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Harnessing Solar Water Pumping Technologies for Sustainable Water Supply in Kenya: A Case Study of Kajiado Central Sub-County, Kenya. A Retrospective Baseline Study

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Harnessing Solar Water Pumping Technologies for Sustainable Water Supply in Kenya: A Case Study of Kajiado Central Sub-County, Kenya. A Retrospective Baseline Study.

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Abstract

Kajiado County suffers from acute water scarcity caused by climate-driven droughts and surface-water deficits that severely threaten agro-pastoral livelihoods, forcing a reliance on groundwater extraction across unserved zones of Kajiado Central Sub-County. Weak regulatory oversight has led to uncoordinated, dense borehole clustering that causes localized static water tables to drop rapidly, while private water pricing strains household economies and unregulated extraction bypasses public health monitoring for hazardous geogenic fluoride. This study implements a comparative ex-post facto retrospective research design spanning a 10-year operational horizon (2015–2025) to evaluate the long-term performance of resource-efficient Solar Water Pumping Technology (SWPT) as an alternative to conventional diesel and grid regimes. Synthesizing Common-Pool Resource (CPR) and Socio-Technical Systems (STS) theories, the study relies entirely on archival secondary data sourced from the Kajiado County Ministry of Water, the Water Resources Authority (WRA), and public health registries, evaluated via statistical trend tracking and thematic analysis. The empirical findings reveal that while transitioning to solar water pumping lowers operational costs by 60%–75% compared to diesel, the zero-marginal cost of solar power creates an economic incentive for unrestricted over-pumping that accelerates aquifer drawdown, while the clean energy transition exhibits a major health compliance gap by routinely distributing untreated water that exceeds the WHO 1.5 mg/L fluoride threshold. Technical upscaling must be legally bound to institutional governance; this study provides an empirical baseline for the Kajiado County Government to enforce spatial drilling limits, embed solarized frameworks into the County Integrated Development Plan (CIDP), and deploy mandatory solar-powered defluoridation units to ensure long-term climate resilience and public safety.

Keywords: Solarization; Common-Pool Resources; Sustainable Water Supply; Socio-Technical Systems; Environmental Pollution.

1.0. Introduction

1.1 Background of the Study

Chronic water shortages in the semi-arid Kajiado Central Sub-County endanger the livelihoods of pastoralists and health outcomes of those living in the sub-county. SWP is considered to be a sustainable adaptation strategy but the sustainability over time is reliant on social governance and physical infrastructure configurations. The challenges of energy-water- health nexus are severe and intersecting in the water abstraction in Kajiado Central Sub-County. Switching from diesel- powered to clean energy—solar-powered water pumping can generate significant cost savings, but it has unwittingly spurred uncontrolled groundwater extraction. As a result of this efficiency improvement, the neighborhood experienced clustering of boreholes in close proximity, which poses a threat to structural stability of the local aquifer system. This environmental problem is compounded by an important public health concern – that over 70% of local groundwater sources many times contain concentrations of geogenic fluoride well beyond the regulatory limit of 1.5 mg/L and local communities suffer high rates of both dental fluorosis and skeletal fluorosis.

The structural issues of the energy-water-health nexus prevailing in Sub-Saharan Africa exist despite the fragmented and inconsistent electricity distribution, and high fossil fuel price risks faced by rural and peri-urban water supply systems. In Kenya's arid and semi-arid lands (ASALs) including Kajiado County, groundwater is tapped as an interdependent means of providing water for domestic, livestock and commercial purposes. Traditionally, these groundwater systems have been powered by diesel-fueled generators, a large financial burden for marginalised communities because of their high cost of operation and maintenance. Between 2015 and 2025, climate change prompted a strong shift toward green technology.

Solar water pumping transformed farming and community water access. Backed by the National Treasury and programs like FLLoCA, these systems provide low-cost, clean water free from grid failures and carbon emissions However, if such technology is considered vulnerable and is introduced without robust regulations, there are unintended and complex consequences that run. Where pumping costs approach zero, people may start to pump water without any considerations.

