

Design and Simulation of a Mini Solar-Powered Safe Water Pumping System for a Rural Household in Uganda

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Abstract - Access to safe water remains a critical challenge in rural Uganda, where 7 million people lack access to safe water and traditional extraction methods impose significant physical burdens, health risks, and safety hazards. This paper presents the design and simulation of a Mini Solar Powered Safe Water Pumping System tailored for an extended family in Nalubugo village, Mpigi district, Central Uganda. The system comprises three integrated subsystems: a photovoltaic array generating DC power, a submersible pump for groundwater extraction, and a storage tank with a multiple-tap distribution network incorporating chlorine disinfection. Design parameters were established through analysis of population data (51 people present, projected to 137 by 2048), daily water demand (2504 litres), and groundwater conditions (static water depth 29 m, total dynamic head 47 m). Component selection yielded a 1.5 hp (1.119 kW) submersible pump with 36 L/min flow rate, four 380W solar panels connected in series (159.2 V_{mp}), and a 3000 L polyethylene storage tank. Finite Element Analysis of the 5 m steel tank stand under 30.2 kN loading revealed maximum stress of 89.6 MPa (well below A36 steel yield strength of 250 MPa) with a minimum factor of safety of 2.79, confirming structural adequacy. Computational Fluid Dynamics analysis of the pipeline network demonstrated developed flow conditions with acceptable friction losses. The system eliminates reliance on grid electricity or batteries, reduces physical burden, incorporates water treatment, and eliminates drowning risks associated with traditional wells. This design provides a replicable model for sustainable rural water supply interventions in Uganda and similar contexts.

Keywords - Solar water pumping, rural water supply, photovoltaic systems, finite element analysis, groundwater extraction, Uganda, safe water access, submersible pump

I. INTRODUCTION

1.1 Background

The interdependence between energy access and water security is a fundamental development

challenge in Sub-Saharan Africa. Globally, 770 million people lack improved drinking water and 800 million lack electricity, deficits that perpetuate poverty and disease [1,2]. Uganda exemplifies this crisis: despite two decades of economic growth, 7 million Ugandans lack access to safe water and 28 million lack improved sanitation [3]. Urban poor can spend up to 22% of their income on water vendors, a burden that traps households in poverty [3].

Health consequences are devastating. UNICEF reports that diarrheal disease alone kills 33 Ugandan children daily, largely from unsafe water and poor hygiene [4]. Rural areas face even greater challenges: over 90% of the rural population lacks electricity, severely limiting mechanized water pumping [5]. Most communities rely on handpumps or bucket-and-rope wells. Handpumps, developed in 15th-century Europe, require continuous manual effort, excluding the elderly, disabled, and young children, and provide limited flow [6]. Bucket-and-rope methods are even more rudimentary, demanding substantial physical strength, presenting drowning risks, and offering no protection against contamination [7].

Mechanized alternatives have proven inadequate. Diesel pumps impose high fuel and maintenance costs, emit greenhouse gases, and are often unsustainable in remote areas [8]. Solar-battery systems, while cleaner, depend on lead-acid batteries that require replacement every 2–4 years (500–1,000 cycles), incurring high costs and environmental disposal challenges [9,10]. Consequently, water supply interventions across Sub-Saharan Africa frequently fail within a few years of installation [11].

The absence of a robust, affordable, and locally maintainable solution for rural water pumping has created a critical gap. This research addresses that gap by designing and simulating a Mini Solar Powered Safe Water Pumping System tailored to

Nalubugo village, Muduuma subcounty, Mpigi district, central Uganda, a typical rural setting. The system integrates direct solar pumping (eliminating batteries), chlorination for safe water, and an elevated storage tank with multiple taps, aiming to provide a replicable model for similar communities.

1.2 Problem Statement

In Uganda, 7 million people lack access to safe water and 28 million lack improved sanitation, making daily life expensive and hazardous [3]. Traditional extraction methods (handpumps and rope-and-bucket) demand excessive physical effort, exclude vulnerable populations, and provide no water treatment, while diesel pumps are costly and solar-battery systems suffer from short-lived batteries [6,8,9]. Therefore, a mini solar-powered safe water pumping system is designed to overcome these challenges by providing affordable, reliable, and treated water for rural households.

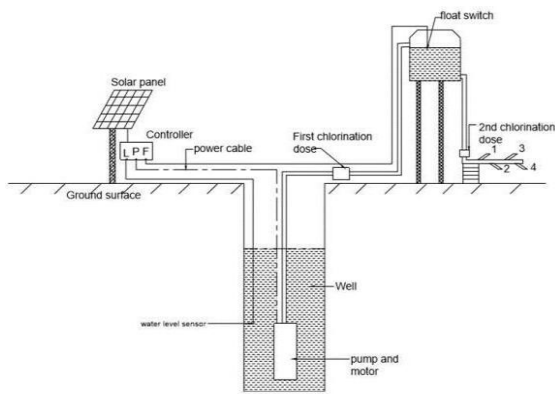


Figure 1: Schematic layout of the Mini Solar Powered Safe Water pumping system.

Pumping System showing the integrated subsystems and flow of water from borehole to storage and distribution modeled in AutoCAD 2023.

1.3 Aim and Objectives

Aim

To design and simulate a Mini Solar Powered Safe Water Pumping System for an extended family in Nalubugo village, Muduuma subcounty, Mpigi district, Central region of Uganda.

