are typically derived from site-specific ecohydraulic studies or precautionary rules (e.g., a percentage of mean annual flow or Q90-derived releases) and are used to preserve habitat for aquatic organisms, maintain water quality, and support livelihoods that depend on river resources. Even well-designed E-flows cannot fully eliminate ecological impacts, particularly for migratory species or in highly altered rivers – so E-flow measures must be combined with other mitigations and careful cumulative-impact assessment when multiple abstractions or cascades are planned (Lange *et al.,* 2019; O'Brien, Dickens, Mor, & England, 2021).

Fish passage and connectivity measures are another critical area. Where SHP schemes interrupt longitudinal connectivity, engineered fish passes (e.g., nature-like bypass channels, technical fish ladders) or low-velocity bypasses can reduce risk to migratory and resident fish populations. The effectiveness of fish passage solutions depends on local species' swimming ability and behaviour, hydrological variability, and proper siting and detailed hydraulic design; therefore, fish-passage requirements should be informed by baseline ecological surveys and monitoring (Lange *et al.,* 2019; O'Brien *et al.,* 2021).

Sediment dynamics are a major operational and ecological concern in many Tanzanian catchments. Intensified rainfall events and land-use change can increase sediment yields, which in turn cause turbine abrasion (especially for Pelton and Francis runners), accelerate wear, and reduce hydraulic efficiency. Empirical studies demonstrate that fine and coarse suspended sediments and bedload must be addressed through appropriately sized desanders, settling basins, and sluicing/flushing regimes; these installations protect E&M components and preserve downstream sediment transport regimes where geomorphic functions are important (Padhy & Saini, 2009). Regular sediment sampling and an operations plan for scheduled flushing are standard adaptive measures to manage abrasion and accumulation.

In Tanzania's mountain catchments, land-use change (deforestation, agricultural expansion, and road construction) has elevated soil erosion and altered runoff timing, exacerbating both sediment loads and flow variability. This linkage implies that SHP project sustainability is coupled to upstream watershed condition: catchment restoration (reforestation, riparian buffers, and soil conservation measures) reduces sediment delivery, improves baseflows, and enhances long-term plant performance (Finch, Wooller, & Marchant, 2014; Obahoundje & Diedhiou, 2022). Consequently, many best-practice SHP programmes include catchment management components or finance mechanisms that support upstream interventions as part of their environmental mitigation package.

Beyond biophysical measures, E&S practice requires participatory social processes: early stakeholder mapping, free, prior and informed consultation with affected communities, mechanisms for grievance redress, and benefit-sharing arrangements (e.g., local employment, community electricity access, and development funds). Cumulative and landscape-scale impacts, particularly when multiple SHP schemes or upstream abstractions exist, should be addressed through strategic environmental assessment or basin-scale planning, rather than single-site ESIAs alone (Lange *et al.,* 2019).

Finally, monitoring and adaptive management are indispensable. SHP projects should implement monitoring programmes for flows, sediment, fish populations, and socio-economic indicators and incorporate adaptive triggers (e.g., modify E-flow prescriptions, increase desander maintenance) when monitoring shows threshold exceedances. Combining engineering mitigations (desanders, fish passes, appropriately robust turbine choices) with watershed interventions and participatory governance gives the best chance of minimising adverse E&S outcomes while enabling the socio-economic benefits of distributed small hydropower (Finch *et al.,* 2014).

8.0 Opportunities

8.1 Rural Electrification & Socio-Economic Uplift

Small hydropower (SHP) presents a unique opportunity for rural electrification in Tanzania, where extending the national grid to dispersed, low-demand communities is often prohibitively expensive. SHP mini-grids or off-grid stationprovide reliable electricity directly to people living in rural areas, which is in line with the Government of Tanzania's plans to bring electricity to more rural areastegies. Compared with diesel generators and solar-only mini-grids, SHP offers greater supply reliability, higher capacity factors, and reduced lifecycle cost (Kichonge, 2018).

8.2. Climate Change and Sustainability

SHP is a low-carbon renewable technology with a lifecycle greenhouse gas footprint substantially lower than fossil fuel–based generation and even lower than some forms of large hydropower, which often entail substantial land inundation and methane emissions (Zarfl *et al.,* 2015). In Tanzania, where climate change threatens energy security through rainfall variability, SHP offers resilience because projects are typically modular, distributed, and adaptable to local catchment conditions (REGION, 2009).

