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Solar-powered multi-port phone charging for rural energy access in Uganda

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Abstract

Reliable mobile-phone charging remains a critical but under-addressed energy-access need in off-grid rural communities, where mobile devices support communication, mobile money, trade, education, health information, and emergency response. This study designed, constructed, and evaluated a low-cost solar-powered multi-port phone charging system intended for rural energy access in Uganda. The prototype integrated a 17 W monocrystalline photovoltaic module, a 12 V/12 Ah deep-cycle lead-acid battery, a 12/24 V MPPT charge controller, DC-DC buck conversion, and five regulated 5 V USB charging outputs. System sizing was based on estimated daily phone-charging demand, photovoltaic energy yield, storage capacity, and simultaneous charging requirements. Under an assumed six peak-sun-hour operating condition, the PV module produced an estimated 102 Wh/day, while the battery provided 144 Wh of stored energy for use during low-sunlight periods or nighttime operation. Prototype testing showed that a feature phone reached approximately 50% charge within one hour, while a smartphone reached approximately 25% within the same period, corresponding to estimated full-charge times of about two hours and four hours, respectively. The system supported simultaneous multi-device charging and demonstrated capacity for approximately 10 feature-phone-equivalent charges per day under favorable sunlight. These findings indicate that a compact, locally adaptable solar charging architecture can provide a practical and scalable solution for improving mobile connectivity in off-grid rural communities. Further field validation across seasonal weather conditions, diverse phone models, and community-use scenarios is recommended to assess long-term durability, user acceptance, and cost-effectiveness.

Nomenclature and units

Symbol/Abbreviation	Description
P_{PV}	Photovoltaic panel power rating
E_{PV}	Daily photovoltaic energy generation
V_{PV}	Photovoltaic panel voltage
I_{PV}	Photovoltaic panel current
V_{OC}	Open-circuit voltage of PV module

1.0 Introduction

Reliable access to electricity remains one of the most persistent barriers to inclusive socioeconomic development in rural Uganda. Although mobile-phone penetration has expanded rapidly across rural communities, electricity access has not increased at the same pace. This mismatch has created a practical energy-access problem: mobile phones have become essential infrastructure for communication, mobile money, small-scale trade, agricultural coordination, education, transport, health information, and emergency response, yet many users still lack dependable charging options. In such settings, mobile phones are not merely personal consumer devices; they function as digital access points linking rural households to markets, services, institutions, and social networks. Consequently, the inability to charge phones reliably can deepen information exclusion, increase transaction costs, and reduce participation in digitally mediated rural livelihoods (Zamora, 2016; Okubanjo et al., 2022).

Solar photovoltaic technology offers a promising pathway for addressing this gap because it can provide decentralized electricity in locations where grid extension is technically difficult, economically unattractive, or unreliable. Uganda's relatively favorable solar-resource conditions and low levels of household electricity access make small-scale PV systems particularly relevant for off-grid and weak-grid communities (Aarakit et al., 2021; González-García et al., 2022). Solar-powered charging systems can reduce dependence on diesel generators, long-distance travel to trading centers, and fee-based charging services that impose recurring costs on low-income users. However, the effectiveness of such systems depends not only on the availability of sunlight but also on appropriate system sizing, energy storage, charge regulation, output stability, affordability, maintainability, and compatibility with the charging needs of multiple phone users.

Existing phone-charging options in many rural areas remain constrained by distance, cost, low capacity, slow charging, unreliable power supply, and limited energy storage. Household-scale solar chargers are often designed for individual use and may not provide sufficient output for multiple users. Commercial charging points may be inaccessible, costly, or dependent on unstable grid electricity or fuel-based generators. Small portable solar chargers can be useful in some contexts but are frequently limited by small panel ratings, weak storage capacity, poor voltage regulation, and reduced performance during cloudy or rainy conditions. These limitations reduce their suitability for community-level rural charging demand, especially where multiple users require charging throughout the day and during periods of low solar availability (Okubanjo et al., 2022; Kunatsa et al., 2024).

The technical challenge, therefore, is not simply to provide a solar charger, but to develop a low-cost, locally adaptable, multi-port charging architecture that integrates photovoltaic generation, battery storage, charge-control protection, regulated DC output, and practical multi-device performance. Although solar phone chargers, kiosks, solar home systems, and PV mini-grid models have been reported in rural energy-access literature, there remains limited field-oriented design evidence for compact, locally constructible systems specifically optimized for multi-phone charging under rural Ugandan conditions (Cartland et al., 2022; González-García et al., 2022). In particular, more applied evidence is needed on how modestly rated PV modules, affordable battery storage, DC-DC buck conversion, and regulated USB outputs can be combined into a functional prototype capable of supporting simultaneous charging while remaining affordable and maintainable.This study addresses that gap by designing, constructing, and evaluating a low-cost solar-powered multi-port phone charging system for rural energy access in Uganda. The prototype integrates a 17 W monocrystalline photovoltaic panel, a 12 V/12 Ah deep-cycle lead-acid battery, a 12/24 V MPPT charge controller, DC-DC buck conversion, and five regulated 5 V USB charging outputs. The system was sized using estimated daily phone-charging demand, solar energy production, battery storage capacity, and output power requirements. Its practical performance was assessed through prototype testing involving simultaneous charging of a feature phone and a smartphone.

The aim of the study was to develop and evaluate a locally buildable solar-powered multi-port mobile phone charging station suitable for off-grid rural communities. Specifically, the study sought to: design and size a PV-based charging system capable of supporting multiple phones; construct a working prototype using accessible and cost-conscious components; evaluate solar generation, battery storage adequacy, regulated USB output, and phone charging performance; and assess the prototype's suitability for rural deployment in terms of reliability, affordability, maintainability, and scalability. As shown in Figure 1, the study frames mobile-phone charging as a targeted rural energy-service need rather than as a minor accessory function of household electrification.

