KAMPALA INTERNATIONAL UNIVERSITY

KIU
Journal of Science, Engineering
and Technology

KJSET

Research Article

Mechanical energy storage for groundwater pumping in rural areas of Uganda: A review of flywheel technologies and the potential of spring-assisted systems

Kabagambe Edward[1,2], Dr. Samuel George Onep[1], Associate Prof. Sathish Kumar[1]

Department of Mechanical Engineering, Kampala International University[1]
Department of mechanical Engineering, Kabale University[2]
edward.kabagambe@studwc.kiu.ac.ug [1], ekabagameb@kab.ac.ug [2], sathishpauto@kiu.ac.ug [1], onep.samuel@kiu.ac.ug [1]
Corresponding Author: edward.kabagambe@studwc.kiu.ac.ug

Paper history:
Received 12 April 2026
Accepted in revised form 19 May 2026

Keywords

Flywheel Energy Storage; Spring-Assist Mechanism; Rural Electrification; Mechanical Energy Storage; Off-Grid Energy; Literature Review

Abstract

Energy and water access are interdependent challenges for rural development in Sub-Saharan Africa. In Uganda, over 90% of the rural population lacks electricity, forcing groundwater pumping to rely on manual boreholes and unsustainable mechanised solutions. Diesel pumps have high fuel costs and emissions, while solar-battery systems suffer from short battery life, expensive replacements, and maintenance difficulties. This paper reviews mechanical energy storage technologies for groundwater pumping in rural Uganda, focusing on flywheel energy storage systems (FESS), spring-assisted mechanisms, and human-powered conversion. The review analyses low-speed steel flywheels suitable for local fabrication, spring-assist principles (up to 18.2% energy savings), and human power feasibility (25–100 W). Uganda-specific data (groundwater depth 5–15 m, rural grid access 5.2%) and economic analysis set design requirements: 5–10 L/min at 10 m head, battery-free operation, local maintenance, and affordability. The synthesis reveals a critical gap: no study integrates flywheel kinetic storage, spring-assist energy sustainment, and manual human input into a single rural water supply system. This gap is addressed by a conceptual framework grounded in local availability, affordability, and maintainability. A systematic development plan (design optimisation, prototype development, field deployment, and scaling) is outlined to guide future research and deployment.

Acronyms

Acronym	Full Form
ASTM	American Society for Testing and Materials
AISI	American Iron and Steel Institute
BGS	British Geological Survey
CAD	Computer-Aided Design
FEA	Finite Element Analysis
FESS	Flywheel Energy Storage System
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
ISO	International Organization for Standardization
MEMD	Ministry of Energy and Mineral Development (Uganda)
MWE	Ministry of Water and Environment (Uganda)
RPM	Revolutions Per Minute
SDG	Sustainable Development Goals
UBOS	Uganda Bureau of Statistics
UN	United Nations
WHO	World Health Organisation

1.0 Introduction

1.1 Background

The interdependence of energy and water access represents one of the most acute challenges of sustainable development of the twenty-first century [1]. Globally, approximately 770 million people lack access to better drinking water supplies, and nearly 800 million people of the world live without access to electricity, a burden that is evenly spread as rural residents in the developing world suffer the most [2, 3]. This is a particularly serious problem in Sub-Saharan Africa where the rate of energy poverty is above 75 per cent in most countries and groundwater still remains the primary source of rural water supply [4, 5].

This is a dual crisis evident in Uganda. In spite of the rich water deposits, more than 90% of the rural population do not have access to electricity, which severely limits their access to groundwater pumping using mechanical means [6]. Most communities in rural areas use manual boreholes and covered springs, a labor-intensive method that restricts supply of water especially during dry seasons [7]. This manual reliance hamper with the amount of water and restricts agricultural production [8].

Mechanisation of rural water supply has taken two directions namely, diesel pumps and solar-battery systems. Diesel pumps incur prohibitive operation costs as they require fuel costs, which are further worsened by the transportation problems and increase the amounts of greenhouse gases [9]. Solar pumping systems, being cleaner, need regular supplies of irradiance and battery storage will be required. Lead-acid batteries have a low cycle life (500-1000 cycles), high replacement costs, as well as environmental disposal issues [10, 11]. The result of such restrictions is high failure rates in Sub-Saharan Africa [12].

Flywheel Energy Storage Systems (FESS) provide a kinetic energy alternative; it stores energy as rotating mass. Advantages over batteries include virtually unlimited cycle life, rapid charge-discharge capability, zero operational emissions and potential for local fabrication using available materials. In low-speed applications, solid steel flywheels strike a balance between energy density, manufacturability, and cost [15, 16]. The latest literature has investigated the concept of combining springs with flywheels in order to maintain turnover and lengthen the release period, especially to intermittent human-powered input [17].

In spite of these advances, the literature on the storage of mechanical energy to provide rural water is in pieces. Studies on flywheel technology focus on grid-scale applications in industrialised settings [13, 18]. Studies of spring-assisted pumping are able to save up to 18.2% of energy, but in the industrial electrically-driven environment [17]. Investigations into human energy conversion establish technical feasibility but stop short of coupling with mechanical storage for direct water pumping [19]. No study synthesizes these threads within the socio-technical context of rural Uganda, where design requirements are shaped by local material availability, fabrication capacity, and maintenance capability [20].

1.2 Need for This Review

This review leads to bridging the above gap by (1) synthesizing the existing flywheel energy storage technologies with low-speed steel systems that can be built in local areas; (2) investigating the existing research on the topic of spring-assisted and the human-powered mechanical systems; (3) exploring the gap by analyzing the Uganda-specific data on groundwater resources, energy availability, and economic factors; and (4) bringing these

1.3 Scope and Structure

This review focuses on mechanical energy storage applicable to small-scale groundwater pumping in off-grid rural settings. It omits high-speed composite flywheel systems which need vacuum enclosures that are not practicable to construct. Methodology is outlined in Section 2. Section 3 describes the theoretical foundations. Empirical FESS studies have been reviewed in Section 4. Section 5 looks at spring-assisted and mechanical pumping. In Section 6, analysis is based on Uganda-specific data. Section 7 summarises results in order to find gaps in research. Section 8 presents a conceptual framework. Section 9 provides direction of future research and Section 10 concludes.

