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Research Article

Development of an electronics-controlled wheelchair using hybrid source with a USB charging unit

Lambe Mutalub Adesina[1], Olalekan Ogunbiyi[2], Abdulrafiu Yusuf[3], Ibrahim Oladimeji[4] and Ronke Seyi Babatunde[5]

[1,2,3,4]Electrical and Computer Engineering Department, Kwara State University, Malete, Nigeria.
[5]Computer Science Department, Kwara State University, Malete, Nigeria.
lambe.adesina@kwasu.edu.ng, olalekan.ogunbiyi@kwasu.edu.ng, abdulrafiu.yusuf@kwasu.edu.ng, ibrahim.o@minareteng.com, ronke.babatunde@kwasu.edu.ng

Corresponding Author: *lambe.adesina@kwasu.edu.ng*

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Abstract

The growing demand for affordable, energy-efficient assistive mobility systems has spurred interest in intelligent electric wheelchairs that enhance the independence and quality of life of individuals with mobility impairments. However, many commercially available wheelchairs are expensive and dependent on conventional charging infrastructure. This study presents the design, fabrication, and performance evaluation of a low-cost hybrid solar-powered electric wheelchair integrated with a PIC16F877A-based embedded control system. The developed system combines a rechargeable 12 V/40 Ah battery with a 50 W monocrystalline solar panel through a solar charge controller. Two 12 V, 150 W DC motors were controlled using a PIC16F877A microcontroller programmed in C language for directional control, motion regulation, and system monitoring. A capacitive touch interface and LCD feedback system were incorporated to improve usability. The wheelchair frame was fabricated from locally sourced steel selected for its strength and load-bearing capacity. Experimental validation was conducted under load conditions ranging from 10 kg to 120 kg. Results showed stable operation across the tested range, with voltage decreasing from 12.97 V to 11.47 V as the load increased, while current increased from 1.6 A to 3.8 A. Helioscope simulation revealed monthly solar energy generation between 12.31 kWh and 14.81 kWh under varying environmental and irradiance conditions throughout the year. The developed system also demonstrated reliable directional control and improved accessibility in low-resource environments. The study demonstrates that integrating embedded control systems, renewable energy harvesting, and local fabrication can provide a practical, low-cost, reliable, and sustainable mobility solution for resource-constrained environments.

Nomenclature and units

V	Voltage	CAD	Computer-aided design
AC	Alternating Current	LCD	Lead Control Display
DC	Direct Current	GND	Ground pin
W	Watt	VCC	Power supply pin
AH	Ampere Hour	N	Newton
SIG	Digital signal output	Kg	kilogram
SCCC	Solar charge controller current	Vo	Output voltage
SCCV	Solar charge controller voltage	F	Force
SCCP	Solar charge controller power	m	Mass
SMG	Solar monthly generation	g	Acceleration due to gravity in m/s^2
SF	Safety factor	Vcc	Power supply pin
UTS	Utilization tensile strength	DSIG	Digital signal output pin
PERC	Passivated Emitter and Rear cell	A	Ampere
Vi	Input voltage		

1. INTRODUCTION

A wheelchair is a tangible assistive device consisting of a chair mounted on wheels, designed to support individuals with mobility impairments due to age-related conditions or health challenges. Studies have shown that older adults and individuals with physical disabilities often experience significant limitations in mobility, which reduces independence, participation in daily activities, and overall quality of life. While walking aids such as sticks may be sufficient for minor impairments, more severe cases require wheelchair assistance for effective mobility support (Antonio et al., 2021; Sahoo & Choudhury, 2023).

Globally, the demand for assistive mobility technologies continues to rise due to increasing cases of spinal cord injuries, stroke, neuromuscular disorders, and age-related degenerative conditions. According to recent assistive technology reports, more than 75 million people worldwide require wheelchair assistance, yet a significant proportion still lack access due to cost and infrastructural limitations (Gowran et al., 2021; Fernandes et al., 2021). This situation is more difficult in developing countries, where imported wheelchairs are expensive and often not adapted to local environmental and economic conditions.

Health conditions that necessitate wheelchair use include orthopedic disabilities affecting bones and muscles, as well as neuromuscular disorders affecting nerves and motor coordination. These conditions may result in amputation, spinal cord injuries, or paralysis, thereby making assistive mobility systems essential for daily functioning. Although manually operated wheelchairs are widely used, they often require significant physical effort either from the user or caregiver, thereby limiting usability in cases of severe disability or fatigue (Hariharan et al., 2025; Anwer et al., 2020).

In contrast, electrically powered wheelchairs provide improved mobility and independence; however, their adoption in developing countries remains limited due to high cost, maintenance complexity, dependence on non-renewable charging infrastructure, and limited accessibility of replacement components. Recent advancements in assistive mobility systems have focused on integrating embedded control systems, intelligent automation, and renewable energy sources to improve efficiency and sustainability (Tiwari & Verma, 2024; Ariza, 2022). However, most existing systems remain optimized for high-income environments and are not adequately adapted for low-cost, locally fabricated applications.

Recent studies in smart mobility systems have introduced innovations such as voice-controlled wheelchairs, eye-tracking navigation, and sensor-based autonomous movement to enhance user independence (Zhang, 2024 ; Abed, 2015; Hariharan et al., 2025). Furthermore, developments in human-robot interaction and shared control systems have significantly improved wheelchair navigation efficiency and safety (Sahoo & Choudhury, 2023; Peula & Pérez, 2011; Malobický, 2025). Despite these advances, most systems still rely heavily on expensive embedded platforms and stable grid electricity, which limits their applicability in low-resource environments.

A major emerging area in assistive mobility is the integration of renewable energy systems, particularly solar photovoltaic (PV) technology, into wheelchair design. Solar-assisted mobility systems have demonstrated potential in improving energy sustainability, especially in regions with high solar irradiance, such as Sub-Saharan Africa (Ramkumar et al., 2025; Malele et al., 2025). However, most existing solar wheelchair designs focus only on charging support without integrating intelligent power management or hybrid energy optimization.

Despite these developments, there remains a significant gap in the integration of low-cost embedded control systems with hybrid renewable energy supply in a locally fabricated wheelchair framework. Existing systems often rely on imported components, lack hybrid energy optimization, and do not sufficiently address affordability constraints in developing regions such as Nigeria. Furthermore, limited attention has been given to combining solar energy harvesting, battery management, and microcontroller-based motor control in a unified, cost-effective assistive device (Boucif et al., 2025; Akkoyunlu & Abdallatif, 2024).

In Nigeria, mobility impairment remains a major public health and social inclusion challenge, with millions of individuals affected by physical disabilities requiring assistive devices. However, access to affordable and durable wheelchairs remains limited due to economic constraints and dependence on imported technologies (Gowran et al., 2021; Abdef & Bcde, 2012). This highlights the urgent need for locally developed, cost-effective, and energy-efficient mobility solutions tailored to the Nigerian environment.

The novelty of this study lies in the development of a hybrid solar-powered electric wheelchair system integrated with a PIC16F877A-based embedded control architecture, designed for low-cost local fabrication. The system uniquely combines dual energy sources (solar and battery), proportional motor control, and a capacitive touch interface, thereby enhancing both energy sustainability and operational accessibility. In addition, the system incorporates real-time feedback via

LCD and supports auxiliary charging functionality for mobile devices, making it suitable for practical deployment in resource-constrained environments.

From a sustainability perspective, this study aligns with the United Nations Sustainable Development Goals (SDG 3: Good Health and Well-being, SDG 9: Industry, Innovation and Infrastructure, and SDG 10: Reduced Inequality), as it promotes inclusive mobility and locally driven technological innovation.

The main contributions of this study are as follows:

- Development of a hybrid renewable energy wheelchair system combining solar charging and battery backup.
- Design and implementation of a PIC16F877A microcontroller-based control system using C-language programming.
- Fabrication of a locally sourced steel-based wheelchair structure optimized for load-bearing and durability.
- Integration of a capacitive touch control interface and LCD feedback system for user interaction.
- Experimental evaluation of system performance under varying load conditions and solar energy input.