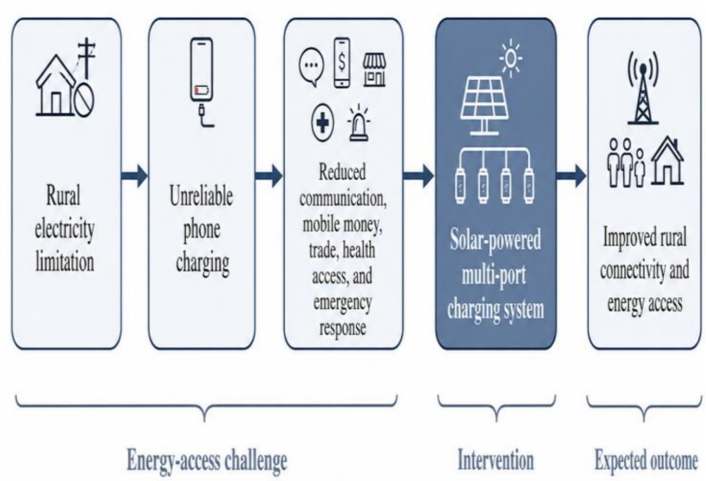


Figure 1. Conceptual framework of solar-powered multi-port phone charging as a rural energy-access intervention. This framework shows how limited grid electricity constrains mobile-phone use in rural communities and how a decentralized PV-battery charging system can reduce charging distance, cost, and service unreliability while strengthening communication, mobile money access, trade coordination, health information, and emergency response.

The main contribution of this work is the development of a practical, low-cost solar charging architecture that is directly aligned with rural Ugandan energy-access constraints. Rather than treating phone charging as a minor auxiliary function of household solar systems, this study positions multi-port phone charging as a distinct rural energy-service need. The contribution lies in integrating system sizing, component selection, storage buffering, regulated multi-port DC output, and prototype-level performance validation into a compact design that can support community-level mobile connectivity. By doing so, the study provides applied engineering evidence for a scalable renewable-energy solution that can reduce charging inconvenience, lower recurring energy costs, and strengthen digital inclusion in off-grid rural communities.

2.0 Materials and Methods

2.1 Study Design

This study adopted an applied engineering design, construction, and performance-evaluation approach. The work was structured around four sequential stages: system sizing, component selection, prototype construction, and functional testing. The objective was to develop a low-cost solar-powered multi-port phone charging system capable of providing regulated USB charging for multiple mobile phones in off-grid rural communities. The design prioritized affordability, local component availability, ease of assembly, maintainability, storage adequacy, and practical reliability under rural-use conditions (Okubanjo et al., 2022).

2.2 Prototype Architecture

The prototype was designed as a stand-alone photovoltaic charging system that converts solar energy into regulated DC output for mobile-phone charging. The system architecture consisted of six functional units: solar energy harvesting, charge regulation, battery storage, voltage conversion, multi-port output distribution, and mobile-phone loading. The energy flow followed the sequence:

Solar PV panel → MPPT charge controller → 12 V battery storage → DC-DC buck converter → multiple USB charging ports → mobile-phone loads

The photovoltaic panel generated DC electricity from incident solar radiation. The MPPT charge controller regulated the transfer of energy from the panel to the battery while protecting the storage unit from overcharging and reverse current. The battery stored excess energy for use during periods of low solar irradiance or nighttime operation. A DC-DC buck converter stepped the 12 V battery output down to a regulated 5 V DC output suitable for USB charging. The regulated output was distributed across five USB ports to enable simultaneous charging of multiple mobile phones. The prototype was designed as a stand-alone PV-battery-DC charging system, with energy flowing from the solar module to regulated USB outputs through charge-control, storage, and voltage-conversion stages (Figure 2).