2.0 Methodology

This review used a narrative synthesis method to analyse literature about flywheel energy storage, technologies which use springs, human-powered devices and rural water pumping in Uganda. The literature was found by using the specific searches in Scopus, Google Scholar and Web of science using combinations of terms such as flywheel energy storage, spring-assisted pumping, human-powered generator, and rural water supply Uganda. The preference was on peer-reviewed journals and conference papers, as well as, technical reports of reputable organizations (World Bank, IRENA, IEA), that were published in 2000-2025. The key papers reference lists were also screened manually so as to pick up other relevant articles. The synthesis was done to focus on abstraction of theoretical constructs, empirical results, design considerations, and contextual information of ground water pumping as applicable in off-grid rural contexts.

3.0 Theoretical Foundations of Flywheel Energy Storage

3.1 Principles of Rotational Kinetic Energy Storage

The power in a rotating flywheel is regulated by.

$$E = \frac{I\omega^2}{2} \dots \dots (1)$$

where *E* is kinetic energy (J), *I* is moment of inertia (kg·m²), and *ω* is angular velocity (rad/s). Energy scales linearly with inertia but quadratically with speed [15]. The systems that benefit the high energy density (10,000–100,000 RPM) involve high-speed and implicates sophisticated composites, vacuum enclosures, and accuracy bearings, which are costlier and more complex to manufacture [13]. The low speed systems (usually less than 10,000 RPM) attain any useful storage by inertia, tolerating a reduced energy density at the cost of simpler construction, reduced cost and increased local fabrication capability [16]. This trade-off greatly prefers the low-speed in rural applications.

3.2 Moment of Inertia and Flywheel Geometry

Given solid disk geometry, which is best suited towards local materials manufacture, moment of inertia is determined using equation 2.

$$I = \frac{1}{2} mr^2 \dots \dots (2)$$

in which m is mass (kg) and r is outer radius (m) [10]. The shape factor K defines how well a particular geometry is able to store energy using the material. Figure 1 shows shape factors of different flywheel geometries.

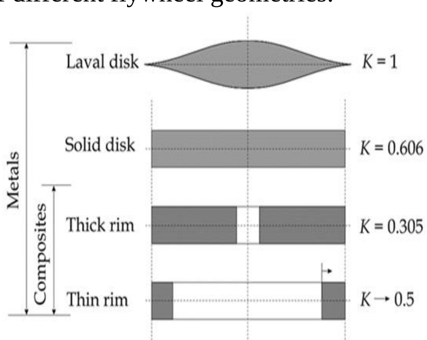

Figure 1: Shape factors for different flywheel geometries. The solid disk (K = 0.606) offers moderate material efficiency but superior manufacturability compared to thin-rim (K ≈ 0.5) or constant-stress (K = 1.0) designs [11].

The solid disk (K ≈ 0.606) gives moderate efficiency with better manufacturability over complex fabrications needed to meet advanced geometries [11]. The solid disk has strong virtues in the case of rural Uganda: It can be produced on regular lathes, it can be made of common material (ASTM A36 mild steel), it can support heavy structural loads, it can be easily contained, and it can be easily repaired locally [23,27].

3.3 Energy Loss Mechanisms

There are three major losses in flywheel systems.

Bearing friction in sealed deep-groove ball bearings, the most practical choice for rural applications, is relatively low; well-designed systems achieve >98% efficiency per bearing pair [23, 25]. Windage losses from aerodynamic drag scale with ω^3 and r^5 [15,16]; at expected operating speeds (<300 RPM), they are minimal and do not justify vacuum enclosures [16,33]. Under driving an alternator, the losses associated with electromechanical conversion are directly proportional and impeding; automotive alternators usually have 50%-60% percent efficiency at design speed, decreasing with lower speed [36]. Accordingly, stored mechanical energy should be much greater than delivered hydraulic energy.

3.4 Theoretical Basis for Spring Assistance

In the case of torsional springs, restorative torque is.

$$T_s = k\theta \dots \dots (3)$$

where k is torsional stiffness (Nm/rad) and θ is angular deflection (rad) [15]. Spring constant depends on material properties and geometry [16]. The elastic potential energy stored is

$$E_s = \frac{1}{2} k\theta^2 \dots \dots (4)$$

The workings of the spring-assist mechanism in a manually powered system are as follows: During charging, the operator turns the flywheel and winds up one set of the springs while keeping another set in tension; both accumulate energy alternately, the former in the form of the kinetic energy of the flywheel, and the latter in the form of elastic energy of the springs. When input ceases, springs apply restorative torque to the shaft, reducing deceleration and extending discharge time [17]. The equation governing the discharge is.

$$I\frac{d\omega}{dt} = -T_{load} - T_{loss} + T_s(\theta) \dots \dots (5)$$

Spring stiffness must provide 30%-50% of the estimated forces of load [18]. The range of deflection is limited by the spatial packing and material elastic limits [26]. Multiple springs may be arranged in parallel (increasing stiffness) or series (increasing deflection) [16].

3.5 Quantitative Performance Estimates

To illustrate the practical energy storage capacity of a flywheel system, consider a typical medium-scale design with a 50 kg steel flywheel (moment of inertia I=6.25 kg·m^2 as per Equation (2)). At a rotational speed of 200 RPM (ω=20.9 rad/s), Equation (1) gives a stored kinetic energy of approximately 1.38 kJ. For a small submersible pump requiring 20 W of mechanical power (typical for 5–10 L/min at 10 m head [32]), this energy would sustain pumping for about 69 seconds, ignoring transmission losses. With the addition of a spring-assist mechanism storing 40 J of elastic energy [37], the total stored energy becomes 1.42 kJ, extending runtime to 71 seconds, a modest but measurable improvement.

At a higher speed of 500 RPM (ω=52.4 rad/s), the kinetic energy rises to 8.6 kJ, sufficient to power the same pump for over 7 minutes. These estimates demonstrate that even moderate flywheel speeds can store useful energy, and that spring assistance provides an incremental benefit, particularly when the flywheel is already near its peak speed.

4.0 Empirical Review of Flywheel Energy Storage Systems

4.1 FESS in Microgrid and Rural Applications

Okou, Sebitosi, and Khan (2009) modeled the flywheel addition to a Ugandan hybrid power system, with a potential increase in reliability of 35% with a smoothed renewable output [8]. The study was purely simulation-based and modeled a high-speed composite design impractical for local fabrication, but established precedent for quantifying flywheel value in Uganda.

Reviewing flywheel-based systems shedding light on a small scale, solid-steel flywheels at moderate speeds (3,000-6,000 RPM), showed efficiencies over 85% (Pena-Alzola et al., 2011) [11]. Their shape factor analysis showed that solid disk geometry provides the optimal trade-off between performance and manufacturability in resource-constrained scenarios.