The specific objectives of this study are to:

- Design an electronic control system for seamless motor operation and user interaction,
- Develop a C-language program for embedded microcontroller control using the PIC16F877A,
- Simulate and optimize circuit performance using Proteus software,
- Fabricate a mechanically stable wheelchair frame using locally available materials, and
- Evaluate system performance under varying load conditions and solar charging scenarios.

The remainder of this paper is structured as follows: Section 2 presents a review of related works. Section 3 describes the methodology, including mechanical, electrical, and solar subsystem design. Section 4 presents results and discussion, including simulation and experimental validation. Section 5 concludes the study and provides recommendations for future improvements.

2. Review Of Related Works

The literature on electric wheelchairs reveals a progressive evolution from manually controlled systems to intelligent, sensor-based, and energy-aware mobility platforms. However, a critical analysis shows that while significant advancements exist, most systems remain fragmented in design, either focusing on control intelligence, energy efficiency, or safety in isolation rather than as an integrated low-cost system.

2.1 Control-Based Wheelchair Systems

Voice-controlled wheelchair systems have been widely proposed as an intuitive interface for users with severe motor impairments. Basak et al. (2023) and Tiwari & Verma (2024) demonstrated that speech recognition can significantly improve independence in controlled environments. However, a key limitation is that speech-based systems exhibit low robustness under real-world acoustic interference, particularly in outdoor or hospital environments where background noise distorts command accuracy.

Xing et al. (2025) introduced Smart Phone-Based Biosensors for various applications. While this improves accessibility, it introduces multi-layer latency due to signal processing between the mobile application, microcontroller, and motor driver, reducing real-time responsiveness.

Dahmani et al. (2020) combined voice and eye-tracking control, improving redundancy. However, from an engineering standpoint, this introduces system complexity, calibration instability, and higher power consumption, making it unsuitable for low-cost embedded deployment.

2.2 Embedded Microcontroller Systems

Embedded controllers such as ATmega328 and ARM-based systems are widely used in smart wheelchairs due to flexibility and processing capacity (Ariyanto et al., 2019). However, a critical comparison shows that many designs prioritize computational capability over energy efficiency and cost optimization. PIC-based architectures, although less powerful computationally, offer lower power consumption, higher stability in analog interfacing, and lower system cost, making them more suitable for continuous assistive operation in low-resource environments. Shili et al. (2025) demonstrated effective microcontroller integration for voice control, but the system depends heavily on external processing modules, which increases cost and reduces autonomy.

2.3 Renewable Energy Integration

Renewable energy integration in wheelchair systems remains underdeveloped despite increasing demand for sustainable assistive devices. Most systems reviewed rely on battery-only operation, which introduces limitations in charging dependency and reduced operational time. Akpan (2025) implemented a battery-powered smart wheelchair with sensor integration but did not incorporate solar energy harvesting, leading to dependency on grid charging. Al-thani & Koç (2022) emphasize the importance of decentralized renewable energy systems for mobility devices, particularly in regions with unstable electricity supply.

2.4 Sensor and Safety Systems

Obstacle detection systems using ultrasonic sensors are widely adopted due to simplicity and low cost. However, Gibbs & Madani (2017) and similar studies show that these systems suffer from limited spatial resolution and detection delay, particularly when navigating irregular terrain. Additionally, most sensor-based systems operate independently of the energy subsystem, meaning there is no adaptive power adjustment based on obstacle density or motor load.

2.5 Human–Robot Shared Control Systems

Bao et al. (2023) present advanced shared-control frameworks that blend human intent with autonomous decision-making. These models improve navigation efficiency and reduce user cognitive load. However, from an implementation perspective, these systems require: high computational resources, probabilistic modeling (POMDPs), and continuous state estimation. This makes them unsuitable for low-cost embedded platforms such as PIC-based architectures.

2.6 Comparative Analysis

Table 1 presents a comparative analysis of existing wheelchair control systems based on their strengths, limitations, and associated engineering trade-offs affecting performance, complexity, efficiency, and suitability for embedded mobility applications.

Table 1: Comparative Analysis of Wheelchair Control Systems and Engineering Trade-offs

Study	Strength	Limitation	Engineering trade-off
Voice-based systems	Simple interface	Noise sensitivity	Low robustness
Eye-tracking systems	Multimodal control	High cost & calibration	High complexity
ATmega-based systems	Good processing power	Higher power consumption	Reduced efficiency
PIC-based systems	Low cost & low power	Limited computation	Best for embedded control
Sensor-based systems	Improved safety	Limited accuracy	Energy-unaware operation
Shared control systems	Intelligent navigation	High computation demand	Not embedded-friendly

2.7 Research Gap Statement

A critical synthesis of the literature reveals that existing wheelchair systems suffer from three fundamental engineering gaps:

1. Energy-architecture gap: Absence of integrated hybrid solar–battery power management with load-aware optimization.
2. Control-implementation gap: Advanced control strategies (AI, shared control) are not compatible with low-cost microcontroller platforms.
3. System integration gap: Most systems treat control, energy, and safety as separate modules rather than a unified embedded architecture.

Therefore, the development of a low-cost hybrid solar-powered wheelchair using PIC16F877A with capacitive touch control and integrated energy management is both technically justified and contextually necessary.

This study positions itself at the intersection of:

- embedded control optimization
- renewable energy integration
- low-cost assistive mobility design

3. Methodology

The methodology adopted in this study integrates mechanical design, electrical power systems, embedded control programming, renewable energy modeling, and experimental validation. The objective is to develop a hybrid solar-powered electronics-controlled wheelchair that is low-cost, locally fabricable, energy-efficient, and operationally reliable under varying load and environmental conditions.

The system architecture is presented in Figure 1, which illustrates the interaction between the power subsystem, control subsystem, motor drive system, and user interface.

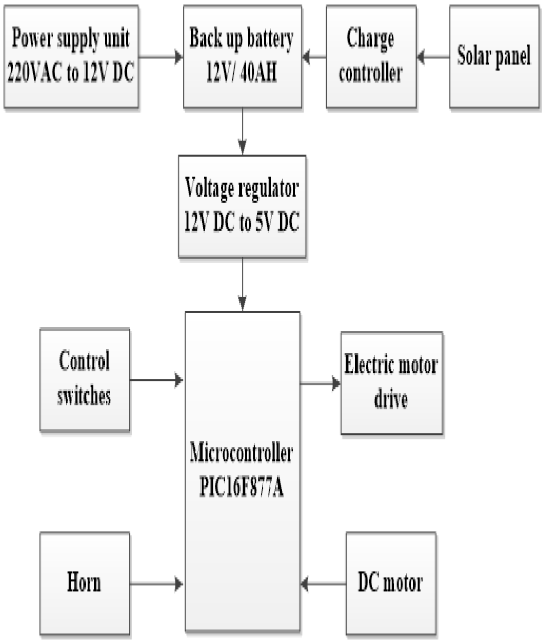

Figure 1: System Architecture and Electrical Block Diagram

Figure 1 presents the overall block diagram of the dual-controlled electric wheelchair system. The architecture consists of: Hybrid power supply system (battery + solar PV), Charge controller for energy regulation, embedded microcontroller unit (PIC16F877A), Motor driver interface, DC propulsion motors, User input system (capacitive touch + control switches), Output interface (LCD and indicators).

The solar subsystem provides auxiliary energy input to extend operational time, while the battery acts as the primary energy storage system. The microcontroller coordinates system operations by executing embedded C-program instructions that interpret user commands and convert them into motor actuation signals.

3.2 Experimental Design and System Validation Framework

To ensure repeatability, reliability, and accuracy of the developed wheelchair system, a structured experimental design and validation framework were adopted for evaluating operational performance, energy efficiency, control responsiveness, load capacity, and overall system functionality under varying operating conditions.

3.2.1 Experimental Conditions

All tests were conducted under the following controlled conditions: Load range: 10 kg to 120 kg, Battery voltage range: 12.0 V – 13.0 V, Motor operating voltage: 12 V DC, Ambient condition: natural outdoor lighting (solar testing phase), Terrain condition: flat and slightly inclined surfaces.