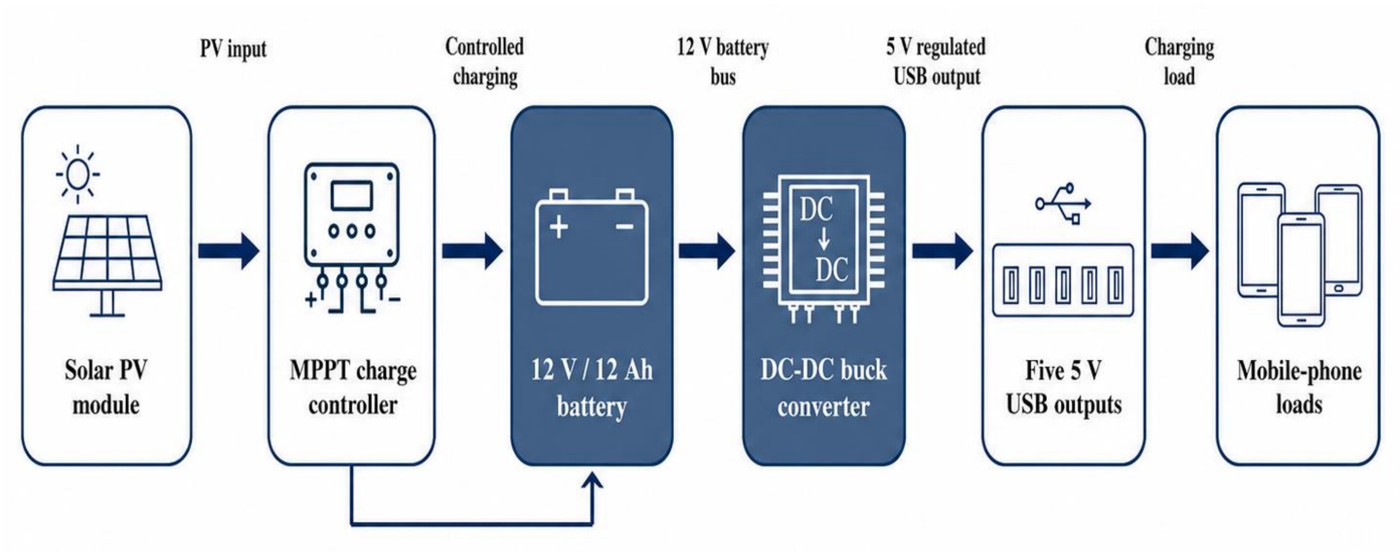


Figure 2. System architecture and energy-flow pathway of the solar-powered multi-port phone charging prototype.

The stand-alone system integrates solar energy harvesting, MPPT-based charge regulation, 12 V battery storage, DC-DC buck conversion, and five regulated USB outputs to provide simultaneous mobile-phone charging under off-grid rural conditions.

2.3 Component Selection and Justification

Components were selected based on electrical compatibility, cost, local availability, ease of replacement, and suitability for low-power rural energy applications. The selected components are summarized in Table 1.

Table 1. Main components used in the solar-powered multi-port phone charging prototype

Component	Specification	Function	Design justification
Solar PV module	17 W monocrystalline panel; open-circuit voltage, 22.32 V; short-circuit current, 1.16 A	Converts solar radiation into DC electricity	Monocrystalline PV was selected because of its relatively high efficiency, compact size, and suitability for small stand-alone systems
Charge controller	12/24 V MPPT charge controller	Regulates PV-to-battery charging and protects the battery	MPPT control improves energy harvesting under variable sunlight and protects the battery from overcharging and reverse current

Battery	12 V/12 Ah deep-cycle lead-acid battery; 144 Wh nominal storage	Stores energy for low-sunlight and nighttime charging	Lead-acid storage was selected because it is affordable, widely available, and familiar to local technicians
DC-DC buck converter	12 V DC input stepped down to 5 V DC output	Provides USB-compatible voltage regulation	Buck conversion enables safe phone charging by converting battery voltage to stable 5 V DC
USB charging outputs	Five 5 V, 1 A USB ports	Provides multi-device charging interface	Multiple USB outputs support simultaneous charging and improve community-level usability
Protective enclosure	20 cm × 10 cm × 20 cm casing	Houses and protects internal components	The enclosure protects wiring, circuits, and storage components from mechanical disturbance and environmental exposure

2.4 Energy-Demand Estimation and System Sizing

System sizing was based on the expected daily energy required to charge multiple mobile phones, the estimated solar energy generated by the PV module, and the nominal energy capacity of the storage battery. The design assumed a target load of five mobile phones per charging cycle, representing a small shared-use rural charging scenario.

For feature phones, the estimated energy required for full charging ranged from 2.96 Wh to 5.55 Wh per device. Therefore, the daily energy demand for five feature phones was calculated as:

Minimum demand = 2.96 Wh $\times$ 5 = 14.8 Wh/day

Maximum demand = 5.55 Wh $\times$ 5 = 27.75 Wh/day

For smartphones, the estimated energy required for full charging ranged from 7.4 Wh to 18.5 Wh per device. Therefore, the daily energy demand for five smartphones was calculated as:

Minimum demand = 7.4 Wh $\times$ 5 = 37 Wh/day

Maximum demand = 18.5 Wh $\times$ 5 = 92.5 Wh/day

The solar panel was rated at 17 W. Assuming six peak sun hours per day, the theoretical daily energy generation was estimated as:

PV energy generation = 17 W $\times$ 6 h = 102 Wh/day

The battery capacity was calculated from its voltage and ampere-hour rating:

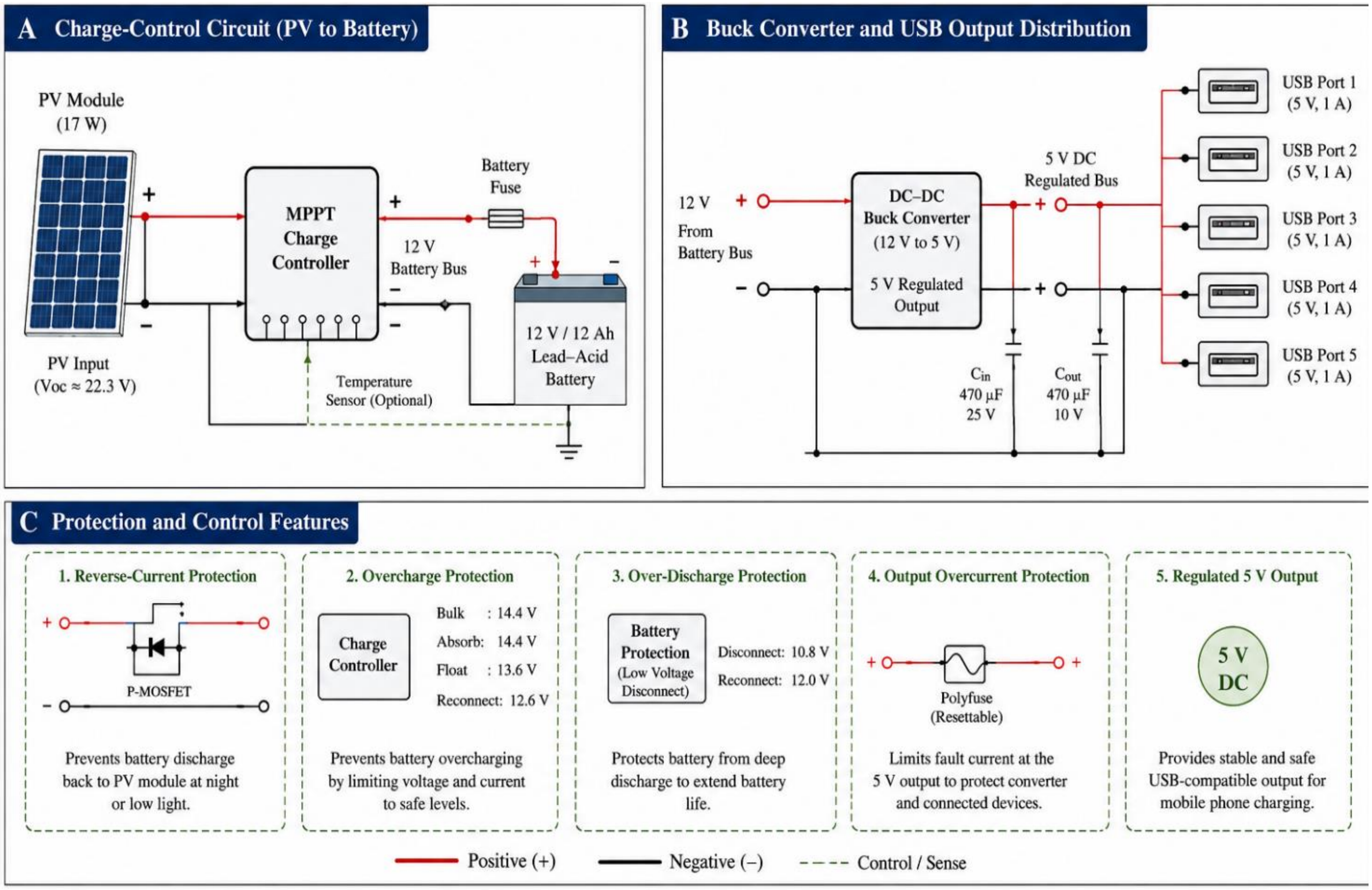
Battery storage = 12 V $\times$ 12 Ah = 144 Wh

This energy balance indicates that, under favorable sunlight, the 17 W PV module can theoretically meet the estimated daily demand for five smartphones, while the 144 Wh battery provides additional storage for periods of low solar availability. The battery capacity also provides a buffer for feature-phone-dominant use, where daily energy demand is substantially lower.

2.5 Circuit Design and Operating Principle

The circuit was designed to ensure controlled energy transfer, stable voltage regulation, and safe multi-device charging. The electrical operation was organized into three main stages: charge control, voltage conversion, and USB output distribution. The circuit design provided three essential control functions: safe battery charging, protection against reverse current and voltage instability, and conversion of the 12 V battery output to USB-compatible 5 V DC charging outputs (**Figure 3**)

Figure 3. Circuit-level configuration of charge regulation, storage protection, and USB output conversion.



The circuit integrates PV-to-battery charge control, reverse-current protection, battery buffering, DC-DC voltage step-down, and regulated 5 V USB distribution to enable safe and stable multi-device charging.

2.5.1 Charge Controller Operation

The charge controller regulated the voltage and current supplied from the PV module to the battery. Its primary function was to protect the battery from overcharging, reverse current flow, and unsafe voltage fluctuations. During periods of sufficient sunlight, the controller allowed energy from the PV module to charge the battery. When the battery approached its upper charging threshold, the controller reduced or interrupted the charging current to prevent overcharging. During low-light or nighttime conditions, reverse-current protection prevented stored battery energy from flowing back into the solar panel. This control stage was essential for improving battery safety, extending battery life, and maintaining system reliability.

2.5.2 DC-DC Buck Conversion

The battery delivered a nominal 12 V DC output, which is unsuitable for direct USB charging. Therefore, a DC-DC buck converter was used to step the battery voltage down to a regulated 5 V DC output. This conversion stage enabled compatibility with standard mobile-phone charging requirements. Voltage regulation was necessary to prevent under-voltage, over-voltage, unstable charging, or potential damage to connected phones.

2.5.3 Multi-Port USB Output Arrangement

The regulated 5 V DC output was distributed across five USB ports, each rated at 5 V and 1 A. This arrangement enabled simultaneous charging of multiple devices. The multi-port output configuration was designed to improve practical usability in shared rural settings, where several users may require charging access at the same time. Current distribution across the output ports was arranged to maintain stable charging while reducing the risk of overload at any single output point.

2.6 Prototype Construction and Assembly

The prototype was assembled by integrating the PV module, charge controller, battery, buck converter, USB output board, wiring, and protective casing. The casing measured 20 cm in length, 10 cm in breadth, and 20 cm in height, providing sufficient internal space for the circuit board, battery, and wiring layout. The circuit board was mounted securely inside the enclosure to reduce vibration and prevent loose electrical contact during operation.

The annotated prototype layout shows the integration of the 17 W monocrystalline PV module, MPPT charge controller, 12 V/12 Ah lead-acid battery, DC-DC buck conversion stage, five USB charging ports, and protective enclosure used for compactrural deployment.