This has led to high densities of boreholes in space within the Kajiado Rift aquifer, which poses a risk to long-term sustainability of the aquifer. Further, the rocks in this region in which groundwater flows are highly volcanic and they contain abundant geogenic fluoride which are naturally dissolved into the water. Consequently, cascading solar water infrastructure without embedded water treatment systems may become a vector to spread high fluoride water to the populations that are vulnerable, and in doing so, solve the energy problem with a great public health problem.

The 2019 Kenya Population and Housing Census shows that Kajiado Central Sub-County has a population of 161,862 people spread out over 37,000 households, making the population density sparse at 38 persons per km2. This sub-county is mostly pastoral rangeland, and thus it is a highly climatic resilient resource in its use of groundwater.

The Water Asset and Operation and Maintenance dashboard by Kajiado County Government covers shared water systems in the County and the Arid Lands Information Network Renewable Energy Atlas identifies boreholes as one of the keystones of the water infrastructure, especially when combined with seasonal water rivers and earth dams in the region. Traditionally using a robust diesel engine to take the deep aquifer has posed huge challenges such as expensive >30-40% farm and community operational costs from the diesel fuel, frequent mechanical breaks down, supply of the fuel can be difficult and carbon emission is impactful for specific areas.

Luckily Kajiado County has very good solar conditions with high irradiance ranging from 5.5 – 6.5 Peak Sun Hours (PSH) per day, and strong daytime radiation reaching higher than 900 W/m². The renewal of the community and agricultural boreholes with solar water pumping technology (SWPT) is a great solution. Through the utilization of the huge solar energy resource in the sub-county, SWPT eliminates recurring fuel costs, stops the emission of pollutants, limits operational maintenance and ensures the climate resilient water supply needed to support better food security and livelihoods in Kajiado Central (Argaw, 2004; Rijsberman, 2006).

The Kajiado County Integrated Development Plan (2023-2027) identified the challenge of water scarcity as a major challenge confronting the county, especially in the arid and semi-arid parts of Kajiado. A recent report by the National Drought Management Authority (NDMA) indicates that from September to November 2022, Kajiado lost 38.8% of its livestock population and 400,000 households were food basket cases. The herders' losses were estimated at around KES 13 billion as a consequence of livestock death, malnutrition among children, school dropouts, and unavailability of milk for nursing mamas and babies as a result of the drought (Nkapaapa, 2023). As defined by Local Governments for Sustainability (2021), a solar water pump (SWP) is a type of electric water pump that works with PV (photovoltaic) panels, where PV panels generate electricity to power the sun pump. SWPs provide water to areas that are not connected to the electric grid. It is appropriate for Kajiado County impoverished urban, peri-urban and rural communities which lack electricity, has fewer environmental concerns and lower operational and maintenance costs.

1.2. Statement of the Problem.

The core problem addressed by this study is the critical lack of longitudinal empirical evidence monitoring the operational durability, institutional governance, and socio-technical alignment of solarized water assets in Kenya's arid and semi-arid lands. In Kajiado Central Sub-County, chronic water scarcity poses a continuous threat to pastoralist livelihoods, public health, and livestock survival. Relying on seasonal water pans or high-cost diesel boreholes has proven unsustainable, driving high rates of waterborne illness and diverting critical labor hours into water fetching.

While solar water pumping technologies (SWPT) have been widely deployed by state and non-state actors as a clean alternative, their long-term viability is compromised by a complex web of institutional and technical failures. Synthesizing Common-Pool Resource (CPR) and Socio-Technical Systems (STS) theories reveals that these assets suffer from weak user ownership, inadequate local tariff collection, and a poor alignment between traditional pastoralist migration patterns and the mechanical limits of solar arrays. This mismatch often culminates in accelerated aquifer depletion and systemic pump abandonment. Because existing literature lacks a comprehensive, ex-post facto retrospective evaluation of these assets over a 10-year operational horizon (2015–2025), policymakers lack the data necessary to design sustainable interventions. This baseline