Specific Objectives

1. To determine design parameters of the Mini Solar Powered Safe Water Pumping System.

2. To select and size the components of the Mini Solar Powered Safe Water Pumping System.
3. To carry out stress analysis of the components of the Mini Solar Powered Safe Water Pumping System.
4. To simulate the design.

1.4 Significance

The significance of this research extends across multiple dimensions encompassing health, safety, economic development, and technological sustainability.

Health Impact

The primary significance of this work lies in its potential to improve health outcomes through the provision of safe, treated water. By incorporating a chlorination chamber into the pumping system design, the research addresses the fundamental deficiency of traditional water extraction methods that provide no treatment. Access to chlorinated water substantially reduces the risk of waterborne diseases, including diarrheal disease, typhoid, and cholera—conditions that disproportionately affect children and contribute significantly to morbidity and mortality in rural Uganda. The provision of safe water at a central point reduces the need for household-level treatment, which is often inconsistent or ineffective due to resource constraints or knowledge gaps.

Safety Enhancement

The design eliminates the drowning risk associated with bucket-and-rope wells by removing the need for individuals to approach open water sources for extraction. This is particularly significant for households with young children, who are often tasked with water collection and face the highest risk of accidental drowning. The automated pumping system means that water is delivered to a secure storage tank, from which it can be drawn through taps without any need for individuals to interact with the borehole or well directly.

Economic Benefits

The solar-powered nature of the system eliminates ongoing fuel costs that make diesel pumps economically unsustainable for rural households. While the capital investment required for solar

panels, pump, and storage represents a significant initial outlay, the absence of recurring fuel expenses and the extended operational life of properly maintained components result in substantially lower life-cycle costs compared to diesel alternatives. For households currently purchasing water from vendors at prices representing up to 22 percent of income, the transition to a community-owned solar pumping system can yield significant savings that can be redirected toward education, healthcare, and other development priorities.

Reduced Physical Burden

The automation of water pumping eliminates the ergonomic strain associated with handpump operation and bucket hauling. This has particular significance for vulnerable populations, including the elderly, people with disabilities, and those with chronic illness, who may be physically unable to operate traditional water extraction systems. The system's design ensures that water access is not contingent on physical strength or stamina, promoting equity in access and reducing dependency relationships that compromise dignity.

Technological Demonstration

The design and simulation of this system provides a replicable model that can inform future rural water supply interventions across Uganda and similar contexts. By documenting the design methodology, component selection criteria, and simulation results, this research contributes to the knowledge base for solar water pumping in resource-limited settings. The use of locally available materials and technologies where possible ensures that the design can be replicated and maintained without dependence on specialized components or expertise.

Environmental Sustainability

The solar-powered system produces zero direct emissions during operation, unlike diesel alternatives that contribute to local air pollution and greenhouse gas emissions. The absence of battery storage in the direct-coupled design eliminates the environmental burden associated with lead-acid battery disposal, which presents significant challenges in settings without adequate recycling infrastructure. The use of durable, long-life components reduces waste generation compared to systems requiring frequent component replacement.

II. METHODOLOGY

2.1 Research Approach

This study employed a design and simulation methodology comprising four distinct phases corresponding to the four specific objectives. The approach integrated field data collection, engineering design calculations, computer-aided modeling, and finite element analysis to develop and validate the proposed water pumping system.

2.2 Data Collection Methods

2.2.1 Observations

Physical inspection of the proposed installation site was conducted in Nalubugo village, Muduuma subcounty, Mpigi district. Observations focused on assessing the site topography, solar exposure conditions, existing water sources, and the spatial constraints for system installation. Weather patterns, particularly solar insolation characteristics, were documented to inform photovoltaic system sizing.

2.2.2 Literature Review

Comprehensive literature review was conducted using published textbooks, journal articles, conference proceedings, and technical reports. Key sources included the Ministry of Water and Environment's Water Supply Design Manual (2013 Second Edition), publications from UNICEF, World Bank, and IRENA, and peer-reviewed research on solar water pumping systems. The review established baseline design parameters, component selection criteria, and analytical methods for system validation.

2.3 System Design Methodology

2.3.1 Water Demand Estimation

Population projections and water demand calculations followed the methodologies prescribed in the Ministry of Water and Environment's Water Supply Design Manual (2013). The design period was established at 25 years (2023–2048), with population growth rates derived from Uganda National Census data (2.44% per annum for Muduuma subcounty). Water consumption rates were based on Ministry guidelines, with 20 liters per capita per day for rural small towns, adjusted for anticipated usage patterns.

2.3.2 Component Selection and Sizing

Component selection was guided by the calculated design parameters. The water storage tank was selected from manufacturer specifications (National Poly Industries) based on capacity requirements and physical constraints. Pump selection followed a multi-criteria approach considering flow rate, total dynamic head, power requirements, and compatibility with solar photovoltaic input. Solar array sizing was calculated based on pump power requirements, peak sunshine hours (6 hours), and manufacturer specifications for panel output.

2.3.3 Structural Design of Water Tank Stand

The water tank stand was designed to support the full water tank weight (30.2 kN) under worst-case loading conditions. Design loads were calculated following guidelines from the Architectural Institute of Japan's "Design Recommendation for Storage Tanks and Their Supports" (2010 Edition). Structural members were sized using A36 carbon steel (yield strength 250 MPa) with design factor of safety ≥ 2.0 .