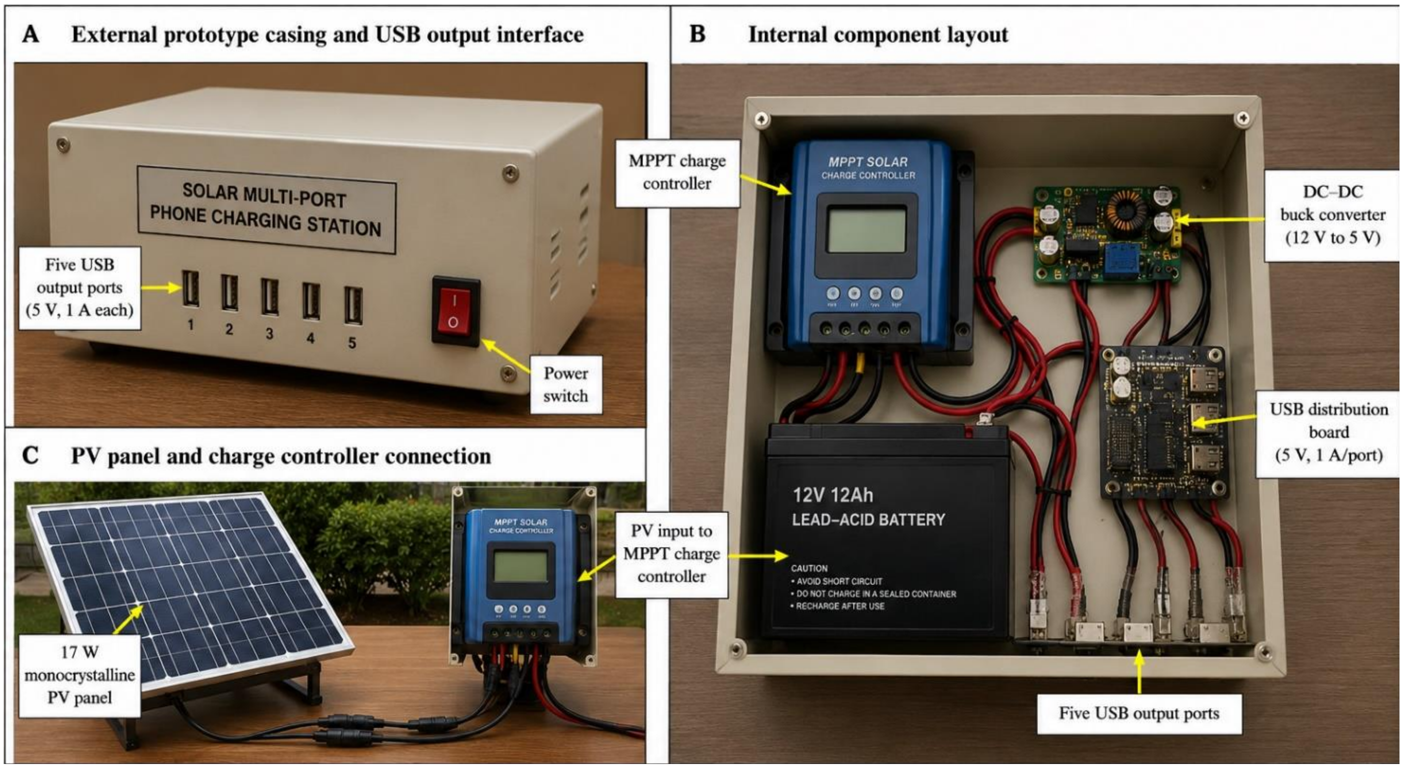


Figure 4. Hardware configuration of the constructed solar-powered multi-port phone charging prototype.

The battery was positioned firmly within the casing to prevent movement during handling or transport. Electrical connections were checked for correct polarity, secure contact, and continuity. Proper grounding and insulated wiring were applied to reduce the risk of short circuits. The USB output ports were positioned for user accessibility, while the internal wiring was arranged to minimize mechanical stress and accidental disconnection. The enclosure provided physical protection for the electrical components and improved the suitability of the prototype for rural-use conditions. The constructed system used a compact enclosed layout to protect the battery, wiring, converter circuit, and USB outputs while maintaining user accessibility for multi-device charging (Figure 4).

2.7 Testing Protocol

Prototype testing was conducted to evaluate charging functionality, battery-supported operation, simultaneous charging capability, and practical charging performance. The testing procedure involved four main stages.

First, the system was placed under direct sunlight to allow the PV module to charge the battery through the MPPT charge controller. Battery charging was observed until the storage unit reached full charge. This test assessed whether the PV module and charge controller could supply sufficient energy to restore the battery under daylight conditions.

Second, the solar panel was disconnected after the battery had been charged. This battery-only test was used to evaluate whether the stored energy could support mobile-phone charging without direct solar input. This stage simulated evening, nighttime, or cloudy-period operation.

Third, simultaneous charging was tested using two phone types: a feature phone and a smartphone. Both devices were connected to the USB outputs at the same time. Their charging progress was recorded after one hour to assess practical charging speed under shared-output conditions.

Fourth, the estimated full-charge time was derived from the observed one-hour charging performance. Functional stability across the USB outputs was assessed by observing whether the connected phones charged continuously without interruption, abnormal heating, or visible output instability.

2.8 Performance Indicators

The prototype was evaluated using technical and practical performance indicators relevant to rural deployment. The main indicators were:

1. **Estimated daily PV energy generation:** calculated from PV module rating and assumed peak sun hours.
2. **Battery storage capacity:** calculated from the nominal voltage and ampere-hour rating of the battery.
3. **Energy-demand coverage:** assessed by comparing estimated phone-charging demand with PV generation and battery storage.
4. **Simultaneous charging capability:** assessed by the number of USB ports and the system's ability to charge more than one phone at the same time.
5. **Charging time:** estimated separately for feature-phone and smartphone charging.
6. **Output suitability:** assessed based on the regulated 5 V USB output required for mobile-phone charging.
7. **Battery-only reliability:** assessed by testing phone charging after disconnecting the PV panel.
8. **Rural deployment suitability:** assessed qualitatively based on affordability, local component availability, ease of maintenance, enclosure protection, and scalability.