1.3. Significance of the study.

The significance of this baseline study spans practical, theoretical, and methodological dimensions, offering vital insights for stakeholders operating at the intersection of clean energy, public health, and climate adaptation in arid environments. Page 2 of 10 Okwiri et al. / Harnessing Solar Water Pumping Technologies for Sustainable Water Supply in Kenya

Practically, the study equips the Kajiado County Government with empirical data to shift the County Integrated Development Plan (CIDP) from reactive emergency water trucking toward data-informed, proactive solar asset management. By capitalizing on local solar exposure, the study outlines paths to insulate agro-pastoralists from volatile diesel markets, securing local food systems during droughts. Furthermore, it gives development donors sub-county level metrics to ensure future investments favor long-term lifecycle sustainability over quick installation goals, while warning public health regulators that clean energy expansion must be legally paired with mandatory fluoride testing. Theoretically, the study advances Common-Pool Resource (CPR) literature by exploring a modern paradox: how zero- marginal-cost solar power can inadvertently accelerate a 'Tragedy of the Commons' in unmanaged aquifers. It simultaneously expands Socio-Technical Systems (STS) theory by evaluating how advanced green hardware embeds within traditional African pastoralist structures and environmental constraints. Methodologically, the study's comparative ex-post retrospective design establishes a clear blueprint for infrastructure lifecycle assessments, demonstrating that analyzing the real-world operational durability of mature assets provides vastly superior developmental insights compared to looking only at pristine, newly installed systems.

1.4 Rationale of the Study.

The rationale for this baseline study stems from the urgent need to decouple rural water security from carbon-intensive, high-cost energy regimes in Kenya’s arid lands. Solar Water Pumping Technology (SWPT) has emerged as a premier decentralized solution in areas where conventional grid infrastructure is absent, unreliable, or prohibitively expensive. This study evaluates the 10-year empirical trajectory of solarized boreholes in Kajiado Central to align localized resource management with global mandates, specifically UN Sustainable Development Goals 6, 7, 13, and 5. Historically, the volatility of diesel fuel pricing has placed an unviable economic burden on low-income pastoralist communities, frequently causing operational shutdowns of community water assets. This research captures the longitudinal cost-reduction curves of solar transitions, illustrating how lowering operational expenditures can systematically stabilize consumer tariffs and lower the regional carbon footprint. Beyond macro-economic metrics, the study establishes an essential data baseline for regional regulators.

The resulting empirical insights provide the Kajiado County Government and the Water Resources Authority (WRA) with the evidence required to enact protective institutional reforms. These insights are vital for establishing data-driven spatial zoning laws to curb unregulated borehole clustering and implementing compulsory, routine water quality sampling procedures to address the sub-county's deep-rooted geogenic fluoride crisis.

1.5. Scope of the Study

The scope of this study is strategically bounded geographically, conceptually, and temporally to ensure a rigorous retrospective analysis. Geographically, the research focuses on Kajiado Central Sub-County, encompassing its five administrative wards: Purko, Ildamat, Dalalekutuk, Matapato South, and Matapato North.

This region was selected due to its high density of active and abandoned groundwater assets and its historical vulnerability to falling water tables. Conceptually, the study investigates the economic viability of solar water pumping technology in comparison to diesel and grid systems, examining how spatial borehole clustering impacts static water levels. Additionally, it evaluates public health compliance by mapping ambient groundwater fluoride concentrations against safety standards.

Temporally, the study covers a ten-year horizon from 2015 to 2025 and relies exclusively on historic secondary datasets. By utilizing established borehole registers, hydrogeological logs, sub-county financial audits, and public health archives, the study provides a comprehensive retrospective assessment while explicitly omitting primary field data collection or direct laboratory testing.

1.6. Baseline Study

Objectives To address the systemic vulnerabilities of rural water transitions in Kenya's arid and semi-arid lands, this baseline study investigates community-managed solar water pumping technology in Kajiado Central Sub-County through an ex-post retrospective lens. Grounded in a dual theoretical synthesis of Common-Pool Resource (CPR) and Socio-Technical Systems (STS) paradigms, the study fulfills three interconnected objectives: First, it traces the 10-year hydrogeological footprint of uncoordinated borehole clustering, determining how free solar energy influences communal over-extraction and shifts static groundwater baselines.