Vidyanandan and Senroy (2015) demonstrated flywheel response to load changes in under two seconds in a wind-diesel microgrid, substantially faster than batteries or diesel governors [17]. This rapid response capability is directly relevant to managing intermittent human input.

Olabi et al. (2021) provided a comprehensive comparison of low-speed steel versus high-speed composite FESS [7]. For applications where cost, local maintainability, and simplicity outweigh maximum energy density, low-speed steel systems are the preferred choice.

Table 1: Low-Speed vs. High-Speed FESS: Comparative Analysis

Parameter	Low-Speed FESS	High-Speed FESS	Implication for Rural Uganda
Rotor Material	Steel	Advanced composites	Steel locally available
Speed Range	<10,000 RPM	>10,000 RPM	Lower speeds reduce bearing stress
Enclosure	Open air	Vacuum chamber required	Vacuum technology unavailable
Bearings	Standard ball	Magnetic/precision ceramic	Standard bearings available
Energy Density	Low (5–30 Wh/kg)	High (50–150 Wh/kg)	Acceptable trade-off
Cost per kWh	Low ($200–$500)	High ($1,000–$5,000)	Affordability critical
Local Fabrication	Feasible	Not feasible	Determinant factor
Maintenance	Simple	Complex	Favors simplicity

4.2 Recent Advances and Applications

More recent studies continue to validate and expand the role of flywheel energy storage for off-grid applications. Saberi et al. (2024) demonstrated that a combination of flywheels and fuel generators can effectively replace traditional battery banks in tropical climates, achieving an energy cost of 0.156/kWh, reducing excess renewable electricity from over 160.156/kWh, reducing excess renewable electricity from over 16/kWh [41]. Mulumba & Farzaneh (2023) proposed a hybrid PV-wind-battery-flywheel system for a remote county in Kenya, achieving a levelised cost of electricity of 0.519 USD/kWh and a reliability indicator of 0.997, while realising an annual 858 kWh storage capacity gain in the battery when coupled with the flywheel [42]. A recent systematic review by Matos et al. (2025) confirmed that flywheels are characterised by high power density, rapid response times, exceptional cycle life and high efficiency, making them particularly suitable for applications requiring immediate power delivery and frequent cycling, such as smoothing intermittent renewable generation [43]. Ahmadi et al. (2025) compared battery–flywheel with battery–hydrogen storage in off-grid hybrid renewable systems across four climates, concluding that the flywheel configuration remained a viable option despite the higher cost-effectiveness of the hydrogen system [44]. An experimental implementation by Faithpraise et al. (2025) showed that a flywheel-assisted photovoltaic system reduced battery net discharge by 81.3% by contributing kinetic energy and recovering additional energy, effectively extending battery lifespan in off-grid settings [45]. These recent contributions confirm the growing interest and technical viability of flywheel-based storage for decentralised, off-grid applications, directly supporting the relevance of the spring-assisted concept proposed in this review.

4.3 Key Findings from FESS Literature

1. Technical viability confirmed.

Several studies confirm the technical feasibility of FESS use in applications with a high number of charge-discharge cycles, and efficiencies greater than 85% are established [7, 11, 13].

2. Design trade-offs favor low-speed steel in rural situations.

The low-speed steel systems provide adequate performance and can be found in local workshops [7, 20].

3. Critical gap-absence of spring-assisted FESS research.

No known research has investigated spring-assisted flywheel systems for any application, much less in groundwater pumping. Integration of torsional springs with flywheel rotors, optimization for human-powered input, and experimental validation remain unexplored.

4. Other gap-No research done about direct mechanical coupling with water pumps.

There is no direct mechanical linkage (flywheel to water pump) research that has been done in a configuration applicable to rural off-grid solutions. The literature presupposes the electrical interfaces [17].

5.0 Review of Mechanical and Spring-Assisted Pumping Systems

5.1 Spring-Assisted Energy Systems

The experiment of Meng et al. (2017) on spring-assist in pumping showed that it was 18.2% more energy-efficient than traditional direct-drive systems [18]. The strongest evidence of their study is revealed in Figure 2. The mechanism lowered peak motor current through storage during periods of low demand, followed by the release upon peak demand.

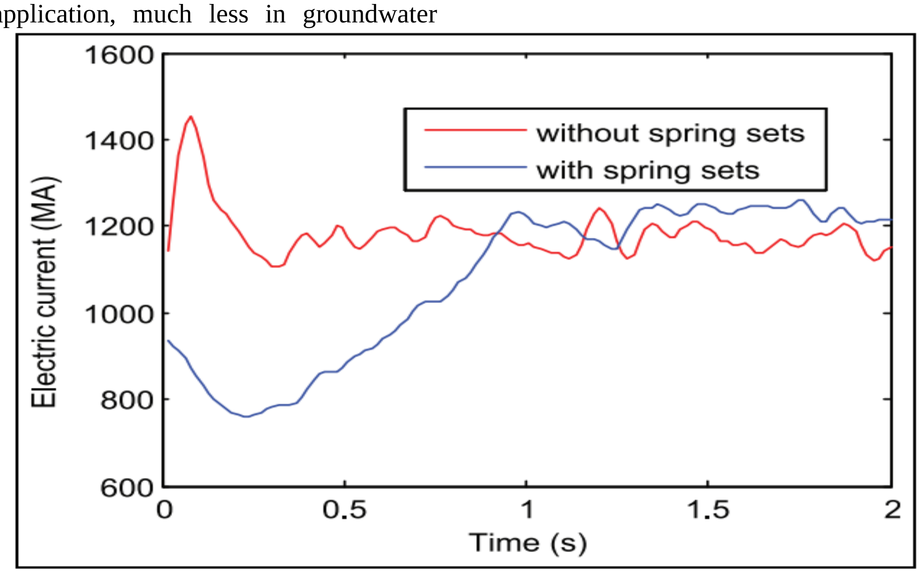

Figure 2: Comparison of motor starting current with and without spring energy storage. The spring-assisted system shows dramatically lower initial current draw, reducing motor stress and energy consumption. Source: Meng et al. [18].

Nevertheless, it was a system with an electric drive powered, intended to serve industrial uses, not to be made to be human powered or adapted to rural environments.