This methodological framework allowed the prototype to be evaluated not only as an electrical circuit but also as a rural energy-access solution designed for practical use in off-grid communities.

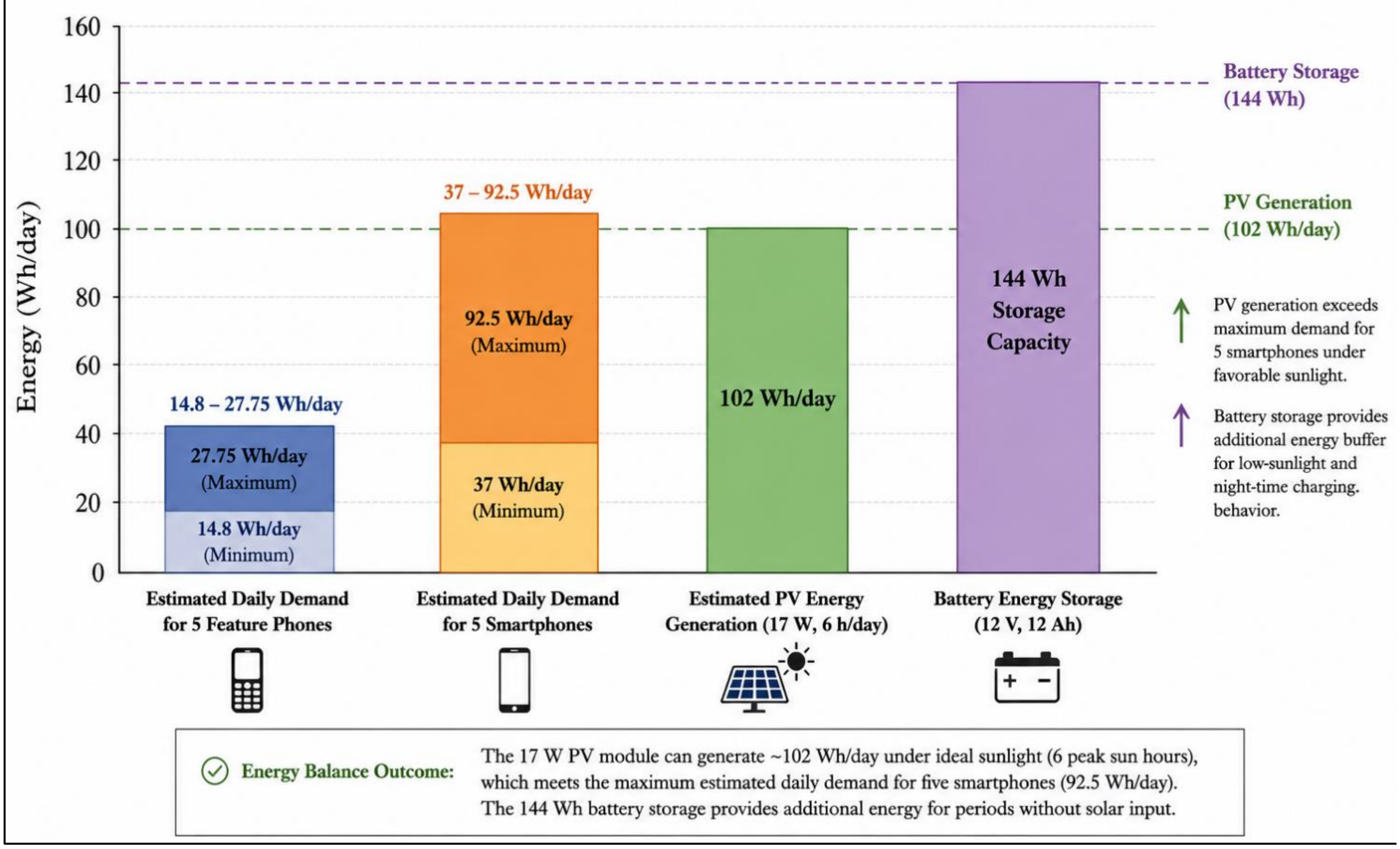
3.0 Results and Discussions

3.1 Results

3.1.1 Prototype Configuration

The completed prototype was configured as a stand-alone solar-powered multi-port phone charging system for off-grid use. The system consisted of a 17 W monocrystalline solar photovoltaic module, a 12/24 V MPPT charge controller, a 12 V/12 Ah deep-cycle lead-acid battery, DC-DC buck conversion circuitry, and five regulated USB charging outputs. This configuration is consistent with solar mobile-charging prototypes reported in the literature, where PV modules, charge controllers, batteries, voltage regulation circuits, and USB charging outlets are commonly integrated to support mobile-device charging in off-grid or public-use contexts (Udayalakshmi et al., 2018; Tran et al., 2021; Kabir et al., 2021). The photovoltaic module supplied DC power to the charge controller, which regulated battery charging and protected the storage unit from unsafe charging conditions.

Figure 5. Energy-balance comparison between estimated daily phone-charging demand, photovoltaic energy generation, and battery storage capacity.