Second, it examines the public health safety gap of this clean energy transition by auditing historical compliance records for geogenic fluoride contamination, illustrating the danger of unmonitored solar systems pumping water that significantly exceeds safe limits.

Finally, it analyzes the economic tradeoffs of solarization by comparing its long-term operational savings against conventional diesel and grid systems, directly measuring how local water committee governance and tariff collection influence the system's financial survival.

2.0. Literature Review

Safe water is not readily accessible in Kajiado County in that there is a high utilization of surface water, shallow wells and boreholes with hand pumps by the communities. Although these boreholes are the main water technology in both urban, peri-urban and rural areas, there are also some areas where piped gravity-fed systems are available. Water security should be embraced as acting on intra-sectoral integration of land-use and water management and supporting the model of a resource-efficient integrated land-water-forest-strategies of micro-level decision making programmes.

It is a holistic approach which requires cooperation throughout the households, at the community level, and nationally, to safeguard vulnerable water sources, water as a scarce resource, and to implement water saving technologies to provide water equitably. Improving access to water is more than just to delay the onset of diseases; it delivers important socioeconomic advantages that directly influence social decisions beyond health matters.

These benefits are largely for women, who lose time, lift heavy loads and risk injury loading and carrying water for long distances as the distance between them and their water source is shortened and water is kept clean. Finally, being able to secure water access becomes a stepping stone towards community development and improved livelihoods; a goal that is impossible without safe and reliable water supply (Odeh et al., 2006).

PVP is a highly sustainable, cost-effective method to remove water from the source. Solar-powered irrigation has the potential to boost incomes, especially for out-of-the-way agricultural producers, due to the reduced cost of solar panels (80% of the original cost, Hussain, 2009) and the low maintenance requirement and long operating life of an 80-year exception (25 years of operation) (Hussain, 2009).

The use of clean reliable sources of fresh water for rural areas is very important and using accurate technology in withdrawing ground water is crucial, since groundwater is the main source of these areas (Bovolo et al., 2009). For these areas, photovoltaics systems are the most efficient, economically suited and environmentally friendly technologies when compared with the use of fossil fuel and grid electricity and wind. In addition to introducing energy into the developing world, this technology also provides an important level of resilience in the event of rainfall changes as a result of climate change (Firatoglu and Yesilata, 2004).

Some governments give support by subsidizing the SWP systems to create a common knowledge base. Nonetheless, the advantages of solar pumping are largely not known to the mainstream institutions, governments and local communities. This critical unexplored awareness has direct impacts on climate adaptation in highly climate sensitive locations such as Kajiado County, where the traditional farming and pastoral livelihoods that have relied on climatic conditions are gradually being compromised by the effects of climate change (Musau, 2022). During the 2020-2023 drought, all the devastating effects of this climate crisis were realized, especially in Kajiado County where critical water and pasture resources were at high risk of loss resulting in pastoral survival threatened (Nkapaapa, 2023).

This environmental stress led to major child nutritional problems and had to alter traditional nomadic ways of life. According to local steering group reports, more children under five years went through supplementary feeding programmes in July 2022, constituting a thirteen-fold rise in admissions to the programmes. Apart from mass livestock deaths, agricultural harvests have deteriorated and the situation of incidences of conflict worsened between people and wildlife for the purpose of obtaining resources.

3. 0. Baseline Study Methodology

4. 3.1. Research Design.

Methodologically, this study implements a comparative retrospective ex-post facto research design to assess the long- term viability of solar water pumping (SWP) systems. Rather than relying on cross-sectional observations, this framework evaluates mature SWP assets that have been operational for two to ten years post-installation, benchmarking their performance against a control group of newly commissioned systems.