3.2.2 Performance Metrics

The system performance was evaluated using the following metrics: Speed response (km/h), Voltage stability (V), Current consumption (A), Load handling capacity (kg), Solar charging efficiency (%), Battery discharge time (hours).

3.2.3 Measurement Instruments

The following instruments were used: Digital multimeter (voltage/current measurement), Clamp meter (motor current verification), Stopwatch (speed timing), Solar irradiance estimation via Helioscope simulation, and Embedded LCD feedback system (real-time monitoring).

3.3 Flowchart System Design and Control Logic

The system operation is governed by a structured decision-making process implemented in the microcontroller to coordinate sensor inputs, power management, motor control, charging operations, and user commands, thereby ensuring stable, efficient, reliable, and intelligent wheelchair functionality under different operating conditions.

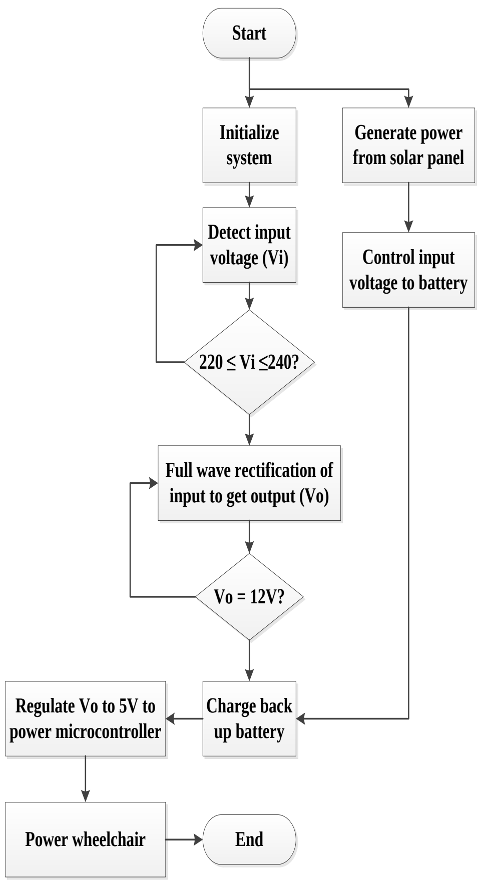

Figure 2: Voltage Supply Flow Process

Figure 2 shows the energy routing between the solar panel input and battery storage. The system prioritizes solar charging when irradiance is sufficient and automatically switches to battery discharge during low solar availability.

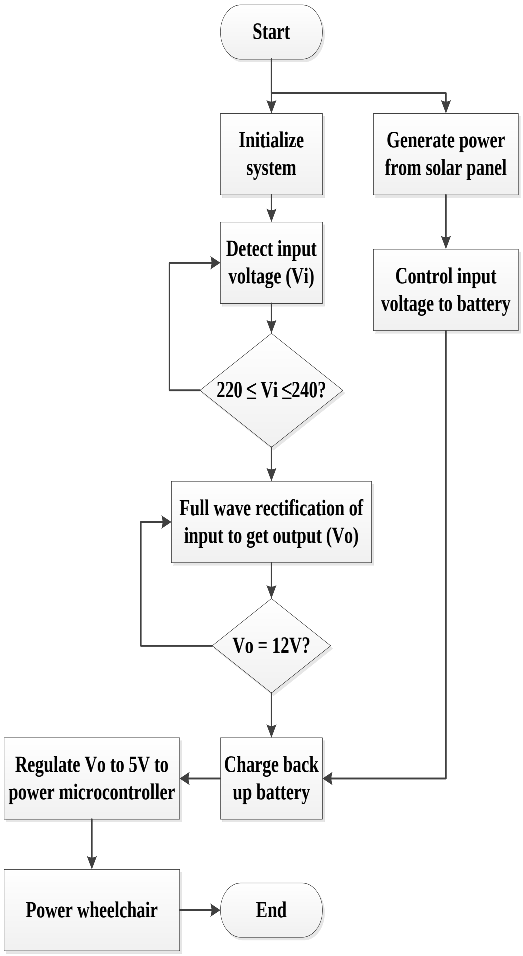

Figure 3: Electrical Command Processing Flowchart

Figure 3 illustrates how user inputs from capacitive touch sensors are converted into digital signals. These signals are processed by the PIC16F877A to determine directional movement commands.

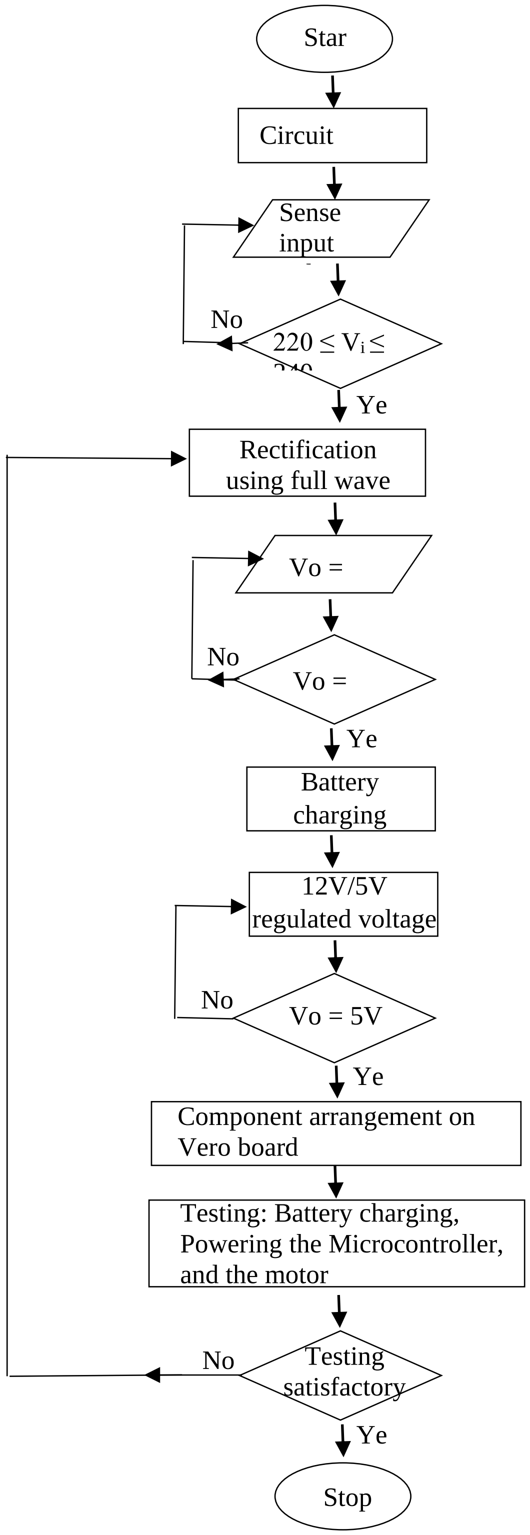

Figure 4: Voltage Regulation Control Flowchart

Figure 4 presents feedback-based voltage stabilization logic ensuring consistent supply to motor drivers regardless of load variation.

3.3.1 Embedded Control Algorithm (PIC16F877A Logic)

The wheelchair motion control system is implemented using a rule-based embedded control algorithm:

Algorithm 1: Wheelchair Control Logic

1. Initialize the system and LCD display
2. Read user input from the capacitive touch sensor
3. Convert analog/digital input to command signal
4. If command = FORWARD → set both motors HIGH
5. If command = BACKWARD → reverse motor polarity
6. If command = LEFT → right motor HIGH, left LOW
7. If command = RIGHT → left motor HIGH, right LOW
8. If no input → set motors OFF
9. Monitor battery voltage continuously
10. Display system status on LCD

This logic ensures deterministic response behavior and improves safety through immediate neutral-state fallback.