5.2 Human-Powered Energy Systems

Ikechukwu and Anthony (2016) developed and constructed a power generator that operates on pedals, producing 37.5 Watts [19]. Their work reported design issues of critical concern: ergonomics (crank geometry, seat positioning), structural integrity and transmission optimization. Figure 3a shows the overall system architecture. The energy pathway begins with human pedalling, passes through a speed-increasing gear train, and ends at an electrical generator. Figure 3b details the gear train: a driver gear with 44 teeth drives a smaller gear with 18 teeth via a chain, providing the mechanical advantage needed to reach generator operating speed.

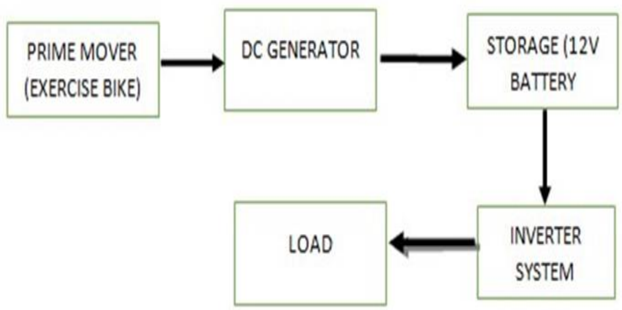

Figure 3a: Block diagram of a pedal-operated power generator, showing the energy pathway from human input to electrical load. Adapted from Ikechukwu and Anthony [19].

Figure 3b: Gear train of the pedal-operated generator. A driver gear (44 teeth) drives a smaller gear (18 teeth) via a chain to increase rotational speed. Adapted from Ikechukwu and Anthony [19].

Such observations guide the design of a spring-assisted FESS manual input mechanism. Extended literature has confirmed the human power feasibility of 25Watts to 100 Watts over short periods of time with comfort and fatigue of the user being major factors of concern [27-28].

5.3 Field Studies on Pumping System Sustainability

Armstrong, Mahan and Zapor (2017) compared life-cycle costs of eight countries, which reported a high failure rate of battery-intensive problems in remote locations [20]. Battery life routinely less than 2 years, replacement often not locally available and replacement costs were cumulative compared to the initial capital. They demanded less complex and more durable technology that had less dependence on parts that had to be changed on a regular basis. These trends are supported by research studies [9, 11, 29].

5.4 Synthesis of Review of Mechanical and Spring-Assisted Pumping Systems

Three important findings emerge from this review: (1) the spring-assist principle is confirmed (18.2% energy savings) [18], but it will need to be adapted to human-powered, low-speed, locally fabricated systems; (2) human power is viable (25–100 W) [19], although current studies emphasise electrical conversion instead of direct mechanical storage; (3) battery-free systems are urgently needed due to documented field failures [20].

To further contextualise these findings, Table 3 compares diesel pumps, solar-battery systems, standalone flywheels, and the proposed spring-assisted flywheel across key performance parameters. Diesel and solar-battery systems suffer from low energy efficiency, high maintenance, and poor local repairability [5,11,20]. Standalone flywheels offer high mechanical efficiency and low maintenance but have limited discharge duration [11,13]. The spring-assisted flywheel retains these advantages while extending runtime via stored elastic energy [18], making it a sustainable, locally maintainable alternative for off-grid groundwater pumping.

Despite these advantages, no study has integrated all the required elements, spring assistance, human power, local fabrication, and direct water pumping duty, into a unified system for groundwater pumping. This is precisely the gap that the present review addresses and that future research should fill.

Table 2: Comparative performance characteristics of pumping technologies for off-grid rural applications

Parameter	Diesel Pump	Solar-Battery	Standalone Flywheel	Spring-Assisted Flywheel
Energy efficiency	Low (engine losses)	Low (conversion + battery losses)	High (mechanical)	High (mechanical + spring assist)
Storage capacity	Fuel tank (large)	Battery (kWh-scale)	Kinetic (kJ-scale)	Kinetic + elastic (kJ-scale)
Discharge duration	As long as fuel lasts	2–4 hours typical	Minutes	Extended by springs
Maintenance	Frequent (engine)	Moderate (battery, panels)	Low (bearings)	Low (bearings, springs)

Local repairability	Moderate	Low (electronics, battery)	High	High

6.0 The Uganda Context: Grounding Design in Local Realities

6.1 Groundwater Resources and Pumping Requirements

Uganda is well endowed with aquifer systems [30]. The mean difference in stature of water in rural boreholes is usually 5-15 meters [21, 31]. Based on this, a target total dynamic head of 10 meters is reasonable, accounting for static lift plus friction losses [32]. In the case of low-scale community water systems (100-300 individuals) 5-10 L/min is a sufficient flow rate to fulfill domestic demand as well as permitting a few productive applications [5, 39].

6.2 Energy Access Landscape

Access to grids is limited to 5.2% of rural households, as illustrated by the trend in Figure 5 [3].

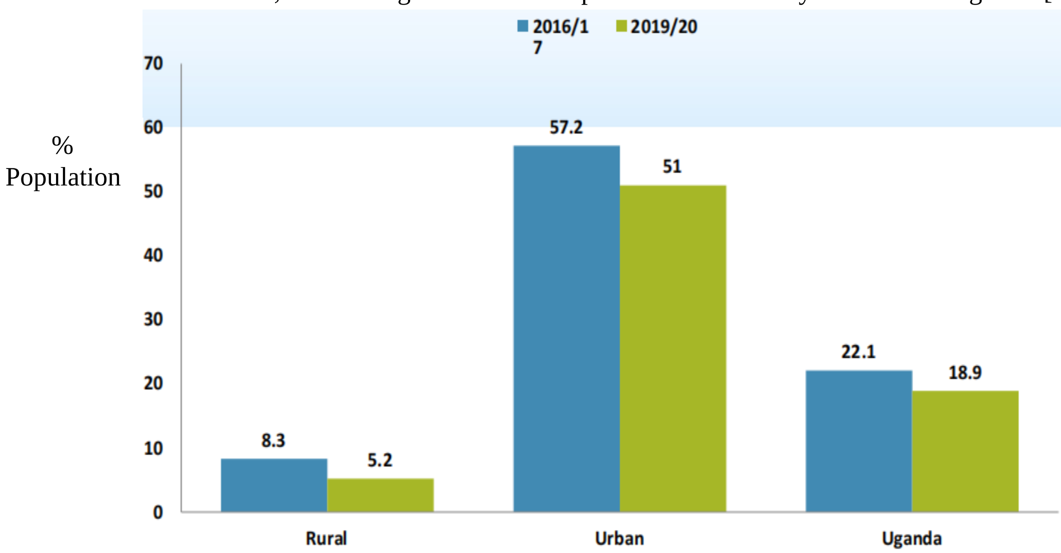

Figure 4:Rural electrification trends in Uganda (2016/17 – 2019/20). Only 5.2% of rural households have grid access, underscoring the need for off-grid pumping solutions. Adapted from UBOS [3].