Another major advantage of SHP is its shorter development cycle (typically 2.5–4 years) compared to large hydro or thermal plants, enabling rapid scaling of renewable capacity to meet growing energy demand. This agility aligns with national targets for sustainable development and climate mitigation, particularly under Tanzania’s NDC commitments.

Moreover, many SHP projects can be implemented as run-of-river schemes, avoiding large reservoirs and thereby minimising ecological and social disruption (Gaudard *et al.,* 2016). Such designs support integrated watershed management by encouraging land restoration and sustainable agricultural practices in upstream catchments, which in turn stabilise flows and reduce sediment loads. This integrated approach makes SHP not only a power generation option but also a driver of climate-resilient watershed stewardship in Tanzania (Gaudard, Avanzi, & De Michele, 2018).

8.3 Private Sector Engagement

The role of the private sector is increasingly pivotal in scaling up small hydropower (SHP) in Tanzania. Over the past decade, policy frameworks and institutional reforms have signalled greater openness to private participation in electricity generation. Key instruments include the introduction of Standardised Power Purchase Agreements (SPPAs) and the anticipated Feed-in Tariff (FiT) mechanisms, which aim to provide predictable revenue streams and reduce transaction costs for small-scale independent power producers (IPPs) (Gaudard *et al.,* 2018; Karekezi & Kithyoma, 2003a). In parallel, the streamlining of licensing processes, for example, through the Rural Energy Agency (REA) and the Energy and Water Utilities Regulatory Authority (EWURA)—has reduced regulatory barriers that previously discouraged investment in decentralised projects (Painuly, 2001).

9.0 Challenges

9.1 Technical and Infrastructure Constraints

A fundamental challenge to SHP development in Tanzania is the remoteness of many resource sites, which are often located in mountainous or rural catchments where rivers have sufficient gradients and flow for hydropower generation. These areas frequently lack reliable access roads, transmission lines, and construction logistics, thereby increasing project costs and implementation timelines (Kichonge, 2018). Transporting turbines, penstocks, and civil works equipment into such areas can require temporary infrastructure investments, inflating capital expenditure relative to urban or peri-urban renewable projects (Ahlborg & Hammar, 2014).

Another significant constraint lies in the shortage of skilled local manpower for hydropower planning, installation, and operation. Although Tanzania has developed technical training through REA and universities, there remains a dependency on external contractors for electro-mechanical assembly, turbine commissioning, and advanced control systems. Similarly, limited domestic manufacturing capacity for turbine runners, control systems, and electrical equipment halocalisation efforts, despite some promising progress in theess in small-scale fabrication of cross-flow turbines (Bishoge, Kombe, & Mvile, 2020). This reliance on imports increases costs and exposes projects to currency exchange volatility.

9.2 Environmental, Social and Financial Risks

Siltation from upstream agricultural practices and land degradation is a persistent problem in Tanzanian SHP projects. Catchments in regions such as Iringa, Mbeya, and Ruvuma are subject to high erosion during rainy seasons, which increases sediment load, reduces turbine efficiency, and accelerates mechanical wear (Thapa *et al.,* 2010). Combined with variable river flows, driven by bimodal rainfall regimes and climate variability, this results in fluctuating energy yields and undermines plant reliability (Ahialey, Kabo–Bah, & Gyamfi, 2023). Climate change introduces additional risks, as projections suggest higher flow extremes (floods) interspersed with more frequent droughts, amplifying the technical and financial risks of run-of-river SHP schemes (Cervigni *et al.,* 2015).

On the financial side, SHP projects often face high upfront capital compared to other decentralisedalised energy options. Although lifecycle costs are low, the absence of strong local financing mechanisms forces developers to rely heavily on donor funds or concessional loans (Painuly, 2001). Policy uncertainties—such as delays in operationalising feed-in tariffs (FiTs)—add to the financial risk profile, discouraging private investors. Moreover, demand-side risks exist in rural areas where household incomes are limited; rural consumers may struggle to afford tariffs that reflect cost recovery, leading to low willingness-to-pay and underutilisation of installed capacity (Groth, 2019).