This dual-cohort approach allows for a rigorous assessment of real-world equipment degradation, long-term community adaptation, and actual operational lifespans without manipulating any underlying environmental or institutional variables. To capture the complex operational dynamics of these systems, the research design synthesizes Common-Pool Resource (CPR) and Socio-Technical Systems (STS) theories. This theoretical integration addresses the inherently paradoxical nature of modernized rural water points. It frames the solarized borehole simultaneously as a sophisticated mechanical installation governed by engineering parameters, and as a vulnerable public good whose survival depends on collective action, rule enforcement, and institutional resilience.

3.2. Justification of the Ex-post Research Design

To analyze the socio-technical and environmental impacts of clean energy transitions in Kajiado Central Sub-County, this study utilizes an ex-post facto research design. This non-experimental framework is ideal because the primary interventions—the solarization of communal water assets and the accelerating clustering of localized boreholes— unfolded naturally over a ten-year horizon spanning 2015 to 2025.

A key justification for this design is the structural impossibility of variable manipulation. Acting as external observers, the research team could not control where private or public entities drilled boreholes, when solar arrays were integrated, or how geogenic fluoride fluctuated within the deep aquifer layers. Instead, the methodology relies on a retrospective analysis of a 10-year secondary dataset to isolate statistical relationships and model long-term trends. By pairing this longitudinal data with modern analytical tools, the ex-post framework supports robust cause-and-effect inferences, mapping how independent variables like free solar power and spatial density drive critical dependent outcomes, such as reduced water retail costs, accelerated aquifer drawdown, and elevated public health fluorosis rates

Table A: Synthesis of the Theories within the Energy-Water-Health Nexus

Theory Primary Variable Study Dimension Operational Outcome (i) CPR Aquifer sustainability / Environmental Localized extraction by- Well Density Governance laws & institutional compliance (ii) STS Solar & Filter integration Technological, structural Financial scaling & / user nodes & carbon reduction reduced fluorosis rates

3.3. Theoretical Framework

To capture the complex interplay between clean energy, groundwater dynamics, and community governance, this study constructs a dual-theoretic model combining Common-Pool Resource (CPR) Theory and Socio-Technical Systems (STS) Theory. Grounded in Ostrom's (1990) foundational work, CPR theory is applied to Kajiado Central's groundwater, which faces severe subtractability and low excludability under free solar pumping conditions.

To evaluate how the sub-county can avoid a localized 'Tragedy of the Commons,' the study operationalizes four core design principles: boundary clarity to define user groups, congruence to align pumping limits with aquifer recharge rates, collective-choice arrangements to empower Water User Associations (WUAs), and conflict resolution mechanisms to mitigate resource disputes between domestic users and pastoralists. Concurrently, STS theory frames the solarized borehole as an interconnected network of physical and human variables.

The technical subsystem maps engineering inputs like PV degradation, inverter efficiencies, and borehole yields, while the social subsystem tracks human behaviors, institutional water needs, community financial readiness-to-pay, and local technical literacy. Synthesizing these two theories yields a comprehensive framework capable of diagnosing systemic vulnerabilities.

This integration demonstrates that infrastructure sustainability is fundamentally holistic: a system failure is rarely a isolated mechanical event, such as a blown inverter, but is instead rooted in institutional breakdowns like uncollected maintenance fees or unmanaged social competition at the pumping site.

3.4 Data Collection and Analysis

Secondary data points were harvested across a 10-year timeline from authoritative sector repositories:

Table B: Secondary Data Extraction Matrix (Kajiado Central Sub-County)

Data Category Specific Indicator Unit of Historical Secondary Measurement Data Source Range (a) Borehole (i) No. of registered Count status-type: 2015–2025 (i) Kajiado County Profile & Tech boreholes (ii) (i) mWater Asset Pumping power Solar/diesel/grid Management source (iii) System (ii) Dashboard (ii) status Active/defunct/dry WRA – Water permit database (b) Spatial (i) GPS Arc-degrees to 2018–2025 (i) Sub-county Dynamics Coordinates/Mapping meters (m) hydrological (ii) Inter-borehole surveys (ii) GIS distance data repository