Even connected areas experience frequent outages (>100 hours/year) [6]. Any feasible pumping solution should be all off-grid [33].

6.3 Economic Analysis of Existing Solutions

1. **Diesel systems**

Diesel pumping systems have low capital cost ($500–$1,000) but very high operational costs, with fuel representing 60%–80% of lifetime expenses [5]. Figure 5 illustrates the life-cycle cost structure. Fuel dominates, while maintenance and replacement parts contribute smaller shares. Transportation challenges in remote areas further increase effective fuel prices [9].

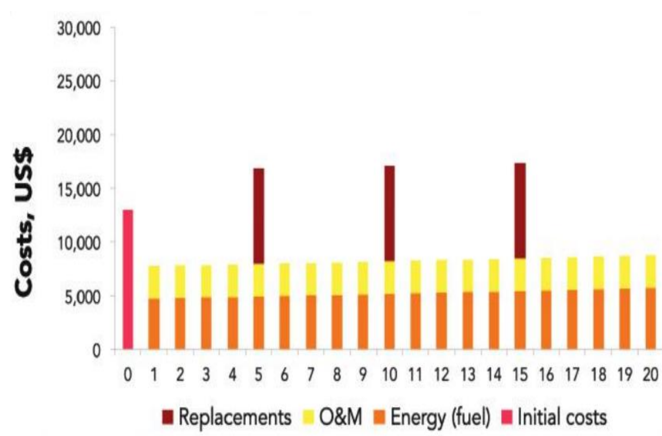

Figure 5: Life-cycle cost analysis of diesel pumping systems. Fuel dominates the cost structure (60–80% of lifetime costs). Adapted from World Bank [5].

Effective fuel prices rise due to transportation challenges [9].

2. **Solar-battery systems**

Solar-battery systems require higher capital investment ($2,000-$5,000) and have no fuel costs, but batteries must be replaced every 2–4 years [6]. Figure 6 shows that battery replacement costs can exceed the original capital over a 10-year lifespan [20]. Although solar panels last 20+ years, the recurring battery expense and logistical challenges of replacement in rural areas undermine long-term sustainability.

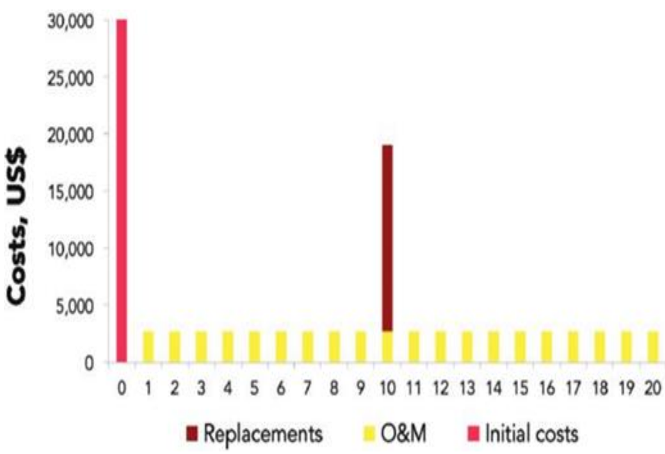

Figure 6: Life-cycle cost analysis of solar pumping systems with battery storage. Battery replacement dominates operational costs. Adapted from World Bank [5].

6.4 Implications for FESS Design

An effective substitute should be

(1) Off-grid and battery-free;

(2) Very cost-effective in set-up and running;

(3) Maintained locally with the available skills and tools;

(4) Hydraulic targets: 5-10 L/min at 10 m head. It should be designed to allow intermittent human operation, and be fabricated with standard workshop tools, and available materials in the immediate area [20, 33].

6.5 Implementation Barriers in Rural Uganda

Beyond technical performance, the successful adoption of any mechanical energy storage system in rural Uganda depends on local implementation capacity.

1. **Local manufacturing** of precision components (e.g., torsion springs, bearings) is limited. Most metalworking shops in rural towns can perform basic welding, cutting, and lathe operations, but custom spring winding and precision balancing may require support from urban centres [33].
2. **Maintenance expertise** is constrained by the scarcity of trained technicians. Basic mechanical skills (bearing replacement, belt tensioning, welding) are available in many villages, but specialised training on spring fatigue monitoring and flywheel balancing would be needed to ensure long-term reliability [20].
3. **Material availability** is mixed. Mild steel sections, standard bearings, V-belts, and automotive alternators are widely available in district towns like Mbarara, Jinja, and Gulu. However, high-quality torsion spring steel wire and pre-wound springs may have to be sourced from Kampala or abroad, increasing lead time and cost [5].
4. **Rural financing mechanisms** present a major hurdle. Most households cannot afford upfront capital costs. Community-based models – such as village savings and loan associations (VSLAs), pay-as-you-pump schemes, or cooperative ownership – could make the technology accessible [5,20]. Policy support (tax exemptions on mechanical components, subsidised training for local artisans) would further lower barriers.

Recognising these challenges is essential for designing a system that is not only technically sound but also practically deployable and sustainable in the Ugandan context.

7.0 Synthesis and Identification of Research Gaps

7.1 Summary of Key Findings

1. FESS technology is at the maturity level but grid-oriented.

Literature provides little to no assistance regarding the direct mechanical drive, human-based input, or situations when local fabrication is in the forefront [7, 13].

2. The spring-assist works but it is not rural-adapted.

It is proven on industrial-sized electrically-driven apparatuses but has yet to be studied in human-powered, slow-speed, locally-crafted designs [18].

3. Mechanical storage of human power is possible and not well exploited.

Conversion to electricity is under study, and the direct mechanical storage and coupling to pumps have not been developed [19].

4. Uganda's context demands an integrated solution.

No existing solution satisfies all requirements: off-grid, battery-free, affordable, maintainable, meeting hydraulic targets [3, 5, 20, 21].