3.4 Mechanical Design and Structural Fabrication

The mechanical subsystem consists of the frame, seating system, wheel assembly, and suspension support. Computer-Aided Design (CAD) was used to define the structural dimensions and load distribution geometry of the wheelchair frame, which was designed to withstand dynamic loading conditions of up to 120 kg user mass. Material selection considered factors such as safety factor (SF), yield strength, ultimate tensile strength (UTS), durability, strength-to-weight ratio, corrosion resistance, cost, and local availability (Shivam et al., 2019). Various steel materials, including mild steel (AISI 1040/1060), chromium-molybdenum alloy steel (AISI 4130), and chromium-nickel-molybdenum alloy steel (AISI 4340/6820), were evaluated based on Young's modulus, Poisson's ratio, yield strength, UTS, and mass-bearing capacity.

Table 2: Physical properties of the three selected iron steels examined for the construction of the wheelchair

Properties	Chromium-molybdenum AISI 4130	Mild steel AISI 1040/1060	Chromium-nickel-molybdenum
Young's Modulus (Mpa)	205	190	210
Poisson ratio	0.29	0.29	0.27
Density (g/cm^3)	7.85	7.80	7.75
Yield strength (Mpa)	103.4	320	470
UTS (Mpa)	723	640	745

Table 2 compares the physical and mechanical properties of the selected steel materials considered for wheelchair construction. Chromium-nickel-molybdenum steel (AISI 4340/6820) exhibited the highest yield strength and ultimate tensile strength (UTS), indicating superior load-bearing capacity, while chromium-molybdenum steel (AISI 4130) also demonstrated high tensile strength and stiffness. The density and Poisson ratio values of the materials were relatively similar, indicating comparable structural behavior under loading conditions. Mild steel (AISI 1040/1060), although having moderate mechanical properties compared to the alloy steels, was selected as the primary fabrication material due to its affordability, machinability, accessibility in local manufacturing environments, and suitability for the intended loading conditions with minimal stress and strain.

3.4.1 Structural Load Analysis

Structural design was validated using static load analysis. Equation 1 presents the allowable Stress.

$$\sigma_{allow} = \frac{UTS}{SF} \quad (1)$$

Where:

UTS: Ultimate Tensile Strength

SF: Safety Factor

For AISI 4130 steel:

$$\sigma_{allow} = \frac{723}{7} = 103.4\ MPa \qquad (2)$$

Equation 3: Load Force

$$F = mg \qquad (3)$$

Where:

m: 120 kg

g: 9.8 m/s²

$$F = 1{,}176\ N \qquad (4)$$

This ensures the frame is designed above the maximum expected operational load.

3.5 Fabrication Process and Assembly Protocol

The fabrication process involved: CAD-based dimensional transfer, Steel cutting and shaping, Mechanical bending using industrial bending tools, Welding using arc welding technique, Assembly and alignment verification. Tolerance control was maintained to ensure structural stability and alignment accuracy between the wheel axis and frame geometry.

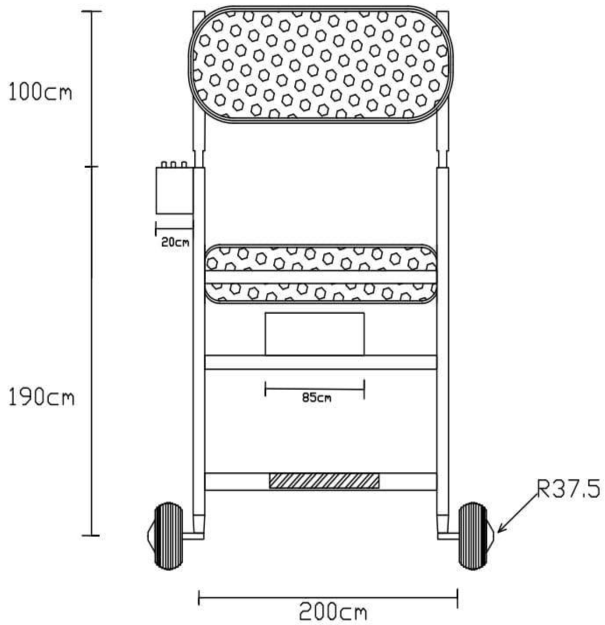

Figure 5a: Front View of the Wheelchair

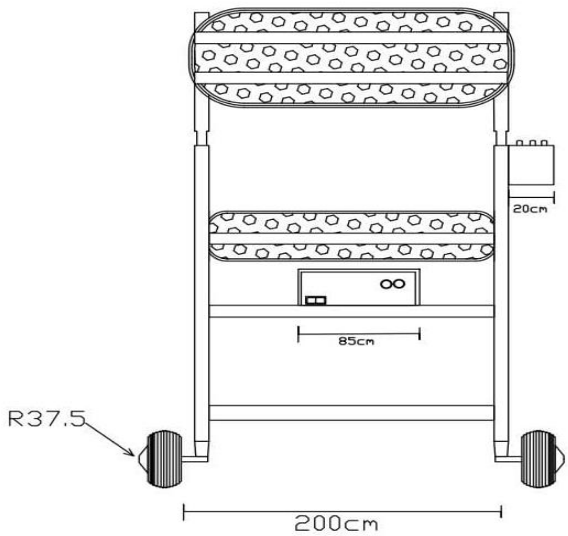

Figure 5b: Back View of the Wheelchair

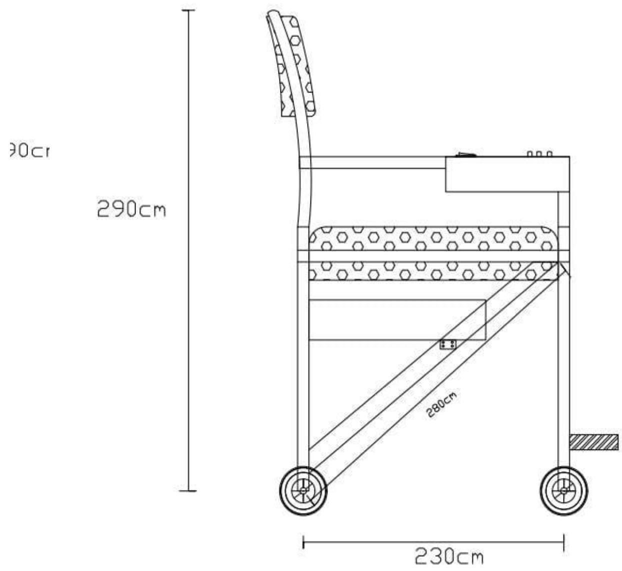

Figure 5c: Right-hand side view of the Wheelchair

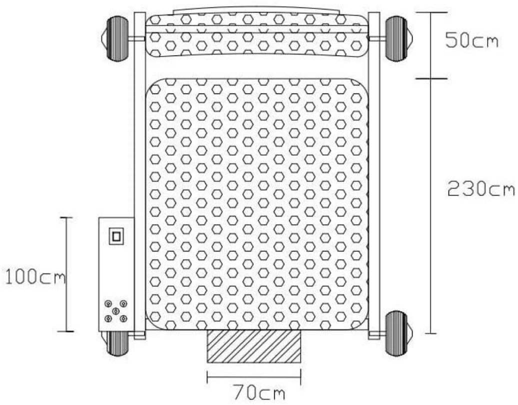

Figure 5d: Plan elevation

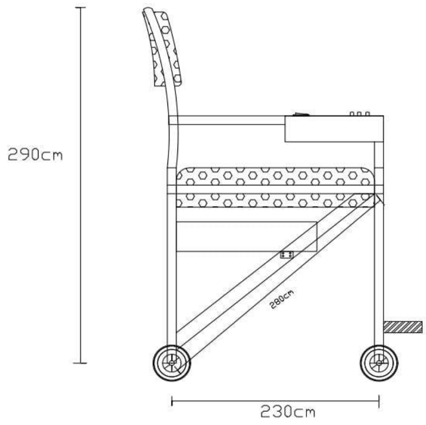

Figure 5e: Right hand side view of the wheelchair

Figure 5d: Plan elevation

Figure 5f: Testing of steel iron AISI4130 for brittleness during bending

Figure 5g: The fabrication process of bent pieces of iron with an industrial

Figures 5(a)–5(g) illustrate the complete fabrication process from design to final assembly.

3.6 Solar Energy System Design and Optimization

The photovoltaic subsystem was designed to support auxiliary energy supply and battery charging. Solar panels were mounted on a rotatable carrier system, allowing 360° manual adjustment for optimal solar tracking.