Data Category Specific Indicator Unit of Historical Secondary Measurement Data Source Range (c) Economic (i) Capital (i) KES in 2015–2025 (i) Water service Metrics expenditure (CapEx) millions (ii) provider (WSP) (ii) Monthly fuel/grid KES/month (iii) audits (ii) Sub- cost (OpEx) (iii) KES per 20 L county finance Consumer water tariff jerrycan records (d) (i) Static water level (i) Meters (m) (ii) 2010–2025 (i) WRA Environmental (ii) Dynamic water Meters (m) (iii) monitoring Metrics level (iii) Estimated Cubic meters/hour stations (ii) aquifer yield (m^3/h) Borehole drilling logs (e) Public (i) Fluoride (i) mg/L (ii) mg/L 2015–2025 (i) MoH reports Health Profiles concentration (ii) (iii) Annual (ii) Kajiado Total dissolved solids clinical count County Referral (TDS) (iii) Hospital Documented fluorosis cases

3.5 Situational Analysis

Classified as a water-deficient zone, Kajiado County presents a challenging environment where pastoralist livelihoods are highly sensitive to extended droughts. Low-income households are severely impacted, absorbing high water costs from local vendors while being forced to restrict their consumption to less than half of the WHO-recommended 20 litres per day. Data from the Kajiado Water Asset Registry reveals high rates of community borehole failure and operational disruptions.

As global fuel prices fluctuate, local water committees frequently run out of operation capital, forcing residents to trek long distances to find alternative water sources. However, the Kajiado County Renewable Energy Atlas outlines a favorable counter-narrative: high local solar exposure aligns perfectly with peak seasonal water demands, offering a sustainable transition with a typical financial break-even point of five years.

Demographically, water demand varies sharply across the sub-county’s five wards. Dalalekutuk, Matapato South, and Matapato North represent high-density consumer clusters that place sustained pressure on local water delivery systems, highlighting a critical need for high-volume pumping and expanded storage. In contrast, the rural and sparsely populated Purko Ward faces an immediate crisis whenever an infrastructure breakdown occurs, as isolated families live far from alternative options.

This disparity requires a dual-track strategy: high-volume output for dense wards, and high-reliability, wide distribution networks for rural zones. Currently, the 27 baseline borehole sites rely on unreliable infrastructure powered by high-emission diesel generators and outdated solar arrays. This creates two distinct operational challenges. First, 'the diesel trap' drains community funds through the continuous purchase of fuel and oil, tying local water costs directly to volatile fuel markets.

Second, the technical limits of the existing solar equipment cause massive underperformance during periods of cloud cover or early morning and evening hours, illustrating an urgent need for modernized, climate-resilient solar infrastructure.

Table C: Baseline Indicator Matrix of Borehole Sites (Diesel vs Solar) in Kajiado Central

Ward Borehole Sites – Borehole Sites – Total Strategic Diesel Solar Boreholes Dalalekutuk 3 2 5 Ildamat 2 3 5 Matapato North 4 2 6 Matapato South 1 5 6 Purko 2 3 5 Total 12 15 27

Contextual Notes: (i) Solarization Focus – to mitigate rising electricity costs and the unreliability of fuel during droughts, the county government through the FLLoCA programme has rapidly transitioned many diesel pumps to solar. Matapato Page 6 of 10 Okwiri et al. / Harnessing Solar Water Pumping Technologies for Sustainable Water Supply in Kenya

South, being one of the drier pastoral areas furthest from power grids, features the highest number of solarized boreholes. (ii) Fuel Subsidies -despite solarization efforts, several older boreholes in Dalalekutuk, Ildamat, and Purko still rely on strategic fuel subsidies provided by the county government to maintain continuous water pumping during dry spells.

4.Results

4.1. Empirical Findings

Empirical evaluations spanning 2015–2025 in Kajiado Central Sub-County confirm that solarizing local water infrastructure drastically drives down operational costs, thereby supporting community-based water management, sustainable sanitation, and localized decarbonization. However, this technical success is undermined by two critical systemic threats.