Table 3: Synthesis of Literature and Identified Research Gaps

Author	Key Findings	Research Gap

Olabi et al. [7]	Comprehensive FESS review	No framework for spring-assisted, manually-operated FESS for water pumping
Meng et al. [18]	Spring-assist saves 18.2% energy	Applied to industrial electrical systems, not human-powered rural contexts
Ikechukwu & Anthony [19]	Human power feasible for generation	Ended at electrical output; no direct mechanical storage
Okou et al. [8]	Simulation-based feasibility for Uganda	Modelled high-speed composite design; no adaptation for local fabrication

7.2 The Critical Gap: Absence of Integrated Solutions

There is a demonstrable absence of research that integrates the kinetic energy storage of a flywheel, a spring-assist mechanism, and the practical feasibility of manual human input into a single, balanced system specifically designed for groundwater pumping in off-grid rural environments.

8.0 Conceptual Framework for a Spring-Assisted FESS

8.1 Overview of Proposed System

The proposed system includes five skewed subsystems:

1. **Hand crank of energy input.**

No fuel price, localised operation, compatibility with levels of human resources [19]. Design is guided by human strength literature based on ergonomics [27, 28].

2. **Flywheel kinetic storage.**

Solid steel flywheel (low-speed) chosen on the basis of robustness, manufacturability, and being locally accessible [16, 23].

3. **Spring-assist mechanism.**

The torsion springs store the elastic energy during the charging process and release it during the discharge process to make the rotation sustained [18]. Parameters adjusted to deliver valuable additions, but no excessive charging effort [26, 37].

4. **Electromechanical conversion.**

Power to standard automotive alternator via belt-pulley, selected due to its local availability [25].

5. **Pumping delivery.**

DC submersible pump Low volt DC pump (alternator) to match hydraulic demand (5–10 L/min at 10 m head) [5, 32].

Figure 7 presents a conceptual block diagram of the complete system. The energy flow begins with manual input, which simultaneously charges both the flywheel (kinetic storage) and the springs (elastic storage). During discharge, the springs release their stored energy, supplementing the flywheel torque to drive the alternator and, ultimately, the pump. This parallel storage and combined release are key to extending the pump's operational duration.

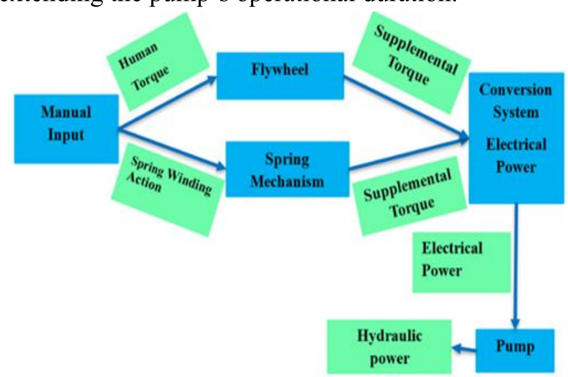

Figure 7: Conceptual block diagram of the spring-assisted flywheel energy storage system. Manual input simultaneously charges the flywheel (kinetic storage) and springs (elastic storage). During discharge, springs supplement flywheel torque to drive the alternator and pump.

Figure 8 shows a three-dimensional conceptual model of the proposed hardware. The flywheel is centrally positioned within a structural steel frame. The double-torsion spring mechanism is mounted on the side of the shaft, while the alternator is placed at the drive end and connected via a belt-pulley system. This layout ensures compact integration, clearances for safety guarding, and accessibility for manual cranking and maintenance.

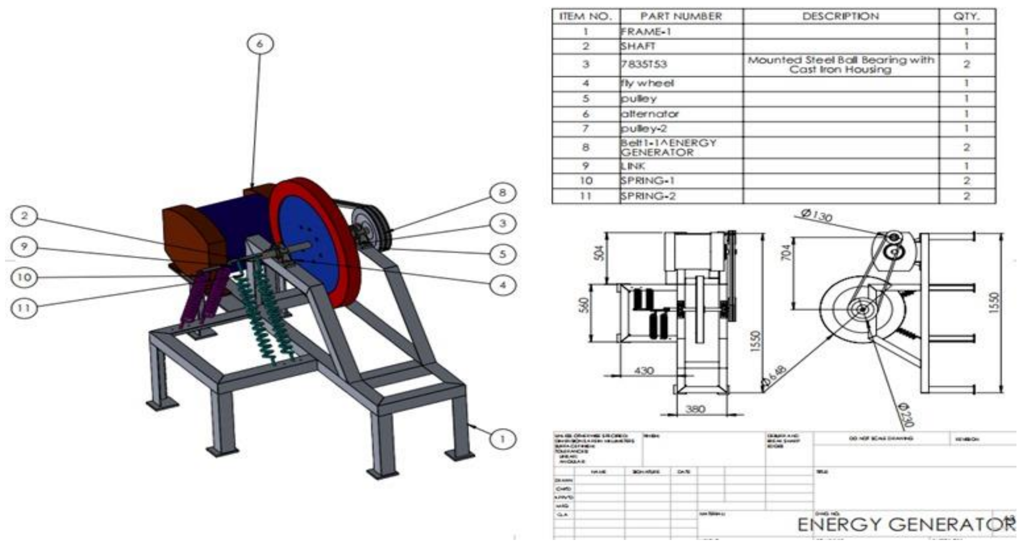

Figure 8: Three-dimensional conceptual model of the spring-assisted FESS, showing the flywheel (centre), double-torsion spring mechanism (side-mounted), structural frame, alternator, and belt-pulley drive. Modelled in SolidWorks 2025.

8.2 Component Rationale

(1) Manual input

Gets rid of fuel and battery requirements; universal; can be easily manufactured and repurposed.

(2) Flywheel

Steel is a common commodity; common lathe processes are adequate; no limits to cycle life; is repairable in area [23, 24, 27].

(3) Spring-assist

Extends discharge time, countermeasures, intermittent input, and gathers power delivery [18].

(4) Safety features

Safety features include a 3 mm thick mild steel guard that meets ISO 14120 standards [12] and a mechanical brake for speed reduction [34].

8.3 Governing Design Approach: Contextual Feasibility

Design choices put priority on: local availability (materials found in the Ugandan markets); affordability (reduced capital and operation expenses); ease of maintenance (modular construction, standard fasteners, ease of adjustment); trade-off between technical performance and socio-technical viability (local fabricability, simplicity, and zero fuel cost).

9.0 Future Research Directions

9.1 Design Optimization

Material selection studies should document actual local availability, characterize properties of locally sourced materials, and identify alternatives [23, 24]. Geometry optimization should explore modified profiles to increase inertia within size constraints [22]. Spring parameter optimization requires parametric studies varying stiffness and deflection to maximize discharge extension while keeping charging effort acceptable, integrating human factors [26, 37].