9.3 Policy and Regulatory Issues

Although Tanzania has made substantial progress in creating policies supportive of renewable energy, including SHP, procedural bottlenecks remain significant. Developers must navigate multiple stages of registration, licensing, environmental approvals, and grid interconnection agreements, often through different agencies, which increases administrative costs and delays project implementation (Fischer, Lopez, & Suh, 2011). Streamlined “one-stop-shop” regulatory frameworks are still emerging, and inconsistencies between national electrification strategies and local-level enforcement often frustrate private developers (Karekezi & Kithyoma, 2003a).

Finally, the financial viability of SHP projects in rural Tanzania is constrained by the socio-economic context: electricity demand in underserved areas is often low and dispersed, reducing economies of scale. Without parallel efforts to promote productive use of electricity (e.g., agro-processing, small-scale manufacturing), many SHP schemes risk operating below optimal capacity utilisation (Ngowi *et al.,* 2019). Therefore, integrating SHP expansion with rural industrialisation and income-generating activities is key to overcoming regulatory and financial barriers.

10.0 Economics and Finance

10.1 Cost Structure and LCOE

The economics of small hydropower (SHP) in Tanzania and East Africa are shaped by site-specific parameters such as head, geology, hydrology, remoteness, and access infrastructure. SHP projects are inherently capital-intensive, but once constructed, they exhibit very low operating costs relative to thermal alternatives. Empirical cost surveys from East Africa and global SHP markets show a typical capital cost distribution of:

i. Civil works (35–55%) – including weirs, intake structures, desanders, canals/penstocks, and powerhouse construction. Costs escalate in rugged geology (e.g., volcanic rock in Northern Tanzania) or where extensive access roads are required (Paish, 2002).

ii. Electro-mechanical equipment (25–40%) – turbines, generators, governors, and control systems. While standardised cross-flow turbines have been locally manufactured at reduced costs, Pelton and Francis turbines are often imported, raising CAPEX (Kaunda, 2013).

iii. Electrical interconnection (5–15%) transformers, switchgear, and distribution lines, which vary depending on whether the scheme is grid-connected or designed for isolated mini-grids (Jeuland *et al.,* 2023).

iv. Owner's and development costs (5–10%) – feasibility studies, permitting, licensing, project management, and financing fees, which are particularly significant in Tanzania due to lengthy regulatory procedures (Ahlborg & Hammar, 2014).

The Levelised Cost of Electricity (LCOE) provides the benchmark for SHP competitiveness. It is expressed as:

$$LCOE = \frac{\sum_{t=0}^{N} \frac{I_t + O\&M_t + F_t}{(1+r)^t}}{\sum_{t=0}^{N} \frac{E_t}{(1+r)^t}} \quad (5)$$

Where:

I_t = investment expenditures in year t,

$O\&M_t$ = operations and maintenance costs,

F_t= fuel costs (typically negligible for SHP),

E_t= electricity generated in year t,

r = discount rate,

N = economic lifetime (often 25–40 years).

For well-sited SHP in East Africa, LCOE estimates typically range from USD 0.06 to 0.15/kWh for grid-connected projects (Kaunda, 2013). This compares favourably with the USD 0.25-0.40/kWh cost of diesel-based generation in rural mini-grids (Kaunda, 2013). SHP mini-grids may exhibit slightly higher costs than grid-connected projects due to distribution infrastructure and lower load factors, but they remain competitive against fossil-fuel-based rural electrification.

Several factors drive these outcomes. High-capacity factors (35–70%) typical of Tanzanian SHP sites enhance cost recovery compared with solar-only systems (Andersson et al., 2018). Meanwhile, long project lifetimes (≥30 years) and low O&M requirements improve financial viability relative to diesel or biomass options. However, upfront capital constraints, foreign exchange risks, and limited local financing mechanisms remain barriers to broader SHP scale-up (Painuly, 2001).

11.0 Case Archetypes in the Tanzanian Context

In Tanzania, small hydropower (SHP) development can be categorised into several case archetypes that align with the country's diverse geography and energy needs. High-head run-of-river projects (1–10 MW) in mountainous catchments are ideal for grid injection, using Pelton or Turgo turbines with short penstocks and delivering high-capacity factors (45-70%) at relatively low environmental footprints where substations lie within 10-20 km (Kaunda, 2013; Paish, 2002). Cascaded mini-grids (2×500 kW–2×1 MW) can harness sequential drops along the same river to power multiple villages, enabling shared O&M and coordinated environmental flow management (Ngowi *et al.,* 2019). Irrigation-canal drop schemes (100–500 kW) exploit existing water infrastructure with low-head Kaplan or screw turbines, offering minimal civil works, stable flows, and co-benefits for water agencies (Carruthers, Carruthers, & Wade, 2018). Finally, hybrid SHP-PV-BESS mini-grids (200–800 kW hydro + PV) combine hydro's reliability with solar's daytime generation and battery storage for ride-through and black start, reducing spillage and enhancing rural energy security (Groth, 2019).