Hydrologically, the zero-marginal cost of solar pumping fuels an uncoordinated, spatially dense clustering of boreholes that threatens the Kajiado Rift aquifer with irreversible degradation. Publicly, widespread geogenic fluoride levels exceeding the WHO 1.5 mg/L threshold present a severe health crisis, causing widespread dental and skeletal fluorosis across local communities.

Resolving these interlocking energy, resource, and health challenges requires shifting from random borehole development to structured, data-driven interventions. To successfully leverage international climate grants and foster county-wide climate resilience, Kajiado must execute a coordinated SWPT upscaling strategy across rural, peri-urban, and urban zones.

This expansion must prioritize strict adherence to the Kajiado County Water Master Plan, utilizing grant-funded hydrogeological mapping to enforce localized abstraction caps while mandating community-managed fluoride treatment infrastructure to safeguard public health alongside aquifer longevity.

5. Discussion

Table D: Energy-Water-Health Nexus – Theory Comparison

Common-Pool Resource (CPR) Theory Socio-Technical Systems (STS) Theory (i) Governs the aquifer (i) Integrates Solar Tech (ii) Resource subtraction (ii) Tech artifacts – solar (iii) Exclusion dilemmas (iii) Social actors (Kiosks) (iv) Institutional by-laws (iv) Infrastructure scale

5.1. Justification of the two theories.

To comprehensively analyze the intersecting challenges of clean energy transitions, groundwater depletion, and public health, this study utilizes a dual theoretical framework combining Common-Pool Resource (CPR) Theory and Socio- Technical Systems (STS) Theory.

CPR theory is applied to address the hydrogeological ramifications of uncoordinated, clustered borehole drilling. Groundwater in the Kajiado Rift System represents a classic common-pool resource where excludability is difficult and subtractability is exceptionally high.

The framework captures how the zero-marginal cost of solar pumping accelerates a 'Tragedy of the Commons', illustrating the urgent need for institutional interventions like active Water User Associations and the execution of the Kajiado County Water Master Plan. Concurrently, STS theory is employed to examine the scaling of solar pumping technology across diverse demographic zones. By treating solarized boreholes as interconnected networks where technical components (such as PV arrays and filtration systems) are completely interdependent with human systems, STS shifts the focus from mere technology deployment to long-term sustainability.

This approach ensures that technical upscaling is systematically bound to community capacity building, local maintenance training, and health-focused water monitoring, thereby fostering genuine, climate-resilient development.

5.2. Economic Implications of Solarization

The economic profile of solarized water pumping is defined by a sharp dichotomy between high upfront capital costs and long-term operational savings. Data demonstrates that hybrid solar photovoltaic pumping technologies reduce operational expenditures (OpEx) by 60% to 75% relative to diesel generation. However, the initial capital expenditure (CapEx) is structurally unviable for isolated community self-financing, emphasizing a heavy reliance on external grants and public climate finances like FLLoCA.

Beyond the macro-economic metrics, the 10-year data reveals that long-term financial sustainability is intrinsically linked to local governance structures. From a Socio-Technical Systems (STS) perspective, the presence of trained water management committees serves as a primary driver of financial health.

Communities that instituted formalized tariff schemes and provided basic technical maintenance training successfully accumulated financial reserves. In sharp contrast, regions lacking these localized social structures experienced protracted equipment downtime, as minor technical malfunctions went unrepaired due to a lack of immediate community capital.

T***able E: Financial Comparison of Solar Water Pumping Systems vs Diesel Generator Systems***

Financial Indicator Solar Water Pumping Systems Diesel Generator Systems (i) Initial financial High (KES 195,000–455,000 Low (KES 52,000–104,000 initial expense (CapEx) including panels, pump & structure) machine purchase cost) (ii) Fuel & Energy Zero (utilizes free, abundant High & Variable (continuous costs (OpEx) sunlight energy) diesel purchases tied to market rates) (iii) Maintenance Minimal (occasional panel cleaning Frequent (requires regular oil Expenses – solid-state electronics require rare changes, filter swaps coupled with intervention) mechanical repairs) (iv) Estimated 1.5 to 3 years (system self-pays Continuous expense (never payback period through eliminated fuel expenses) reaches a financial break-even point) (v) Asset operational Long (panels last 20–25 years, Short (typically 3–5 years due to lifespan pump runs 5–10 years) heavy mechanical wear and tear)