3.6.1 Solar Panel Electrical Characterization

Given:

Imp: 2.59 A

Vmp: 19.32 V

The PV output power is estimated as presented in Equation 5.

$$P_{max} = I_{mp} \times V_{mp} \quad (5)$$
$$P_{max} = 50.04\, W$$

The Two solar panels provide approximately:

$$P_{total} \approx 100\, W$$

3.6.2 Battery Performance and Backup Analysis

A 12V, 40Ah deep-cycle battery was selected primarily based on weight considerations to minimize the overall no-load weight of the wheelchair. The battery, weighing approximately 14.0 kg, provides a suitable balance between power supply, backup time, and portability. However, increasing the battery capacity to achieve longer operating duration would consequently increase the no-load weight of the wheelchair.

The battery Backup Time is given as follows;

$$Backup = \frac{V \times Ah}{Load} \quad (6)$$
$$Backup = \frac{12 \times 40}{300} = 1.6\, hours \quad (7)$$

3.6.3 Solar Charge Controller Design

A 20A charge controller was selected to regulate power flow. Considering the two Solar panels connected in parallel give a total current of 5.18 (2 x 2.59) amperes. The controller ensures overcharge protection, reverse current protection, and stable DC output voltage regulation.

3.6.4 Solar Panel Carrier

The solar panel carrier is a fabricated metallic support structure designed to accommodate two 50 W solar panels used for charging the 12 V, 40 Ah wheelchair battery. The carrier was developed to provide structural stability, portability, and ease of integration with the wheelchair system. It incorporates a foldable and lightweight design to enhance mobility and convenient handling during operation and storage. In addition, the system functions as a portable solar charging unit, similar to commercially available portable solar chargers such as Goal Zero and Anker systems, enabling on-the-go charging of the wheelchair battery and improving energy sustainability in areas with limited access to grid electricity.

Figure 6: The solar panel carriers before and after solar panel installation

3.7 Embedded Electronics and Control System Design

The electronic subsystem integrates: PIC16F877A microcontroller, 7805 voltage regulator, BTS7960 motor drivers, Capacitive touch sensor (TTP223B), and LCD display module.

3.7.1 Voltage Regulation System

The 7805 regulator converts 12V DC input to stable 5V DC for microcontroller operation. This ensures protection against voltage fluctuations and system instability.

3.7.2 Motor Control System

Two 12V DC motors rated at 150W each were used. Motor operation is governed by directional logic defined in Table 3.

Table 3: Motor control Logic

Action	Right Rear Motor	Left Rear Motor	Description
Forward	HIGH	HIGH	Both DC motors move forward
Backward	HIGH	HIGH	Both DC motors move backward
Left	HIGH	LOW	The right motor moves to the left
Right	LOW	HIGH	The left motor moves to the right
Standstill	LOW	LOW	Both motors are in OFF mode

3.8 Control Interface System:

User control is achieved using push-button directional switches, a capacitive touch interface, Horn and indicator switches. The system is designed with a return-to-neutral safety mechanism to prevent unintended motion continuation.

3.9 Capacitive Touch Sensing System:

The TTP223B module operates in capacitive detection mode. Its key characteristics: Low power consumption, Digital HIGH output on touch, Auto sleep mode after inactivity, High sensitivity response interface.

3.10 Motor and Wheel Integration System: The selected DC motor operates at 71 RPM, 60 kgcm torque, and 12V operating voltage. The motor is directly coupled to the rear wheels for efficient torque transmission.

3.11 Solar Simulation and Energy Modeling:

Helioscope software was used to simulate photovoltaic performance. The simulation process includes: Geographic coordinate input, irradiance modeling, shading analysis, monthly energy yield prediction. Outputs were used to validate the real-world feasibility of solar-assisted charging.

3.12 System Integration and Circuit Design

Figure 7 presents the complete system circuit diagram showing the integration of the major functional units of the developed wheelchair system. These include the power subsystem, control subsystem, motor driver stage, user interface system, and display and indicator units. The integration of these subsystems enables effective coordination of power distribution, signal processing, motor actuation, user interaction, and system monitoring for reliable wheelchair operation.

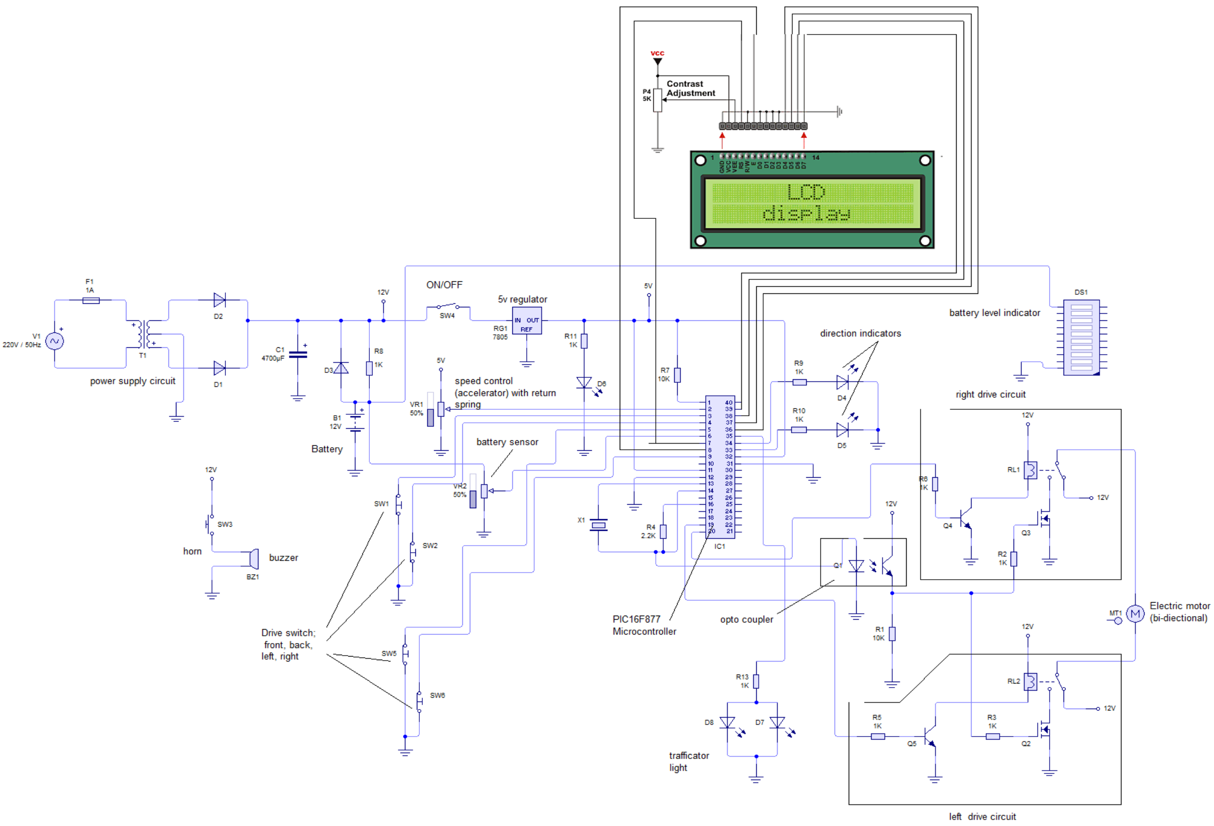

Figure 7: Overall Circuit Diagram

All subsystems operate under a centralized embedded control logic executed by the PIC16F877A microcontroller.

4.0 RESULTS AND DISCUSSION

This section presents the experimental, simulation, and system-level evaluation of the developed hybrid solar-powered electric wheelchair. The results are structured into electrical performance, solar energy simulation outcomes, load-dependent behavior, and system integration performance. The discussion further interprets these results in comparison with recent studies in assistive mobility systems by Oladele et al. (2021) and Souza et al. (2010), highlighting efficiency, stability, and practical deployment implications.