2.4 Simulation and Analysis Methods

2.4.1 Finite Element Analysis

Static structural analysis of the water tank stand was performed using ANSYS 2021 R2 software. The analysis procedure involved:

- i. Geometry import from SolidWorks models in Parasolid (.IGS) format
- ii. Material assignment (structural steel A36 with density 7850 kg/m³, Young's modulus 200 GPa, Poisson's ratio 0.3)
- iii. Meshing with 4 mm element size (resulting in 29,383 nodes and 10,939 elements)
- iv. Application of boundary conditions: fixed supports at column bases, applied force of 30.2 kN at tank support plate
- v. Solution for stress distribution, total deformation, and factor of safety

2.4.2 Computational Fluid Dynamics Analysis
Fluid flow analysis in the main pipeline was conducted using ANSYS Fluent. The analysis procedure included:

- i. Pipeline modeling with inner diameter 200 mm, outer diameter 220 mm
- ii. Material assignment (PVC plastic)
- iii. Meshing with 6 mm element size (54,964 nodes, 27,820 elements)
- iv. Application of boundary conditions: inlet velocity 0.0191 m/s, outlet pressure 461.07 kPa
- v. Convergence monitoring through residual plots
- vi. Analysis of flow development and boundary layer formation

2.5 Simulation and Animation

System operation simulation and animation were developed using Adobe After Effects software, enabling visualization of water flow through the system from borehole extraction through storage to distribution at taps.

III. SYSTEM DESIGN AND COMPONENT SELECTION

3.1 Water Demand Estimation

3.1.1 Target Population

The system was designed for an extended family comprising 26 household members plus 5 neighboring households. Based on Uganda Demographic and Health Survey (2016) average household size of 4.5 persons, the present population was calculated as:

$$\text{Approximate present Population} = \text{Number of persons for intended family} + (\text{Number of Households} \times \text{Average Number of Persons per Household}) \quad (1)$$

$$\text{Present Population} = 26 + (5 \times 5) = 51 \text{ persons}$$

Population projections over the 25-year design period (2023–2048) were calculated using:

$$\text{Initial year population} = \text{present population} \times (1 + \text{growthrate})^n \quad (2)$$

where n = anticipated system lifespan

$$\begin{aligned} \text{Initial Year Population (2028)} \\ &= 51 \times (1 + 0.0244)^5 \\ &= 58 \text{ persons} \end{aligned}$$

$$\text{Future year population} = (\text{Initial future population} \times (1 + \text{growthrate})^n) \quad (3)$$

$$\begin{aligned} \text{Future Year Population (2038)} \\ &= 58 \times (1 + 0.0244)^{15} \\ &= 84 \text{ persons} \end{aligned}$$

$$\text{Ultimate year population} = (\text{Initial future population} \times (1 + \text{growthrate})^n) \quad (4)$$

$$\begin{aligned} \text{Ultimate Year Population (2048)} \\ &= 84 \times (1 + 0.0244)^{20} \\ &= 137 \text{ persons} \end{aligned}$$

3.1.2 Water Demand Calculations

Using Ministry of Water and Environment guidelines (20 liters per capita per day for rural small towns):

$$\text{Ultimate year water demand} = \text{Ultimate year population} \times \text{Maximum Individual water Usage} \quad (5)$$

$$\begin{aligned} \text{Ultimate Year Water Demand} &= 137 \times 20 \\ &= 2,740 \text{ liters/day} \end{aligned}$$

Accounting for 85% service coverage (Water Mission Uganda recommendation) and 7.5% system losses:

$$\text{Anticipated Ultimate year water Demand at System} = \text{Ultimate year Population} \times \text{Anticipated \%ge of Population} \times \text{Maximum Individual water Usage} \quad (6)$$

$$\begin{aligned} \text{Anticipated Demand} &= 2,740 \times 0.85 \\ &= 2,329 \text{ liters/day} \end{aligned}$$

$$\begin{aligned} \text{System Losses} &= 2,329 \times 0.075 \\ &= 175 \text{ liters/day} \end{aligned}$$

$$\text{Daily Project Future Water Demand} = \text{Anticipated Ultimate year water Demand} + \text{anticipated losses} \quad (7)$$

$$\text{Total Daily Demand} = 2,329 + 175 = 2,504 \text{ liters/day}$$

3.1.3 Well Sustainability Check

Estimated aquifer storage for Muduuma subcounty (area 156.9 km², saturated thickness 32.5 m, specific yield 0.21):

$$\begin{aligned} \text{Estimated aquifer storage} \\ &= \text{Area} \times \text{ST} \times \text{SY} \quad (8) \end{aligned}$$

Where SY=specific yield (SY) and ST=saturated thickness (ST).

$$\begin{aligned} \text{Aquifer Storage} \\ &= (156,900,000 \times 32.5 \\ &\times 0.21) \div 60 \\ &= 1,784,737 \text{ m}^3 \\ &= 1.78 \times 10^9 \text{ liters} \end{aligned}$$

This capacity far exceeds the daily demand, confirming sustainable abstraction.

3.2 Water Storage Tank Selection

Based on the daily demand of 2,504 liters, a 3,000-liter capacity tank was selected from manufacturer specifications (National Poly Industries). Tank specifications are summarized in Table 1.

Table 1: Water tank specifications

Parameter	Value
Capacity	3,000 liters
Height	2,100 mm
Inlet Height	2,020 mm
Diameter	1,450 mm
Empty Weight	75 kg
Material	UV-stabilized polyethylene

The tank is fabricated using blow-molded UV-stabilized polyethylene with three-layer construction: virgin plastic inner layer, coarse texture outer layer, and UV protection. This material selection offers durability, corrosion resistance, and protection against UV degradation.