9.2 Prototype Development and Testing

The suggested systematic development procedure to convert the conceptual map into a working prototype is described in Figure 9. Fabrication research should document step-by-step procedures, identify critical dimensional tolerances, and test the fabrication process in local workshops using standard equipment [23]. Experimental validation should then include three core assessments: no-load decay tests to quantify bearing and windage losses; discharge efficiency measurements comparing electrical output to mechanical input; and spring contribution quantification through comparative tests with and without the spring mechanism engaged [18]. These steps will provide the empirical evidence needed to validate the system's energy retention, efficiency, and the added benefit of the spring-assist feature.

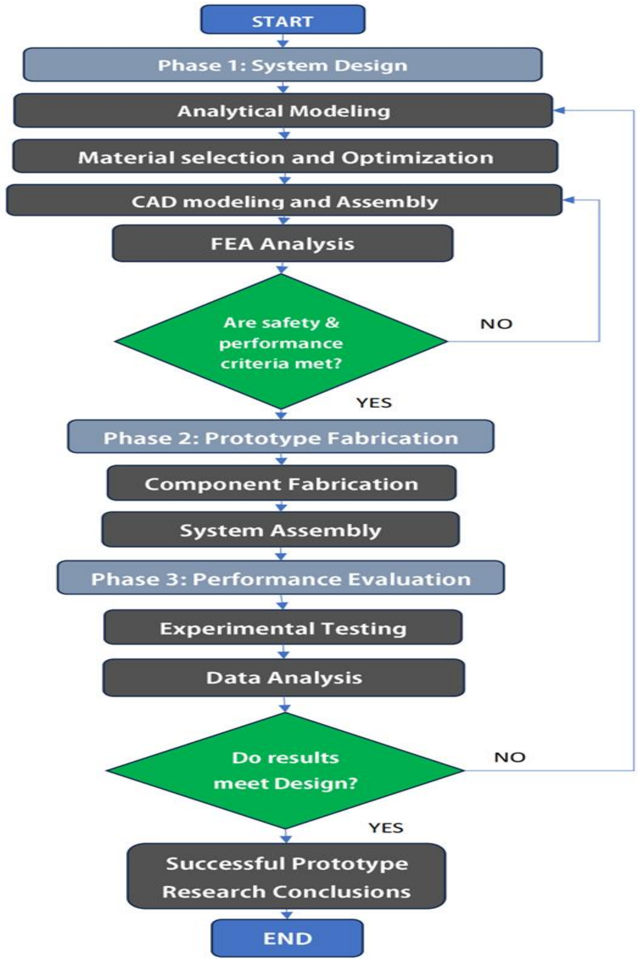

Figure 9: Proposed systematic development process for translating the conceptual framework into a functional prototype. The flowchart shows iterative phases: design, fabrication, testing, and validation.

9.3 Field Deployment Studies

Long-term monitoring in 3–5 Ugandan communities should capture operational reliability, performance degradation, environmental effects, and user behavior. User acceptance studies should assess satisfaction, ergonomics, gender/age considerations, and social dynamics. Maintenance assessment should document events, local repair capacity, failure modes, and costs [20].

9.4 Scaling and Replication

Comparative context studies should assess applicability to neighboring countries [5]. Other applications (grain milling, battery charging) have potential to be considered. Bigger impact requires policy analysis, economic modeling, business model exploration, development of standards, and capacity building [33].

10.0 Conclusion

This review has examined literature on flywheel energy storage, spring-assisted systems, human-powered conversion, and the Uganda context for groundwater pumping. The synthesis reveals a consistent pattern: individual components are validated, but no research integrates them into a unified system tailored to rural off-grid water supply. This gap is significant given documented failures of battery-dependent systems in Sub-Saharan Africa and Uganda's constraints of limited grid access, modest groundwater depths, and need for locally maintainable technology.

The conceptual framework presented addresses this gap by proposing an integrated spring-assisted flywheel energy storage system grounded in contextual feasibility. By prioritizing local availability, affordability, ease of maintenance, and socio-technical viability alongside technical performance, the framework offers a blueprint for developing a battery-free alternative to diesel generators and solar-battery systems. Future research must now translate this framework into optimized designs, functional prototypes, and field-tested solutions. The pathway from concept to impact requires sustained collaboration between researchers, practitioners, and rural communities, but the validated principles and identified opportunity provide a compelling foundation.

Acknowledgements

The authors gladly appreciate the Department of mechanical engineering Kampala International University to have given the academic environment that has facilitated this research. The authors appreciate the Uganda Bureau of Statistics, the Ministry of Water and Environment, and the Ministry of Energy and Mineral Development who present publicly available the data on which this review was based to the context of Uganda. Special thanks are due to the researchers whose work forms the foundation of this review. Finally, the authors acknowledge the rural communities of Uganda whose daily struggle for reliable water access provides the motivation for this work.

References

UN-Water, “The United Nations World Water Development Report 2021: Valuing Water,” United Nations, 2021.

WHO/UNICEF, “Progress on household drinking water, sanitation and hygiene 2000–2020,” World Health Organization and UNICEF, Geneva, 2021.

[3] UBOS, “Uganda National Household Survey 2019/2020,” Uganda Bureau of Statistics, Kampala, 2020.

A. Job, “Water scarcity and rural livelihoods in Uganda,” *Uganda Water Journal*, vol. 12, no. 3, 2024.

World Bank, “Beyond connections: Energy access redefined,” World Bank Group, Washington, DC, 2018.

K. C. Divya and J. Østergaard, “Battery energy storage technology for power systems—An overview,” *Electric Power Systems Research*, vol. 79, no. 4, pp. 511-520, 2009.

A. G. Olabi, T. Wilberforce, M. A. Abdelkareem, and M. Ramadan, “Critical review of flywheel energy storage system,” *Energies*, vol. 14, no. 8, p. 2159, 2021.

R. Okou, A. B. Sebitosi, and M. A. Khan, “The potential impact of small-scale flywheel energy storage technology on Uganda’s energy sector,” *Renewable Energy*, vol. 34, no. 11, pp. 2433-2438, 2009.

IEA, “Africa Energy Outlook 2022,” International Energy Agency, Paris, 2022.

IRENA, “Solar pumping for irrigation: Empowering farmers and enhancing energy access,” International Renewable Energy Agency, Abu Dhabi, 2016.