Together, these archetypes demonstrate how SHP in Tanzania can be adapted to site-specific conditions, balancing cost, performance, and sustainability as indicated in Table 6 (see appendix 1)

12.0 Implementation Roadmap

12.1 National and Basin-Scale Actions (12–24 Months)

At the national and basin levels, the priority is to strengthen hydrological and sediment data programmes, since reliable flow and sediment records are essential for sizing turbines, estimating firm power (Q90–Q95), and designing sediment management structures. This requires rehabilitating and expanding gauging stations in priority basins, such as the Rufiji, Pangani, and Lake Victoria catchments, digitising historical archives, and making datasets openly accessible for developers and researchers (Cervigni *et al.,* 2015; Obahoundje & Diedhiou, 2022). Complementing this, Tanzania should develop and publish basin-level SHP atlases, integrating GIS-based site screening, environmental and social (E&S) constraints, and indicative LCOE estimates. Such atlases can reduce development risks and improve bankability, as demonstrated in East Africa and South Asia (Gaeatlholwe, 2021; Singh, 2009). Parallel efforts should update standardised interconnection and protection codes for small hydro, ensure technical compatibility with the national grid and mini-grids, and publish reference design packages to streamline permitting and engineering (Kaunda, 2013).

12.2 Project Development Cycle (18–36 Months)
At the project level, SHP implementation follows a structured four-stage development cycle. In the pre-feasibility stage (0–6 months), developers conduct GIS-based screening, reconnaissance walkovers, and initial Memoranda of Understanding (MoU) for land access, while also setting up preliminary hydrological monitoring and initiating early community engagement. During the feasibility stage (6–14 months), hydrological flow monitoring over at least one full year or robust regionalisation with uncertainty bounds is required to reduce hydrological risk, alongside geotechnical investigations, Environmental and Social Impact Assessments (ESIAs), preliminary engineering designs, and cost and financial modelling (Ngowi *et al.,* 2019). The financing and detailed design stage (14–20 months) involves securing equity and debt, negotiating Power Purchase Agreements (PPAs), finalising tariffs and guarantees, and procuring electromechanical and civil works contractors. Finally, during the construction and commissioning stage (20–36 months), developers implement environmental management measures, quality assurance protocols, grid compliance tests, operator training, and project handover (Kichonge, 2018).

12.3 Cross-Cutting Enablers
Several cross-cutting enablers can significantly improve the efficiency and sustainability of SHP development. Standardised contractual frameworks—such as model PPAs, EPC agreements, O&M contracts, and Owner's Engineer scopes—help reduce transaction costs and de-risk investment (Jeuland *et al.,* 2023). Expanding local manufacturing capacity for penstocks, gates, and civil works, coupled with vocational training programmes for hydro operators and electricians, strengthens domestic value chains and ensures sustainability (Karekezi & Kithyoma, 2003a). In addition, promoting productive uses of electricity such as milling, cold storage, irrigation pumps, and e-mobility charging can raise load factors and improve the financial viability of SHP mini-grids (Groth, 2019).
Finally, integrating watershed restoration and nature-based solutions, including reforestation, riparian buffer establishment, and soil conservation, helps stabilise dry-season baseflows, reduce sediment transport, and sustain long-term SHP performance (Finch *et al.,* 2014).

13.0 Risk Assessment and Mitigation

The success of small hydropower (SHP) projects in Tanzania depends on proactive identification and management of risks spanning hydrology, geology, construction, regulation, finance, and operations.
Hydrological risk is the most critical, given Tanzania's bimodal/unimodal rainfall regimes and climate variability. Developers should apply probabilistic flow-duration curves (P-levels), alongside climate stress tests under multiple General Circulation Models (GCMs), to ensure robust plant sizing and dependable capacity (Q90–Q95). Structuring Power Purchase Agreements (PPAs) with availability-based payments rather than strict kWh delivery can mitigate financial exposure during drought years (Cervigni *et al.,* 2015; Gaudard *et al.,* 2018).
Geotechnical risk stems from uncertain subsurface conditions, particularly in volcanic or

rift-valley terrains common to Tanzania. Early geologic mapping, borehole drilling, and geophysical surveys are essential to avoid unexpected excavation, slope stabilisation, or blasting costs. For unexpected geotechnical conditions, a contingency budget of 10–15% is usually set aside (Paish, 2002).