The battery served as the energy buffer, allowing the system to continue supplying power when direct solar input was unavailable. The DC-DC buck converter stepped the 12 V battery output down to a USB-compatible 5 V output, which was distributed across the five USB ports for mobile-phone charging. The prototype was housed in a protective casing measuring 20 cm × 10 cm × 20 cm. The casing accommodated the internal circuit board, battery, wiring, and output interface, while reducing the risk of mechanical disturbance and accidental contact with live connections. The circuit board and battery were mounted securely inside the enclosure, and the USB outputs were positioned to allow user access. Similar solar charging-station studies emphasize the importance of protective housing, organized component placement, battery protection, and safe user-accessible charging outlets in practical solar-powered mobile charging systems (Udayalakshmi et al., 2018; Ali et al., 2024). The assembled configuration demonstrated the feasibility of integrating solar generation, storage, voltage regulation, and multi-device charging into a compact prototype suitable for rural deployment.

3.1.2 Energy Balance

The energy balance of the prototype was evaluated using the PV module rating, assumed peak sun hours, battery capacity, and USB output specifications. Table 2 summarizes the key design and energy parameters. The energy-balance comparison in Figure 5 shows that the estimated PV output is sufficient for the calculated daily charging demand of five smartphones under favorable sunlight, while battery storage provides additional autonomy for variable rural-use conditions. This result is comparable with previous solar-powered mobile-device charging studies in which PV generation, battery storage, and regulated DC output were assessed as key determinants of charging reliability and system usefulness (Tran et al., 2021; Kabir et al., 2021; Pangan et al., 2024).

Table 2. Energy balance and output characteristics of the prototype

Parameter	Value
PV module rating	17 W
Assumed peak sun hours	6 h/day
Estimated PV energy generation	102 Wh/day
Battery voltage	12 V
Battery capacity	12 Ah
Nominal battery storage	144 Wh
USB output per port	5 V, 1 A
Number of USB ports	5

Under six peak-sun-hour conditions, the 17 W PV module can generate approximately 102 Wh/day, exceeding the estimated maximum daily demand for five smartphones, while the 144 Wh battery provides additional storage for low-sunlight or nighttime charging.
Based on the assumed six peak sun hours per day, the 17 W PV module can generate an estimated 102 Wh/day under favorable sunlight conditions. This estimated daily generation exceeds the calculated maximum daily energy requirement for charging five smartphones, which was 92.5 Wh/day, and is substantially above the estimated requirement for five feature phones, which ranged from 14.8 to 27.75 Wh/day. The 12 V/12 Ah battery provides 144 Wh of nominal storage, offering additional autonomy for evening use, cloudy periods, or variable charging demand. This energy-balance outcome is consistent with recent solar-powered charging studies showing that compact PV modules, battery buffering, and regulated 5 V outputs can support mobile-device charging when system capacity is matched to expected load demand (Kok et al., 2024; Noer et al., 2023). These results indicate that the prototype was adequately sized for low-power multi-phone charging under favorable rural solar conditions.

3.1.3 Charging Performance

The prototype was tested after the battery had been charged using solar input. To evaluate battery-supported charging performance, the solar panel was disconnected and two mobile phones were connected simultaneously: one feature phone and one smartphone. Charging progress was recorded after one hour of operation. The results are presented in Table 3. As shown in Figure 6, the prototype delivered faster charging for the feature phone than for the smartphone, reflecting the higher battery capacity and energy demand of smartphone devices. This observation aligns with smartphone power-management literature showing that smartphone charging behavior depends on battery capacity, state of charge, charging current, charging-control algorithms, and device-specific power-management characteristics (Hoque & Tarkoma, 2016).

Table 3. Observed charging performance of the prototype

Device type	Charge gained in 1 hour	Estimated full-charge time
Feature phone	Approximately 50%	Approximately 2 h
Smartphone	Approximately 25%	Approximately 4 h

The feature phone reached approximately 50% charge after one hour, indicating an estimated full-charge time of about two hours. The smartphone reached approximately 25% charge within the same duration, corresponding to an estimated full-charge time of about four hours. These results show that the prototype provided functional and stable charging for different phone types during battery-only operation. The slower charging rate observed for the smartphone is expected because smartphones generally have larger battery capacities and higher energy demand than feature phones.

The feature phone gained approximately 50% charge within one hour, corresponding to an estimated full-charge time of about two hours, while the smartphone gained approximately 25%, corresponding to an estimated full-charge time of about four hours.