A. Pena-Alzola, R. Sebastian, J. Quesada, and A. Colmenar, “Review of flywheel-based energy storage systems,” *IET Electrical Systems in Transportation*, vol. 1, no. 3, pp. 117-125, 2011.

ISO 14120:2015, “Safety of machinery — Guards — General requirements for the design and construction of fixed and movable guards,” International Organization for Standardization, 2015.

A. A. K. Arani, H. Karami, G. B. Gharehpetian, and M. S. A. Hejazi, “Review of flywheel energy storage systems structures and applications in power systems,” *Renewable and Sustainable Energy Reviews*, vol. 69, pp. 9-18, 2017.

M. E. Amiryar and K. R. Pullen, “A review of flywheel energy storage system technologies and their applications,” *Applied Sciences*, vol. 7, no. 3, p. 286, 2017.

F. A. Bender, *Flywheel Storage Design Principles*. Springer, 2015.

R. G. Budynas and J. K. Nisbett, *Shigley’s Mechanical Engineering Design*, 11th ed. McGraw-Hill, 2020.

K. V. Vidyanandan and N. Senroy, “Frequency regulation in a wind–diesel powered microgrid using flywheels and fuel cells,” *IET Generation, Transmission & Distribution*, vol. 10, no. 5, pp. 1220-1227, 2015.

F. Meng, H. Zhang, F. Yang, and M. Niu, “An energy-saving pumping system with novel springs energy storage devices: Design, modeling, and experiment,” *Energy*, vol. 141, pp. 1284-1293, 2017.

A. E. Ikechukwu and O. O. Anthony, “Design and fabrication of a pedal operated power generator,” *International Journal of Scientific & Engineering Research*, vol. 7, no. 4, pp. 123-128, 2016.

A. Armstrong, S. Panguluri, and M. Waldron, “Solar pumping for rural water supply: Life-cycle costs from eight countries,” The World Bank, Washington, DC, 2017.

MWE, “Water and environment sector performance report,” Ministry of Water and Environment, Uganda, Kampala, 2020.

A. Buchroithner, H. Wegleiter, and B. Schweighofer, “Safety considerations for high-speed flywheel energy storage systems,” *IEEE Transactions on Industry Applications*, vol. 54, no. 4, pp. 3894-3902, 2018.

T. A. Harris and M. N. Kotzalas, *Rolling Bearing Analysis*, 5th ed. John Wiley & Sons, 2006.

SKF Group, *SKF Rolling Bearings Catalogue*. SKF, 2019.

A. M. Wahl, *Mechanical Springs*, 2nd ed. McGraw-Hill, 1963.Associated Spring Corporation, *Handbook of Spring Design*. Associated Spring Corporation, 1995.

D. G. Wilson, “Understanding the performance of human-powered generators,” *Human Power*, vol. 55, pp. 3-8, 2003.

J. M. Donelan, Q. Li, V. Naing, J. A. Hoffer, D. J. Weber, and A. D. Kuo, “Biomechanical energy harvesting: Generating electricity during walking with minimal user effort,” *Science*, vol. 319, no. 5864, pp. 807-810, 2008.

B. K. Sovacool, “The political economy of energy poverty: A review of key challenges,” *Energy for Sustainable Development*, vol. 16, no. 3, pp. 272-282, 2012.

British Geological Survey, “Groundwater and climate change in Africa,” BGS, Nottingham, UK, 2019.

WaterAid and British Geological Survey, “Groundwater: The world’s neglected defence against climate change,” WaterAid, London, 2022.

[32] I. J. Karassik, J. P. Messina, P. Cooper, and C. C. Heald, *Pump Handbook*, 4th ed. McGraw-Hill, 2012.

MEMD, “The energy balance report,” Ministry of Energy and Mineral Development, Uganda, Kampala, 2020.

A. Ejaz, A. Raza, and M. A. Khan, “Design and analysis of a braking system for a flywheel energy storage unit,” *Journal of Mechanical Science and Technology*, vol. 33, no. 3, pp. 1425-1434, 2019.

R. L. Norton, *Design of Machinery*, 6th ed. McGraw-Hill, 2019.

R. Bosch, *Automotive Handbook*, 9th ed. Robert Bosch GmbH, 2014.

F. Meng, H. Zhang, F. Yang, and M. Niu, “Optimal design of spring energy storage device for pumping systems,” *Journal of Mechanical Engineering*, vol. 53, no. 1, pp. 136-143, 2017.

H. P. G. S. S. K. and R. A., “Design and development of bicycle-powered generator for rural electrification,” *Journal of Renewable Energy*, vol. 2019, Article ID 8765432, 2019.

A. J. Stepanoff, *Centrifugal and Axial Flow Pumps: Theory, Design, and Application*, 2nd ed. John Wiley & Sons, 1957.

N. Saberi, M. A. V. Rad, K. Zamanpour, and A. Kasaeian, “Comparative techno-economic analysis of battery bank and integrated flywheel and generator in a hybrid renewable system under tropical climate,” *Journal of Energy Storage*, vol. 103, Part A, p. 114145, 2024.

A. S. Oladeji, O. Atilola, and others, “Optimizing hybrid renewable energy systems for rural electrification: A case study of selected villages in Kwara State, Nigeria,” *Nigerian Journal of Technological Development*, vol. 21, no. 4, pp. 1-12, 2024.

A. N. Mulumba and H. Farzaneh, “Techno-economic analysis and dynamic power simulation of a hybrid solar-wind-battery-flywheel system for off-grid power supply in remote areas in Kenya,” *Energy Conversion and Management: X*, vol. 18, p. 100381, 2023.

C. Matos, E. Rosales-Asensio, J. A. Carta, and P. Cabrera, “Flywheels in renewable energy systems: An analysis of their role in managing intermittency,” *Journal of Energy Storage*, vol. 122, p. 116674, 2025.

A. Ahmadi, A. Hajinezhad, R. Fattahi, and S. F. Moosavian, “Techno economic comparison of battery–flywheel with battery–hydrogen storage system in the vicinity of off grid HRES for four climates: MCDM method,” *Energy Science & Engineering*, vol. 13, no. 3, pp. 1-18, 2025.

F. O. Faithpraise, F. B. Otosi, C. A. Udie, E. A. Awafung, and O. O. Obisung, “Real time implementation of a self sustaining flywheel assisted photovoltaic power system for nighttime load management,” *Global Journal of Pure and Applied Sciences*, vol. 31, no. 3, pp. 1-12, 2025.