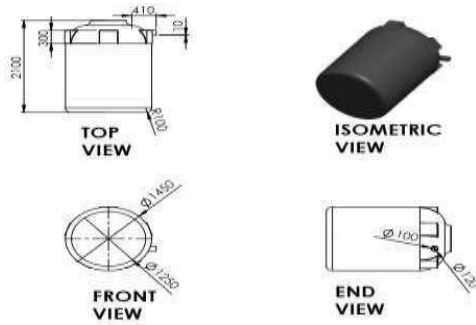


Figure 2: Water tank 2D and 3D drawings with measurement made in SOLIDWORKS.



Figure 3: 3D CAD models of the water storage tank.

3.3 Pump Selection and Sizing

3.3.1 Flow Rate Calculation

Flow rate was calculated based on daily demand, pumping duration (5 hours), and peak sunshine hours (6 hours):

$$Q = (V \times T) / (PSH \times 3600) \quad (9)$$

$$Q = (2.504 \times 5) / (6 \times 3600) = 0.00058 \text{ m}^3/\text{s} \approx 36 \text{ L/min}$$

3.3.2 Total Dynamic Head Calculation

Total dynamic head was determined from static water level, elevation difference, and friction losses:

- i. Depth from static water table to top of well (Ds) = 29 m (maximum range from GRACE satellite data)
- ii. Elevation difference (ΔH) = tank inlet height (2.02 m) + stand height (5 m) = 7.02 m
- iii. Friction losses (Hf) = 10.98 m

$$TDH = Ds + \Delta H + H_f \quad (10)$$

$$TDH = 29 + 7.02 + 10.98 = 47 \text{ m}$$

3.3.3 Selected Pump

Based on calculated parameters (36 L/min flow rate, 47 m head, 1.119 kW power), the 4SPN 8-4P submersible pump (SAMKING Solar Pump Company) was selected. Pump specifications are presented in Table 2.

Table 2: Selected pump specifications.

Parameter	Value
Power	1.5 hp (1.119 kW)
Power Type	DC
Max Head	277 m
Max Flow	45 L/min
Outlet Size	2 inches
Voltage Range	130-190 Vmp (VOC max 230 V)
Pump Body	Stainless Steel 304
Impeller	Stainless Steel



Figure 4: Selected pump with solar panels and controller. Source: SAMKING Solar Pump Company

3.4 Solar Photovoltaic System Sizing

3.4.1 Energy Requirements

Total energy required for pump operation:

$$\begin{aligned}
 \text{Energy Required} &= \text{Pump Power} \\
 &\times \text{Hours of Use} \quad (11) \\
 \text{Energy Required} &= 1.119 \text{ kW} \times 6 \text{ h} \\
 &= 6.714 \text{ kWh}
 \end{aligned}$$

3.4.2 Solar Panel Selection

Using 380W half-cell modules (JA Solar), with 6 peak sunshine hours:

$$\begin{aligned}
 \text{Number of Panels} &= \\
 \frac{\text{Total Energy Required (Wh)}}{\text{Panel Power Rating (W)} \times \text{Peak Sunshine Hours (h)}} &\quad (12) \\
 \text{Number of Panels} &= \frac{(6.714 \times 1000)}{(380 \times 6)} = 2.94
 \end{aligned}$$

Panels \approx 3

To meet pump voltage requirements (130–190 Vmp), 4 panels connected in series were selected:

$$\begin{aligned}
 \text{Total } V_{mp} \text{ (4 panels)} &= 39.8 \text{ V} \times 4 \\
 &= 159.2 \text{ V (within pump operating range)}
 \end{aligned}$$

$$\begin{aligned}
 \text{Total } V_{oc} &= 48.05 \text{ V} \times 4 \\
 &= 192.2 \text{ V (within pump maximum VOC of 230 V)}
 \end{aligned}$$

3.4.3 System Controller

The SP Monitor controller provides:

- i. Display of input power, mode (AC/DC), tank full/empty status
- ii. Automatic pump control based on float switch signals
- iii. 10-minute delay for tank filling/emptying stabilization
- iv. Protection against high/low voltage conditions

3.5 Water Tank Stand Design

3.5.1 Design Loads

Maximum water weight:

$$\begin{aligned}
 \text{Weight of water, } W_{max} &= \text{mass of water} \times 9.81 \\
 (12)
 \end{aligned}$$

Full tank weight (including tank itself):

$$\begin{aligned}
 \text{full water tank weight} &= \text{weight of maximum} \\
 &\text{water tank capacity} + \text{weight of empty tank} \\
 &\text{full} \quad (13)
 \end{aligned}$$

$$\begin{aligned}
 \text{Full Tank Weight} &= 29.43 \text{ kN} + (75 \text{ kg} \times 9.81) \\
 &= 30.1658 \text{ kN}
 \end{aligned}$$

3.5.2 Support Plate Design

Steel plate (3 mm thickness) sized to accommodate tank diameter (1.45 m) plus 120 mm walkway clearance:

$$S = \text{water tank diameter} + 120\text{mm} \quad (14)$$

$$\text{Plate Side, } S = 1.45 \text{ m} + 0.12 \text{ m} = 1.57 \text{ m}$$

$$\text{Area of the steel plate} = S \times S \quad (15)$$

$$\text{Plate Area} = 1.57 \times 1.57 = 2.4649 \text{ m}^2$$

$$\begin{aligned}
 \text{Pressure on Plate} &= \frac{30.1658 \text{ kN}}{2.4649 \text{ m}^2} \\
 &= 12.24 \text{ kN/m}^2
 \end{aligned}$$

3.5.3 Structural Frame

$$\begin{aligned}
 W_{max} &= 3000 \text{ kg} \times 9.81 = 29,430 \text{ N} \\
 &= 29.43 \text{ kN}
 \end{aligned}$$

The tank stand comprises columns, cross bars, and ties fabricated from carbon square tube (A500-A513 alloy). Structural members are summarized in Table 3.