Construction risk relates to delays, cost overruns, and quality deficiencies.

Modular design approaches, contracting experienced EPC firms, and adopting performance-based contracts with liquidated damages for delays and underperformance reduce exposure (Paish, 2002).

Regulatory risk arises from protracted licensing, permitting, and interconnection approvals. Developers should follow up-to-date compliance checklists, maintain constructive engagement with regulators and host communities, and secure water-use permits early in the cycle to avoid delays (Ahlborg & Hammar, 2014).

Revenue and credit risk are concerns in both grid-connected and mini-grid contexts. In grid-connected cases, delayed utility payments can be mitigated by escrow accounts or letters of credit (L/Cs). For mini-grids, diversifying the customer base, integrating anchor loads such as agro-processing, and structuring long-term contracts strengthen revenue streams (Groth, 2019).

Finally, O&M risk is significant in remote areas where spare parts and skilled technicians are scarce. Mitigation involves a spare-parts strategy, training of local operators, contracts with OEMs for periodic overhauls, and remote monitoring systems (SCADA/PLC) to anticipate failures before they escalate (Ngowi *et al.,* 2019).

13.1 Monitoring, Operations, and Digitalisation

Modern small hydropower (SHP) projects increasingly rely on digital technologies to optimise performance, reduce downtime, and ensure sustainability in data-scarce environments like Tanzania.

Hydrometer telemetry plays a critical role in monitoring water availability and sediment loads. Deploying low-power data loggers with GSM or satellite connectivity allows continuous recording of flow, rainfall, and sediment parameters in remote catchments. This real-time monitoring helps with flood early-warning systems, debris alarms, and adaptive turbine dispatch. It lowers the chances of both underperformance and catastrophic damage (Ahialey *et al.,* 2023; Cervigni *et al.,* 2015).

Supervisory Control and Data Acquisition (SCADA) systems, coupled with predictive maintenance tools, enhance operational reliability. Vibration and temperature sensors embedded in bearings, shafts, and Pelton/Turgo nozzles enable condition-based maintenance, extending equipment lifespans and reducing unplanned outages. Automated desander flushing systems further mitigate sediment abrasion risks, a key issue in Tanzanian mountain catchments. Energy dashboards integrated with SCADA also facilitate community engagement, allowing end-users to track consumption, tariffs, and local load factors (Ngowi *et al*., 2019).

Water-energy coordination is equally vital for sustainable SHP operations. Since many Tanzanian catchments support irrigation, domestic water supply, and ecological needs, operators must align hydropower dispatch with upstream irrigation abstractions and mandated environmental flow (E-flow) releases. Seasonal flow variations also necessitate planned maintenance windows during low-flow periods, ensuring turbines are serviced without compromising energy supply. Integrated water-energy governance frameworks can therefore enhance both hydropower reliability and watershed sustainability (Cohen Liechti, Matos, Boillat, & Schleiss, 2015; Gaudard *et al.,* 2016).

14.0 Conclusions

Tanzania's physiography and hydro-climatic regime confer substantial potential for small hydropower to deliver reliable, low-carbon electricity for both the main grid and rural mini-grids. Technically, abundant high- and medium-head streams – especially in the Eastern Arc and Southern Highlands – can host run-of-river and low-impact pondage schemes with capacity factors commonly between 35% and 70%.

This study's multi-method approach, which includes hydrological, geospatial, socio-economic, and policy frameworks, shows that sustainable SHP development can help Tanzania reach its goals for rural electrification, climate resilience, and socio-economic change. Challenges such as upfront capital costs, sedimentation management, technical capacity gaps, and regulatory bottlenecks remain but are addressable through simplified permitting, concessional financing, community engagement, and integrated watershed management.

Moreover, SHP systems offer advantages over solar-only or large-hydropower solutions by providing dispatchable, stable, and scalable power generation with lower environmental and social footprints. The integration of small hydro with solar photovoltaics and battery energy storage in mini-grid configurations further enhances supply reliability and commercial viability in off-grid areas.