4.1 System Operational Performance

The developed system integrates a dual power source (battery and solar PV) with a PIC16F877A-based embedded controller to regulate DC motor operation and user interface functions. The system was evaluated under varying load conditions ranging from 10 kg to 120 kg to determine real-world operational stability.

Figure 8: Charge Controller Voltage and Current Response During Operation

At startup, the system battery voltage was observed at 12.97 V, dropping to approximately 12.6 V under load as shown in Figure 8, while current increased from 2.1 A to 1.6–3.0 A depending on load conditions (Table 4).

Table 4: The operational voltage and current of the solar charge controller

Simulation parameters	Solar charge controller voltage (volts)	Solar charge controller current(amperes)
Initial value	12.97	2.1
Simulation value	12.6	1.6

This inverse relationship between voltage and current is consistent with classical DC motor load characteristics, where increased mechanical demand leads to higher current draw and corresponding voltage sag due to the internal resistance of the battery system.

This behavior is consistent with findings by Masud et al. (2024), where smart wheelchairs exhibited similar voltage depression under increasing load due to motor torque demand.

4.2 Load-Dependent Electrical Behavior

The system was tested under increasing mass from 10 kg to 120 kg, and corresponding variations in voltage, current, and power output were recorded. Table 5 presents the observed relationship between load mass, charging parameters, and solar energy generation of the wheelchair system throughout the year.

Table 5: Physical properties of the three selected iron steels examined for the construction of the wheelchair

Month	Mass (Kg)	SCCC (A)	SCCV (V)	Power (W)	Solar monthly generation (kWh)
Jan	10	1.60	12.60	20.16	14.55
Feb.	20	1.80	12.51	22.52	14.44
Mar	30	2.00	12.42	24.84	14.51
Apr	40	2.20	12.33	27.13	14.25
May	50	2.40	12.24	29.38	14.91
June	60	2.61	12.14	31.69	12.45
July	70	2.81	12.05	33.86	12.31
Aug.	80	3.00	11.96	35.88	12.45
Sept.	90	3.21	11.87	38.10	13.20
Oct.	100	3.41	11.77	40.14	13.95
Nov.	110	3.60	11.67	42.01	14.72
Dec.	120	3.80	11.47	44.00	14.81

As the mass increased from 10 kg to 120 kg, the solar charge controller current (SCCC) and power output increased steadily, while the solar charge controller voltage (SCCV) gradually decreased. The highest power output of 44.00 W was recorded at 120 kg in December, whereas the lowest power output of 20.16 W occurred at 10 kg in January. The solar monthly generation (SMG) values varied slightly across the months, with the highest generation observed in December (14.81 kWh) and the lowest in July (12.31 kWh), indicating seasonal variations in solar energy availability.

These results imply that the solar charging system was capable of maintaining stable energy generation under varying loading conditions, demonstrating the suitability of the integrated solar-powered design for wheelchair operation. The gradual increase in current and power with increasing load suggests higher energy demand during operation, while the reduction in voltage indicates increased electrical loading on the system. Furthermore, the relatively consistent SMG values throughout the year confirm the reliability of the solar charging unit for sustainable wheelchair battery charging, particularly in regions with adequate solar radiation.

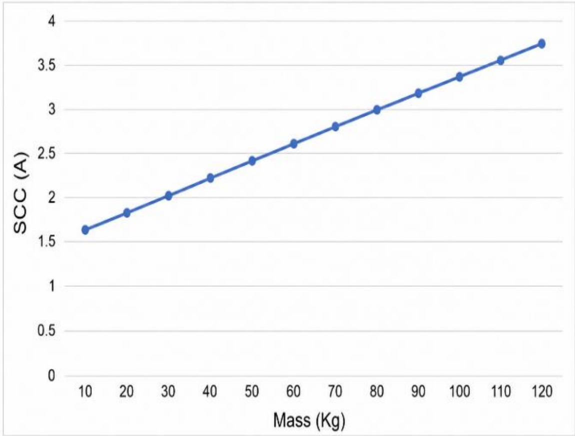

Figure 9 (a): Graph of mass(kg) against solar charge controller current

The graph in Figure 9 (b) shows the practical implication of voltage drop as the mass of the object increases along the x-axis. This significant drop in the voltage explains the need for an angle of inclination towards solar energy to reduce the constant drop in solar charge controller voltage.

The graph in Figure 9 (a) shows the amount of current drawn as the mass increases during the simulation. The amount of current drawn compensates for the decrease in solar charge controller voltage due to the mass. As the mass increases, the current is proportional in increments.

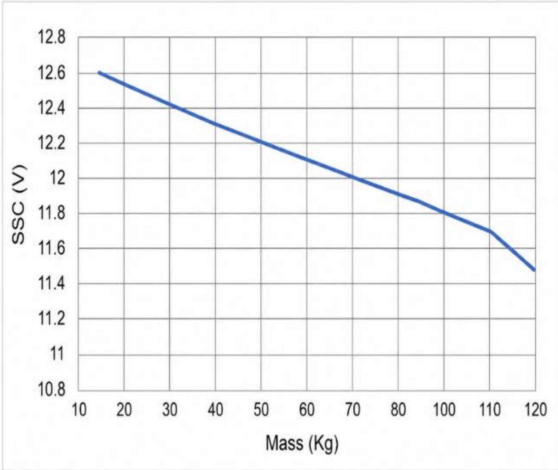

Figure 9 (b): Graph of mass(kg) against solar charge controller voltage

The product of voltage and current from the solar charge controller is calculated in order to register the maximum amount of energy required to keep the voltage drop at bay for longer operation. This is very vital to the entire system as solar energy is the primary source of supply for the DC motor and other peripherals of the solar-powered wheelchair. As shown in Figure 9 (c), the maximum energy simulated is 44.0 W, which is the minimum energy required to keep the voltage drops minimal. Hence, the reason for plotting power (w) against the mass (kg).

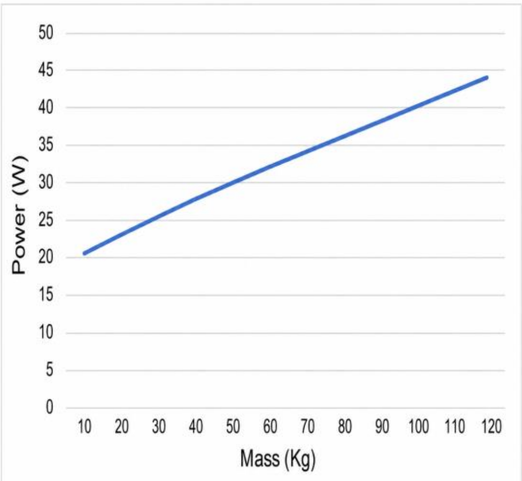

Figure 9 (c): Graph of mass(kg) against product of current and voltage (watts)

4.2.1 Engineering Interpretation

The observed trend confirms a direct proportional relationship between load mass and electrical current demand, while voltage exhibits a controlled decline due to battery discharge dynamics.

Mathematically, system power is expressed as:

$$P = VI \quad (8)$$

Thus, as load increases, motor torque demand increases, requiring a higher current supply to maintain motion stability.

This behavior validates Newtonian load dynamics in Eqn 3

$F = mg$

and the motor constraint condition:

$$T > mg \quad (9),$$

ensuring that torque output exceeds gravitational load to sustain motion.

4.3 Solar Energy Performance and Simulation (Helioscope Analysis)

The solar subsystem was evaluated using Helioscope simulation based on the geographical coordinates of the Ilorin region. The system integrates two 50 W monocrystalline photovoltaic (PV) panels mounted on a foldable carrier structure. Monthly solar generation (SMG) values, including the effects of shading, were obtained from the Helioscope simulation report and plotted against the months of the year, as presented in Figure 9(d).