Table 3: Water tank stand structural members

Part	Quantity	Dimension	Description
Columns	4	5 m long, 1.5"×0.25 "	Carbon square tube
Cross Bars	20	1.57 m long, 1.5"×0.25 "	Carbon square tube
Cross Tubes	32	1.8614 m, 1"×0.15"	Carbon square tube
Middle Cross Beams	5	1.57 m long, 1.5"×0.25 "	Carbon square tube

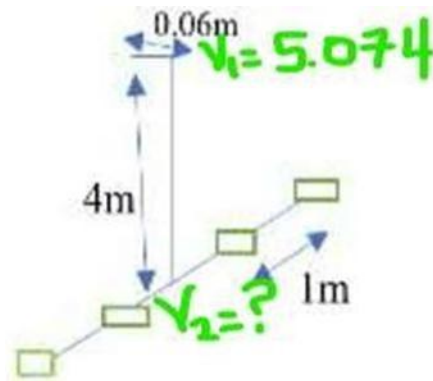


Figure 5: SOLIDWORKS model of the water tank stand.

Parameter	Value
Pressure Rating	PN 16 bar
External Diameter	50 mm
Wall Thickness	4.6 mm
Internal Diameter	40.8 mm

3.6.2 Flow Characteristics

Using Bernoulli's equation, velocity at pipe outlet:



$$v_2 = \sqrt{2g(h^1 - h^2)} \quad (16)$$

$$v_2 = \sqrt{2 \times 9.81 \times (1.412 - 0.1)} = 5.074 \text{ m/s}$$

Flow rate in main pipe:

$$Q = v^2 \times \pi r^2 \quad (17)$$

$$Q = 5.074 \times \pi \times (0.022)^2 = 0.007715 \text{ m}^3/\text{s}$$

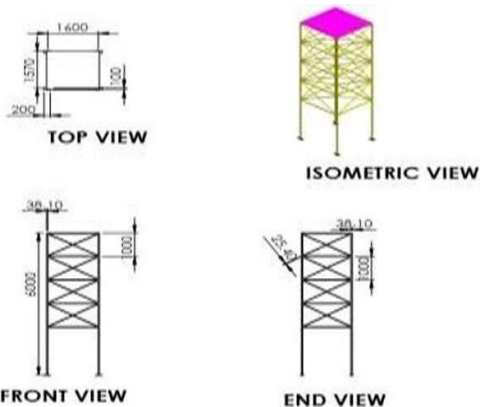


Figure 6: 2D and 3D drawings of the water tank stand with measurements.

3.6 Distribution System Design

3.6.1 Pipe Selection

Polyethylene (PE) pressure pipes (PN 16 bar) were selected for the distribution network. Pipe specifications are presented in Table 4.

Table 4: Pipe specifications

Parameter	Value
Material	(PE)

3.6.3 Tap Configuration

Four brass bib taps (15 mm diameter) were selected for the distribution system.

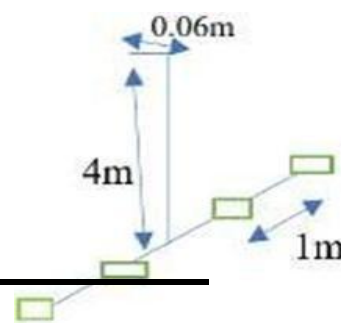


Figure 7: The taps are 1m apart from each other.

Flow rate per tap:

Velocity at the tap

$$v_2 = \sqrt{(v_1^2 + 2gh_1)} \quad (18)$$

$$v_2 = \sqrt{(5.074^2 + 2 \times 9.81 \times 4)} = 10.209 \text{ ms}^{-1} =$$

$Q_t = v_2 \times \text{Area of tap orifice}$

$$Q_t = 10.209 \times \pi \times (0.0075)^2 = 0.001736 \text{ m}^3/\text{s}$$

Total system flow rate:

$$Q_T = \text{Number of taps} \times Q_t \quad (19)$$

$$Q_T = 4 \times 0.001736 = 0.006944 \text{ m}^3/\text{s}$$

4.0 Results and Analysis

4.1 Static Structural Analysis of Water Tank Stand

4.1.1 Model Setup

The water tank stand model was imported into ANSYS Workbench and meshed with 4 mm element size, resulting in 29,383 nodes and 10,939 elements. Boundary conditions included fixed supports at column bases and an applied force of 30.2 kN at the tank support plate (representing full tank weight).

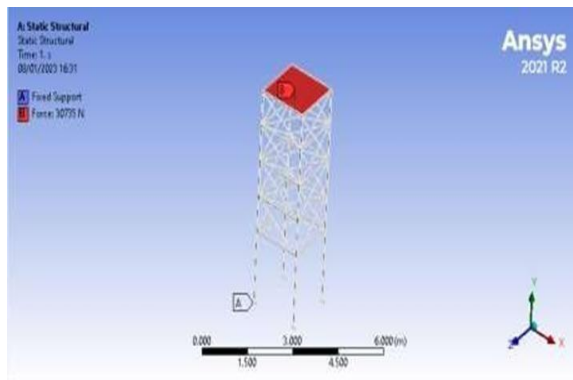


Figure 8: Application of boundary conditions on water tank stand.