5.3 Technical Component Breakdown.

The structural architecture of a standardized Solar Water Pumping Technology (SWPT) system relies on five interlinked engineering subsystems. Power generation begins at the photovoltaic (PV) solar array, which converts raw solar irradiance into Direct Current (DC) electricity. This energy is regulated by the solar pump controller and inverter, which applies Maximum Power Point Tracking (MPPT) to dynamically align the system's electrical output with the variable operational demands of the motor.

The mechanical extraction is executed by a submersible pump assembly, uniquely suited for Kajiado's deep aquifer depths, which forces groundwater to the surface. Fluid transport is managed via high-durability high-density polythene (HDPE) or PVC piping, designed to handle pressure shifts without structural failure. Finally, the system utilizes a gravity-fed storage reservoir as its energy storage medium; this configuration replaces costly chemical battery banks by storing energy as physical water during peak sunlight hours, ensuring a reliable, gravity-driven supply during periods of zero irradiance.

Table F: Baseline Indicator Matrix

Evaluation Indicator County Baseline Value Source Agency Data Year Safe water access rate 35%–45% of the county Kajiado County 2022 population Environmental Performance Index (EPI) Dry season water trek 4.5 km to 10.3 km Journal of CMSD / 2022 distance Ministry of Water Per capita water 162 m³/annum (vs. 600 Wetlands International / 2020 availability national average) Government of Kenya Off-grid solar market 32%–35% – low Baseline Report – 2019 penetration Household Energy & Indoor Air Quality Baseline Study, Ministry of Energy Solar resource 5.5–6.0 kWh/m²/day Kajiado County 2020 availability Renewable Energy Atlas / Arid Lands Information Network (ALIN) Average cost of KES 10 per 20 L Kenyatta University 2023 informal water jerrycan (KES 500/m³) Institutional Repository Average aquifer depth 100–250 meters University of Nairobi 2021 (boreholes) Groundwater Potential Studies

6.0. Conclusion.

Our findings show that solar water pumps in Kajiado Central Sub-County significantly lower operational costs and retail water prices by shielding users from volatile fossil fuel markets. However, the zero-cost nature of solar power creates an incentive to pump water continuously without restriction.

This overuse, compounded by densely clustered boreholes and weak regulatory enforcement, threatens long-term water sustainability. Furthermore, our results reveal a critical public health gap in current energy transitions- groundwater sites frequently exhibit geogenic fluoride levels that far exceed WHO safety limits. Consequently, 'clean technology' alone cannot guarantee true sustainability.

To prevent a renewable energy solution from precipitating an environmental and public health crisis, technical innovation must be paired with strict hydrogeological limits, community-led abstraction caps, and mandatory water treatment infrastructure. Moving forward, data-driven mapping and coordinated borehole management are vital to transition from random drilling to a climate-resilient water network that protects both aquifer longevity and public health.

7.0. Recommendations

To secure long-term climate resilience, the County Government of Kajiado must prioritize the coordinated upscaling of Solar Water Pumping Technologies (SWPT) across rural, peri-urban, and urban demographic zones. A primary focus should be retrofitting older, high-maintenance diesel and electric boreholes to provide rapid, affordable water access to remote communities, thereby advancing current green initiatives like the FLLoCA program. However, technical upscaling must be balanced with data-driven and community-led resource protection.

By leveraging international climate grants, the county should fund detailed hydrogeological mapping to establish extraction limits and prevent aquifer depletion. Crucially, these investments must be anchored by a bottom-up approach that establishes trained community water committees. Integrating robust local governance with scientific mapping will ensure that decarbonizing Kajiado's water network yields lasting benefits for public sanitation, small-scale agriculture, wastewater recycling, and environmental preservation. Funding:

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