Future efforts should focus on closing hydrometric and technical data gaps, promoting enabling policies, and supporting capacity building inclusive of local stakeholders. In conclusion, leveraging Tanzania's abundant, yet underutilised, small hydropower resources, particularly through well-planned, context-sensitive projects like those on the Luswisi River, can accelerate the country's sustainable energy transition and foster inclusive rural development.

15.0 Recommendations

i. National SHP Atlas & Open Data: Develop basin-level atlases with ranked candidate sites, flow/head maps, and constraint layers; publish as open geospatial data.
ii. Hydrometer Revitalisation: Rehabilitate gauging stations in priority basins; standardise methods for low-flow and flood estimation; require at least one hydrological year of measurements or robust regionalisation.
iii. Streamlined Permitting: Create a single-window process with clear timelines; update standardised PPAs/tariffs for ≤10 MW projects; clarify grid-code requirements for small generators.
iv. Blended Finance & RBF: Expand results-based and viability-gap funding; deploy partial risk guarantees and local-currency credit lines for SHP.
v. Productive-Use Integration: Pair SHP rollouts with financing for agro-processing, cold chains, water pumping, and e-mobility to raise load factors.
vi. Climate-Resilient Design: Mandate environmental flows, sediment management, and flood-resilient civil works; adopt climate stress testing in feasibility studies.
vii. Capacity & Local Industry: Support training centres for hydro technicians; promote local fabrication of penstocks, gates, and electro-mechanical auxiliaries.
viii. Community Partnership Models: Encourage community equity or benefit-sharing funds; prioritise local jobs and electrification of public services.

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APPENDICES

Appendix 1

Table 6

Case Archetypes in the Tanzanian

Archetype	Size (indicative)	Site context & layout	Turbine/technology	Grid/mini-grid configuration	Performance notes (typical CF)	Key CAPEX/OPEX drivers	E&S focus	Journal citations
High-head run-of-river for grid injection	1–10 MW	Mountain catchments; short penstock from intake/desander to powerhouse; MV line (10–33 kV) to substation ≤10–20 km	Pelton / Turgo; sometimes Francis at mid-heads	Grid-connected; power factor/voltage support via AVR; remote SCADA	High CF where Q90–Q95 is robust; ~45–70% with small pondage	Civil works share high (intake, desander, penstock); E&M for multi-jet Pelton; interconnection cost vs. substation distance	E-flows and fish passage; cumulative impacts if multiple sites; sediment abrasion control	(Paish, 2002)
Cascaded mini grids along one river	2×500 kW – 2×1 MW	Two drops on same reach; shared O&M base; staged intakes/short penstocks serving clusters of villages/anchor loads	Pelton/Turgo (upper), crossflow/Francis (lower), depending on head	Isolated or partial grid-tie; coordinated dispatch; shared spares; PLC protection	Firm supply improved by cascade diversity; ~40–60% overall	Access/logistics (two sites); shared O&M lowers costs; smaller inter-village distribution network	Coordinated E-flows between plants; fish connectivity; sediment flushing schedules aligned	(Kichonge, 2018; Ngowi *et al*., 2019)
Irrigation-canal drop	100–500 kW	Existing canals / weirs; minimal new civil works; energy recovery at drops	Kaplan/propeller, bulb or Archimedes screw/VLH for very low head	Typically, mini-grid or behind-the-meter for water agencies; simple controls	Stable flows when irrigation constant; ~35–55%	Very low civil CAPEX; compact E&M; low O&M; intertie short	Flow sharing with irrigation; fish-friendly runners; debris/silt screens	(Quaranta & Revelli, 2018)
Hybrid SHP-PV-BESS mini-grid	Hydro 200–800 kW + PV (complementary)	Perennial stream plus good insolation; run-of-river with small pondage; battery housed at powerhouse	Crossflow/Francis/Pelton (per head) + PV array + BESS + EMS	Islanded mini-grid; EMS holds turbine near BEP; PV handles daytime; BESS provides ride-through/black-start	Higher reliability; reduced spillage; evening peak met by hydro; effective CF improved	Added CAPEX for PV/BESS and controls; lower fuel/logistics vs. diesel; fewer outages	E-flows; PV land footprint; battery safety; community benefits via productive use	(Groth, 2019)