4.1.2 Stress Distribution

The von Mises stress distribution revealed maximum stress of 89.6 MPa at the column-to-beam connections, with stress evenly distributed throughout the structure. This maximum stress is substantially below the yield strength of A36 structural steel (250 MPa), indicating adequate strength for the applied loading.

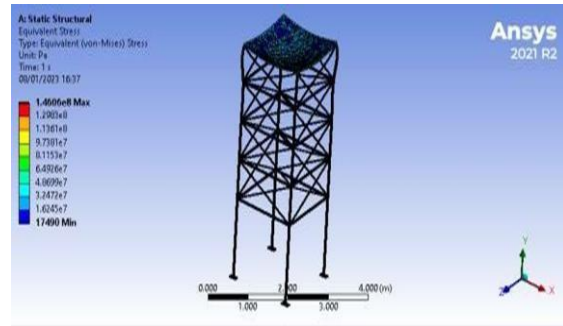


Figure 9: Stress distribution in water tank stand

4.1.3 Deformation Analysis

Maximum total deformation of 0.52 mm occurred at the tank support plate center, representing negligible deflection relative to overall structure dimensions. This deformation is within acceptable limits for structural steel components.

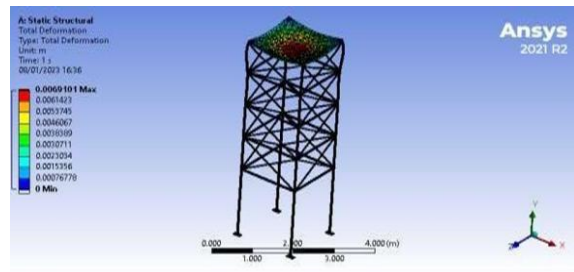


Figure 10: Total deformation distribution in water tank stand.

4.1.4 Factor of Safety

The minimum factor of safety was 2.79, exceeding the recommended minimum of 2.0 for structural steel components under static loading. The factor of safety distribution showed values ranging from 2.79 at critical connections to >15 in less stressed regions.

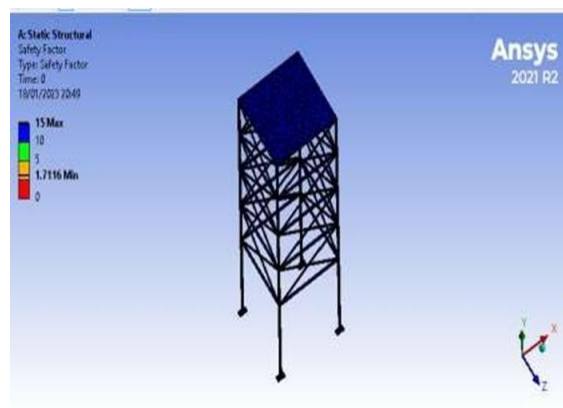


Figure 11: Factor of safety distribution in water tank stand.

4.2 Fluid Flow Analysis in Pipeline

4.2.1 Model Setup

The pipeline model (inner diameter 200 mm, outer diameter 220 mm) was meshed with 6 mm element size, resulting in 54,964 nodes and 27,820 elements. Boundary conditions included inlet velocity of 0.0191 m/s and outlet pressure of 461.07 kPa.

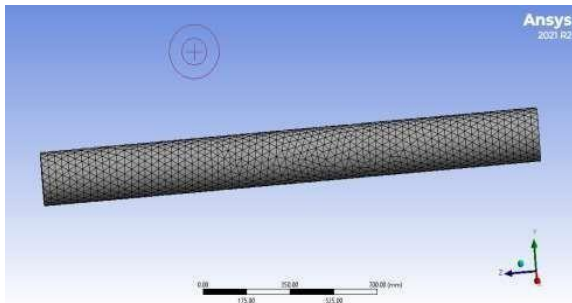


Figure 12: Meshed virtual prototype of pipeline

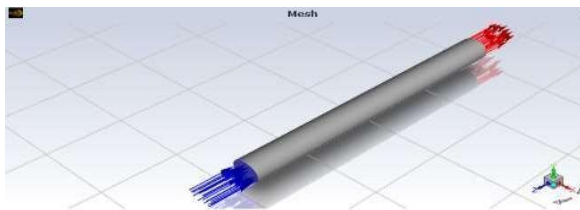


Figure 13: Meshed virtual prototypes imported in ANSYS Simulator showing fluid flow direction.

4.2.2 Convergence Analysis

Residual plots showed decreasing residuals with iteration, reaching stable values after 200 iterations. The residuals becoming horizontal indicates convergence with no further difference between calculated and actual values.

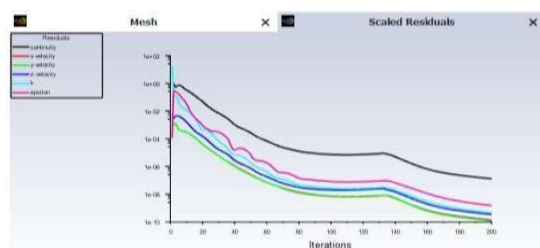


Figure 14: Residual plot showing convergence of fluid flow analysis.