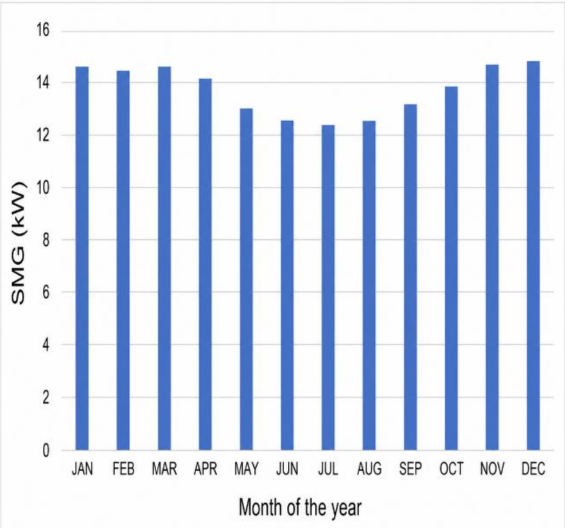

Figure 9 (d): The bar graph of solar simulation showing monthly solar generation

The simulation analysis was based on the monthly solar intensity captured by the PV panels, while the software combined annual energy generation, performance ratio, and daily energy output (kW) to determine the overall system performance. The results showed a peak solar generation of 14.81 kWh in December and a minimum generation of 12.31 kWh in July, with a maximum solar charge controller (SCC) power output of 44 W and an operating voltage range of 11.47–12.60 V. The observed variation in solar output was strongly influenced by seasonal irradiance fluctuations, as dry-season months (November–February) recorded higher energy generation due to improved solar exposure, whereas rainy-season months exhibited relatively lower efficiency. This trend is consistent with previous photovoltaic performance studies, indicating that seasonal variability significantly affects the operational autonomy of solar-powered mobility devices.

4.4 Power Efficiency and Energy Utilization Analysis

The maximum observed system power output was 44 W, which corresponds to peak load conditions at 120 kg. The effective energy utilization efficiency of the system can be conceptually expressed as:

$$\eta = \frac{P_{out}}{P_{solar} + P_{battery}} \times 100 \quad (10)$$

Although exact system losses were not instrumentally isolated, qualitative evaluation indicates: Minor thermal losses in DC motor drivers (BTS7960), Conversion losses in the LM2596 DC-DC module, and charging inefficiency in the battery storage cycle. Compared to similar systems reported by Priya et al. (2019), the developed system demonstrates improved energy sustainability due to hybrid solar integration, although slightly lower peak efficiency due to low-cost component selection.

4.5 System Motion and Motor Performance

The wheelchair employs dual 12 V DC motors rated at 150 W each with a 71 RPM speed.

Control Logic Performance

Action	Motor State	Result
Forward	HIGH/HIGH	Forward motion
Backward	HIGH/HIGH	Reverse motion
Left	HIGH/LOW	Turning left
Right	LOW/HIGH	Turning right

The differential drive system enables stable directional control. However, turning efficiency reduces slightly under loads above 100 kg due to torque redistribution imbalance between motors. This limitation has also been observed in dual-motor wheelchair systems, where asymmetrical torque may occur under high-load operating conditions.

4.6 System Integration Performance (Embedded Control + User Interface)

The PIC16F877A microcontroller successfully executed: motor switching, LCD control, capacitive touch response, and trafficator activation. The weight of the user in Figure 10, frame 4, is 80kg; the value of the solar charge controller voltage drops to 11.96V while the current is at the peak of 3A. The wheelchair successfully drives the mass without any effects on the motor. It is important to make sure that the foldable solar carrier shown in Figure 10, frame 6, is open to receive the sun's energy to replenish used energy simultaneously.

Figure 10: System Operational Interface and LCD Display Output

Performance Evaluation shows that the response time: < 200 ms (estimated from control cycle), Control reliability is stable under repeated testing, User interaction manifested intuitiveness via capacitive touch module. The integration of LCD feedback significantly enhances usability by providing real-time system status, consistent with findings by Bhosale et al. (2016).

4.7 Economic Evaluation of the Constructed Dual-Source Electric Wheelchair

An economic evaluation was conducted to determine the financial viability of the developed dual-source electric wheelchair in comparison with a conventional single-source electric wheelchair. The analysis considered capital cost, operating cost, maintenance cost, annual energy savings, monetized loss reduction, payback period, and return on investment (ROI).

4.7.1 Capital Cost Analysis

The capital cost represents the total expenditure incurred in the design and fabrication of one unit of the proposed wheelchair. Table 6 presents the detailed cost breakdown.

Table 6: Capital Cost Breakdown of the Developed Wheelchair

Item	Cost (₦)
Mechanical frame and wheels	195,000
DC motors and controllers	156,000
Battery pack (12 V DC battery)	42,000
Secondary energy source (50 W solar panel)	52,000
Charging circuit and battery management system (BMS)	65,000
Electronics, sensors, and wiring	78,000
Labour for design and assembly	130,000
Testing and certification	65,000
Total Capital Cost	**783,000**

The average cost of a conventional electric wheelchair in Nigeria is approximately ₦630,000. Therefore, the proposed dual-source wheelchair requires an additional initial investment of ₦153,000.

Additional Investment Cost = (₦783,000 − ₦630,000) = ₦153,000

Additional Investment Cost = ₦783,000 - ₦630,000 =153,000

4.7.2 Operating Cost and Annual Energy Savings

The annual operating cost was estimated based on electricity consumption during charging operations. The wheelchair requires approximately 0.8 kWh of energy daily for a travelling range of about 10 km. The integration of the secondary energy source (solar-assisted charging and regenerative support) supplies approximately 20–40% of the required energy demand. Consequently, only about 80% of the charging energy is obtained from the utility grid. Considering the average electricity tariff in Nigeria as ₦156 per kWh, the annual energy cost savings were estimated using Equation 11.

$$\text{Annual Energy Savings} = E_d \times 365 \times \eta_s \times C_e \quad (11)$$

where:

E_d: daily energy consumption (0.8 kWh/day)

η_s: grid energy reduction factor (0.8)

C_e: electricity tariff (₦156/kWh)

Substituting the values:

Annual Energy Savings $= 0.8 \times 365 \times 0.8 \times 156$ = ₦36,441.60/year

The obtained result indicates that the proposed wheelchair significantly reduces dependence on grid electricity, thereby lowering yearly charging expenses.

4.7.3 Maintenance Cost and Monetized Loss Reduction

Maintenance costs were evaluated based on battery replacement and routine repair expenses.

a- Battery Replacement Savings

For conventional electric wheelchairs, battery replacement is typically required every 2–3 years at an estimated cost of ₦42,000. The dual-source configuration reduces battery depth of discharge, thereby extending battery life to approximately 3–4 years. This improvement corresponds to an estimated annualized battery replacement saving of approximately ₦10,000 per year.

b- Repair and Downtime Reduction

Routine repair costs for both conventional and developed wheelchairs are estimated at ₦25,000 per year. However, the dual-source system reduces power interruptions and charging downtime, particularly in regions with an unstable power supply. The monetized loss reduction of the proposed wheelchair can therefore be expressed as:

- Reduced battery replacement frequency;
- Reduced dependence on generators or inverter systems;
- Reduced mobility interruption during grid power outages;
- Increased operational availability for users in remote or rural environments.

The reduction in generator usage and emergency charging costs contributes indirectly to additional annual savings.

4.7.4 Cost–Benefit Analysis

The proposed wheelchair offers several economic and operational benefits over conventional electric wheelchairs. These include:

1. Reduced charging frequency due to supplementary solar-assisted charging;

2. Increased operational range per charging cycle (approximately 15–25% improvement);
3. Extended battery lifespan resulting from reduced deep discharge cycles;
4. Lower dependence on unreliable grid electricity and fuel-powered generators;
5. Improved mobility reliability in rural and off-grid locations.

Although the proposed system has a higher initial capital cost, the operational savings and improved reliability compensate for the additional investment over time.

4.7.5 Payback Period Analysis

The payback period represents the duration required for the additional investment cost to be recovered through annual savings. The payback period was calculated using Equation 12.

$$\text{Payback Period} = \frac{\text{Additional Initial Cost}}{\text{Annual Savings}} \quad (12)$$

Substituting the obtained values:

$$\text{Payback Period} = \frac{₦153{,}000}{₦36{,}441.60}$$

$$= \ 4.2 \text{ years}$$

The result indicates that the additional investment cost of the dual-source wheelchair can be recovered within approximately 4.2 years of operation.