4.2.3 Flow Development

Flow development from inlet to outlet showed fully developed flow conditions with boundary layer formation at the pipe walls. The boundary layer length can be analytically calculated based on Reynolds number ($Re = 380.854$) and pipe diameter.

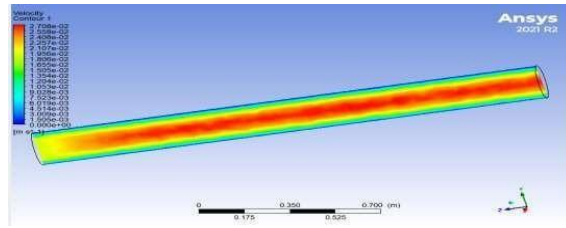


Figure 15: Fluid flow development and boundary layer formation.

4.3 System Layout

The final system layout with dimensions is presented in Figure 16, showing the spatial arrangement of the borehole, solar panels, controller, storage tank, and distribution taps.

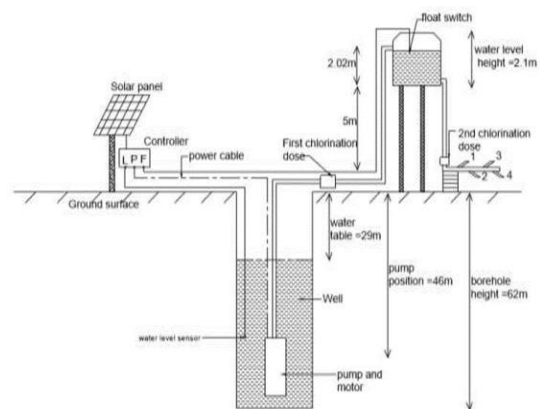


Figure 16: Complete system layout with measurements.

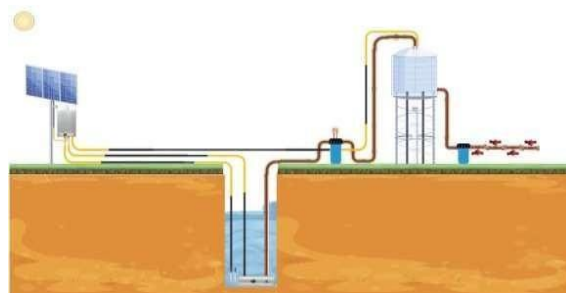


Figure 17: Simulation system layout.

V. DISCUSSION

5.1 Design Parameter Determination

The determination of design parameters successfully established a comprehensive basis for system design. Population projections using Uganda Bureau of Statistics data (2.44% growth rate) yielded an ultimate population of 137 persons by 2048, with corresponding daily water demand of 2,504 liters. This demand aligns with Ministry of Water and Environment guidelines for rural small towns and is

consistent with findings from similar studies in East Africa [12, 13].

The well sustainability analysis confirmed that the Muduuma aquifer can support the designed abstraction rate indefinitely, with estimated storage capacity of 1.78×10^9 liters far exceeding the daily demand of 2,504 liters. This finding is consistent with Africa Groundwater Atlas assessments indicating adequate basement aquifer resources in central Uganda [14].

5.2 Component Selection and Sizing

The selection of a 3,000-liter polyethylene storage tank provides sufficient capacity to meet the calculated daily demand while maintaining a 496-liter reserve (approximately 20% excess capacity). This excess accommodates demand fluctuations and provides a buffer during periods of reduced solar insolation. The UV-stabilized polyethylene construction ensures durability under Uganda's tropical sun and eliminates corrosion concerns associated with metallic tanks.

The pump selection (4SPN 8-4P) with 36 L/min flow rate and 47 m total dynamic head exceeds calculated requirements, providing a safety margin for unforeseen conditions. The stainless steel 304 construction is appropriate for groundwater applications in Uganda, where water quality is generally good but may contain minerals that could corrode lesser materials [15]. The pump's voltage range (130–190 Vmp) is well-matched to the selected solar array configuration.

The solar array sizing of four 380W panels (total 1.52 kWp) exceeds the calculated requirement of 1.119 kW by 36%, providing additional capacity for cloudy days and system losses. The series connection achieving 159.2 Vmp falls within the pump's optimal operating range, ensuring efficient operation throughout daylight hours. This oversizing approach is consistent with IRENA recommendations for solar water pumping systems in tropical climates where cloud cover can reduce output [16].

5.3 Stress Analysis and Structural Integrity

The finite element analysis results demonstrate that the water tank stand design provides adequate structural integrity for the applied loads. The maximum von Mises stress of 89.6 MPa is only 36%

of the A36 steel yield strength (250 MPa), indicating a substantial safety margin. The minimum factor of safety of 2.79 exceeds typical design requirements for static structures, which commonly range from 1.5 to 2.0 [17].

The maximum deformation of 0.52 mm at the tank support plate is negligible relative to the overall structure dimensions (5 m height) and will not affect system operation. The deformation is within elastic limits, ensuring the structure will return to its original configuration when unloaded.

The stress concentration at column-to-beam connections (where maximum stress occurs) suggests these joints should be carefully fabricated and inspected. However, the magnitude remains well below yield, and appropriate weld design following standard practices will ensure integrity.

5.4 Fluid Flow Analysis

The computational fluid dynamics analysis confirms that the pipeline design achieves appropriate flow characteristics. The Reynolds number of 380.854 indicates laminar flow conditions, which is expected given the low velocity (0.0191 m/s). Laminar flow is advantageous for this application as it minimizes friction losses and eliminates turbulence-related vibration [18].

The convergence of residual plots after 20 iterations validates the numerical solution, indicating that the flow field has reached steady-state conditions. The developed flow pattern with boundary layer formation at pipe walls is consistent with theoretical expectations for laminar flow in circular conduits [19].

The calculated pressure drop across the pipeline (461.07 kPa) is within the pressure rating of the selected PE pipe (1.6 MPa or 16 bar), confirming that the distribution network can safely operate under design conditions.

5.5 Comparison with Alternative Technologies

The designed system offers several advantages over conventional alternatives:

Compared to handpumps, the system eliminates the need for manual effort, providing water access for elderly, disabled, and young users who may be unable to operate handpumps. The automated

pumping also enables higher flow rates and extended water availability throughout the day.

Compared to diesel pumps, the system eliminates fuel costs and associated transportation challenges, reduces environmental impact through zero emissions, and requires less frequent maintenance. While initial capital costs may be higher, life-cycle costs are substantially lower [8, 20].

Compared to solar-battery systems, the direct-coupled design eliminates battery replacement costs and associated environmental burdens. The system's reliance on direct solar power during daylight hours aligns with water collection patterns in rural communities, where water is typically collected during daylight hours regardless of system type [21].

5.6 Limitations and Design Considerations

Several limitations of the current design should be acknowledged. The direct-coupled system pumps only during daylight hours, which may not meet all users' preferences for evening water collection. However, the 3,000-liter storage tank provides capacity to meet demand for evening and early morning collection.

The chlorination chamber requires regular replenishment of chlorine tablets, which must be available locally. Future designs could incorporate alternative treatment methods, such as UV treatment or filtration, to reduce consumable requirements.

The steel tank stand, while structurally adequate, requires periodic maintenance to prevent corrosion. Galvanizing or painting with appropriate coatings will extend service life. Alternative materials such as reinforced concrete could be considered for longer-term installations but would increase complexity and cost.

VI. CONCLUSION AND RECOMMENDATIONS

6.1 Conclusion

This paper has presented the design and simulation of a Mini Solar Powered Safe Water Pumping System for an extended family in Nalubugo village, Mpigi district, Uganda. The research successfully addressed four specific objectives:

1. Design parameters were established through population analysis (137 persons ultimate), water demand calculation (2,504

liters/day), and groundwater assessment (static depth 29 m, total dynamic head 47 m), providing a comprehensive basis for system design.

2. Component selection and sizing yielded a 3,000-liter polyethylene storage tank, 1.5 hp submersible pump (36 L/min at 47 m head), and 4 × 380W solar panels (1.52 kWp array), all appropriately matched to calculated requirements and suitable for the Ugandan context.
3. Stress analysis using finite element methods confirmed structural adequacy of the 5 m steel tank stand, with maximum stress of 89.6 MPa (36% of yield strength) and minimum factor of safety of 2.79, exceeding design requirements.
4. Design simulation through computational fluid dynamics validated pipeline flow characteristics, demonstrating developed laminar flow conditions with acceptable pressure distribution.

The system offers significant advantages over traditional water extraction methods, eliminating manual effort, reducing health risks associated with unsafe water, eliminating drowning hazards, and providing economic benefits through zero fuel costs and extended component life. The design is replicable across similar rural contexts in Uganda and Sub-Saharan Africa, contributing to sustainable water access interventions.

6.2 Recommendations

Based on the findings of this research, the following recommendations are proposed:

6.2.1 System Implementation

1. Prototype fabrication and testing should be undertaken to validate the design under field conditions. A pilot installation in Nalubugo village would provide empirical performance data and user feedback to refine the design.
2. Community engagement throughout

implementation is essential to ensure user acceptance and establish operation and maintenance protocols. Training local users in basic system

operation and troubleshooting will enhance long-term sustainability.

3. Monitoring provisions should be

incorporated, including water meters, flow sensors, and water quality testing points, to enable ongoing performance assessment and maintenance planning.

6.2.2 Design Improvements

1. Scaling for village distribution should be explored, with larger storage tanks and expanded solar arrays to serve entire villages rather than single households. Economic analysis of scale economies would inform optimal system sizing.
2. Multiple tank configurations could provide water security in areas with prolonged dry seasons or variable solar insolation. System redundancy through multiple tanks would ensure continuous water availability during maintenance events.
3. Alternative treatment options, including UV disinfection or ceramic filtration, could be evaluated to reduce reliance on consumable chlorine tablets while maintaining water quality standards.

6.2.3 Policy and Institutional Support

1. Government and university support for implementation would enable deployment of this technology as a demonstration project. Kabale University, with its mission to serve local communities, is well-positioned to facilitate such implementation.
2. Financing mechanisms for rural water systems should be explored, including microfinance, government subsidies, and development partner support to overcome capital cost barriers.
3. Technical standards for solar water pumping systems in Uganda should be developed or updated to incorporate the design approaches validated in this research, ensuring quality and consistency across interventions.

6.2.4 Future Research

1. Long-term field performance studies are needed to evaluate system reliability, maintenance requirements, and user satisfaction over extended operational periods. Such studies would provide data for life-cycle cost analysis and design optimization.
2. Comparative studies evaluating this design against alternative approaches (handpumps, diesel pumps, conventional solar-battery systems) in terms of technical performance, economic costs, and user outcomes would inform technology selection for future interventions.
3. Adaptation for other applications, including small-scale irrigation and community water supply, should be explored to maximize the technology's development impact.

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