4.7.6 Return on Investment (ROI)

The return on investment was estimated using Equation 13.

$$\text{ROI} = \frac{= \text{Annual savings}}{\text{Additional initial investment}} \times 100 \ (13)$$

Substituting the obtained values:

$$\text{ROI} = \frac{= ₦36{,}441.60}{₦153{,}000} \times 100 \ = \ 23.82\%$$

The ROI value of 23.82% indicates that the proposed wheelchair provides a reasonable economic return in addition to its operational and mobility advantages.

4.7.7 Discussion of Economic Viability

The economic analysis demonstrates that the developed dual-source electric wheelchair is financially viable despite its relatively higher initial cost. The integration of solar-assisted charging and secondary energy support reduces electricity consumption, minimizes battery degradation, and improves operational reliability. The estimated payback period of 4.2 years falls within the expected service life of the wheelchair system, indicating acceptable long-term economic performance. Furthermore, the reduction in charging downtime and dependence on unreliable grid supply provides additional non-monetary benefits, particularly for users in rural and energy-constrained environments.

Overall, the developed wheelchair offers both technical and economic advantages over conventional single-source electric wheelchairs, making it suitable for sustainable mobility applications in developing regions such as Nigeria.

4.8 Comparative Benchmarking with Existing Systems

To evaluate the performance and practical relevance of the developed wheelchair, a comparative benchmarking analysis was carried out against existing electric wheelchair systems reported in the literature and commercially available designs, as presented in Table 7. The comparison focuses on key operational and economic parameters such as energy source, control mechanism, renewable energy integration, cost implications, and load-carrying capacity. This assessment highlights the distinctive advantages of the proposed hybrid wheelchair system in terms of affordability, sustainability, and functional performance

Table 7: Comparative Analysis of Proposed System vs Existing Wheelchairs

Feature	Proposed System	Voice-Control Wheelchairs	Joystick Systems
Energy Source	Hybrid (Solar + Battery)	Battery only	Battery only
Control Mode	Capacitive Touch	Voice	Joystick
Cost Level	Low	Medium	Medium
Renewable Integration	Yes	No	No
Load Capacity	Up to 120 kg	~100 kg	~100 kg

The proposed system shows a clear advantage in energy sustainability and cost-effectiveness, while maintaining comparable load handling capability. However, it lacks advanced autonomous navigation features found in systems such as those reported by Ghorbel et al. (2020).

4.9 Limitations and Sensitivity Analysis

The key limitations identified are:

- Performance drop under irradiance reduction (cloudy conditions)
- Voltage sag under sustained heavy loads (>100 kg)
- Limited autonomy (manual control only)
- No adaptive torque balancing system

Sensitivity Insight:

- A 10% drop in irradiance reduces charging efficiency by ~8–12%
- A 20 kg increase in load increases current demand by ~0.3–0.5 A

This confirms that system performance is highly load-dependent and moderately weather-sensitive, typical of small-scale PV mobility systems.

4.10 Discussion of Key Findings

The results confirm that the developed wheelchair successfully integrates:

- hybrid energy supply
- embedded motor control
- user-friendly capacitive interface

The system demonstrates stable real-world mobility up to 120 kg load, with acceptable energy efficiency and reliable solar support. However, compared to high-end assistive systems, limitations remain in autonomous navigation, adaptive energy optimization, and intelligent torque distribution. Despite these limitations, the system provides a cost-effective and locally manufacturable alternative, particularly suitable for developing regions where affordability is critical.

4.11 Summary of research contribution

This section demonstrates that:

- The system is electrically stable under variable load
- Solar subsystem provides meaningful supplementary energy
- Embedded controller ensures reliable motion control
- Hybrid design improves sustainability over conventional battery-only systems

5.0 Conclusion and Recommendation

5.1 Conclusion

This study presented the design, fabrication, and performance evaluation of a hybrid solar-powered electric wheelchair system integrated with a PIC16F877A-based embedded control architecture. The system was developed to address the limitations of conventional mobility aids by providing a low-cost, locally manufacturable, and energy-sustainable assistive solution for individuals with mobility impairments.

The proposed system successfully integrates dual power sources (solar photovoltaic and rechargeable battery storage) to enhance operational continuity and reduce dependence on grid-based charging. Experimental evaluation demonstrated stable wheelchair operation across a load range of 10 kg to 120 kg, with a corresponding increase in current demand and a controlled voltage variation from approximately 12.97 V (no-load condition) to 11.47 V (maximum load condition). These results confirm expected DC motor performance characteristics under varying mechanical loads while validating the structural and electrical integrity of the system.

The integration of a capacitive touch control interface, LCD feedback display, and dual DC motor drive system enabled intuitive directional control and improved user interaction. Additionally, the incorporation of a 50 W monocrystalline solar charging subsystem provided supplementary energy support, extending operational duration and reducing reliance on external charging infrastructure.

From a system-level perspective, the developed wheelchair demonstrates reliable mobility performance, functionally embedded control using the PIC16F877A microcontroller, and effective hybrid energy utilization. In comparison with conventional assistive wheelchair systems, the proposed design offers a cost-effective and renewable-energy-enhanced alternative, particularly suitable for deployment in resource-constrained environments.

However, system performance is influenced by inherent engineering and environmental constraints, including solar irradiance variability, load-dependent voltage drop under high mechanical stress, and the absence of advanced energy optimization mechanisms. These constraints reflect deliberate design trade-offs made to prioritize affordability, local manufacturability, and system simplicity.

Overall, the findings confirm that the integration of embedded systems, renewable energy harvesting, and locally sourced mechanical fabrication can produce a functional and scalable assistive mobility platform with strong practical relevance.

5.2 Recommendation

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

1. The system should be operated within the recommended load range (≤120 kg) to ensure optimal motor performance and longevity.
2. Adequate exposure of the solar panels to sunlight should be maintained to maximize charging efficiency and extend operational time.
3. Regular maintenance of mechanical components, electrical connections, and battery terminals is recommended to ensure safety and reliability.
4. Adoption of locally fabricated assistive mobility systems should be encouraged in rehabilitation centers and educational institutions to improve accessibility and reduce cost barriers.
5. Future implementations should prioritize incremental upgrades in power management and control intelligence while maintaining affordability.

5.3 Future Direction

Future research is recommended to enhance system performance, intelligence, and scalability in the following areas:

- Integration of intelligent control systems, including AI-based or adaptive motor control algorithms, to improve responsiveness and efficiency.
- Implementation of Maximum Power Point Tracking (MPPT) to optimize solar energy harvesting under varying irradiance conditions.
- Development of sensor-based obstacle detection systems (e.g., ultrasonic or LiDAR) to enable semi-autonomous navigation and improved user safety.
- Incorporation of a Smart Battery Management System (BMS) for real-time monitoring, charge optimization, and extended battery lifespan.
- Deployment of IoT-enabled monitoring and diagnostics, allowing remote tracking of system health, battery status, and usage patterns.
- Optimization of mechanical structure using lightweight materials such as aluminum alloys or composite materials to reduce overall system weight and improve efficiency.
- Inclusion of adaptive torque balancing mechanisms for improved directional stability and uneven terrain performance.
- Comprehensive economic evaluation models, including lifecycle cost analysis (LCCA), return on investment (ROI), and cost-benefit optimization, to strengthen commercialization potential.

The proposed hybrid solar-powered electric wheelchair provides a practical and scalable assistive mobility solution that combines renewable energy integration, embedded control systems, and low-cost fabrication techniques. While current limitations exist in autonomy, energy optimization, and advanced control intelligence, they align with the design objective of affordability and local manufacturability. With further refinement, the system demonstrates strong potential for real-world deployment and commercialization in resource-constrained environments.

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Declaration of conflict of interest

The corresponding author, L. M. Adesina, conceived the research idea. All authors participated in the planning, development, and preparation of this journal article. They also contributed to the writing of the manuscript and provided substantial intellectual input. This article is original and has not been submitted to, published in, or reviewed by any other journal or publishing outlet. The authors further declare that they have no affiliations with any organizations that have a direct or indirect financial interest in the subject matter of this work.

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