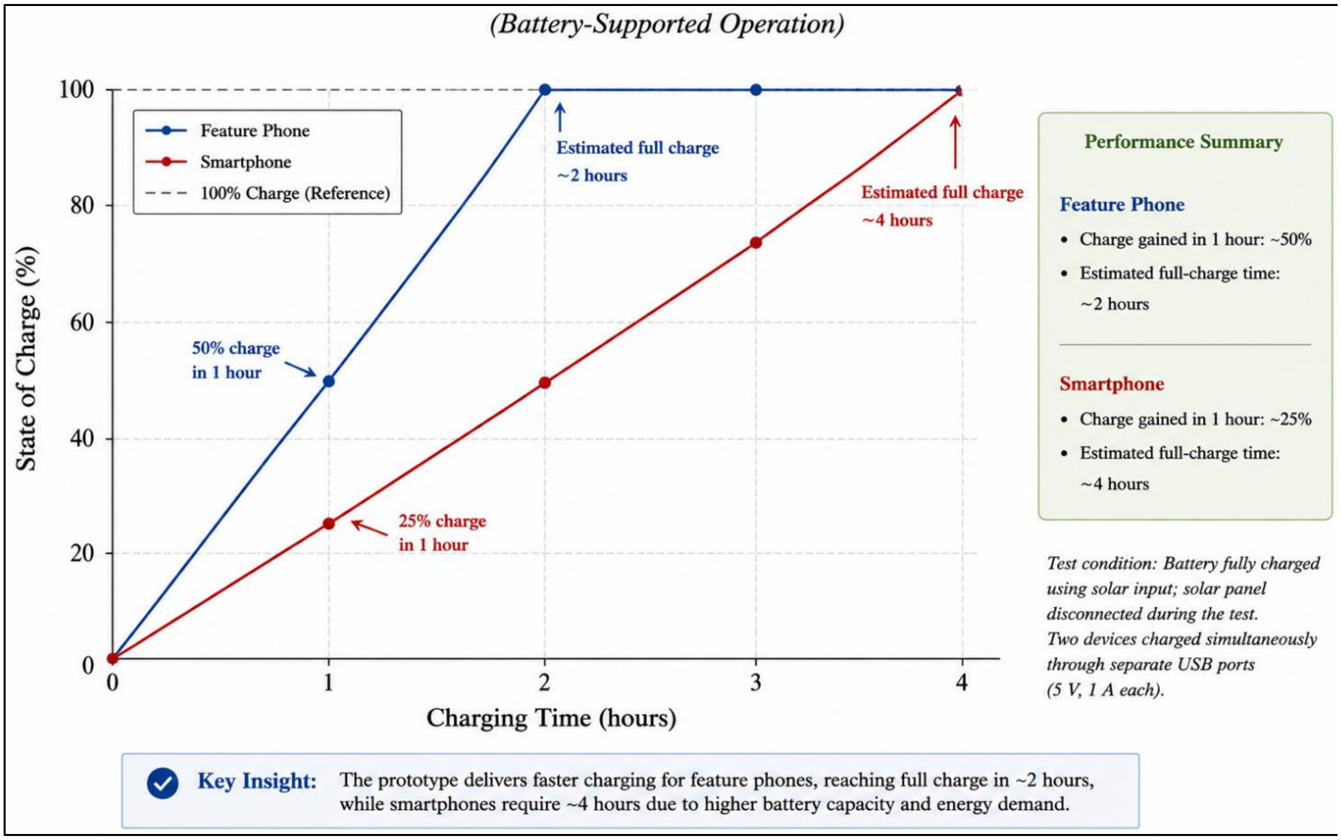


Figure 6. Prototype charging performance for feature-phone and smartphone loads during battery-supported operation.

3.1.4 Multi-Device Charging Capability

The five USB output ports enabled the prototype to support simultaneous phone charging. Each port was designed to provide a regulated 5 V, 1 A output, making the system compatible with typical mobile-phone charging requirements. This configuration is comparable to multi-output solar charging-station prototypes reported in the literature, where PV generation, storage batteries, charge-control circuits, and multiple USB outlets are integrated to support shared mobile-phone charging access (Morales et al., 2023; Ismail et al., 2019). The multi-port configuration increases the practical value of the system in rural contexts where several users may require charging access at the same time.

Based on the observed charging performance and the estimated energy balance, the system can support approximately five simultaneous devices and up to about 10 feature-phone-equivalent charges per day under favorable sunlight and battery conditions. Actual daily charging capacity will vary depending on solar irradiance, battery state of charge, phone battery capacity, depth of discharge, charging behavior, and the number of smartphones relative to feature phones. Similar PV mobile-charging studies show that charging performance is strongly affected by available solar input, storage capacity, charging current, voltage regulation, and connected load demand (Attia et al., 2014; Ismail et al., 2019). Therefore, the prototype is best interpreted as a small community-scale charging unit suitable for mixed phone-charging demand rather than as a high-capacity commercial kiosk.

3.1.5 Field-Observation-Based Comparison with Common Rural Chargers

The prototype's performance was compared qualitatively with low-efficiency solar chargers reportedly used in the researcher's village. Those existing chargers were described as having limited charging speed and low reliability, with smartphones struggling to exceed approximately 30% charge after a full day and feature phones sometimes requiring an entire day to charge fully. In contrast, the developed prototype charged a smartphone by approximately 25% in one hour and a feature phone by approximately 50% in one hour.

This comparison suggests that the prototype may offer improved practical charging performance relative to some commonly used low-capacity rural chargers. However, this finding should be interpreted cautiously because the comparison was based on field observation rather than a controlled side-by-side experimental test. Previous field and prototype-based studies emphasize that solar mobile-charging performance should be assessed using controlled measurements of irradiance, battery condition, charging current, output voltage, charging time, energy yield, and user-load conditions (Attia et al., 2014; Ismail et al., 2019; Zou et al., 2007). Future work should compare the prototype with commercially available rural solar chargers under identical irradiance, load, battery-state, and environmental conditions to quantify relative efficiency, charging time, cost per charge, and long-term reliability.

3.2. Discussion

3.2.1 Technical Performance of the Prototype

The prototype demonstrated that a modestly rated photovoltaic system can provide functional multi-phone charging when solar generation, storage capacity, voltage regulation, and output distribution are appropriately integrated. The estimated daily PV generation of 102 Wh/day was sufficient to meet the calculated charging demand for five feature phones and, under favorable sunlight, could also meet the upper estimated daily demand for five smartphones. This indicates that the system was reasonably sized for low-power rural charging applications, particularly where demand consists of a mix of feature phones and smartphones. Similar small-scale solar charging studies have shown that PV-based mobile charging systems can be technically viable when the PV module, storage unit, and regulated output circuit are matched to the intended load demand (Goudar, 2019; Fathabadi, 2016).

The inclusion of a 12 V/12 Ah battery was central to the prototype's reliability. By providing 144 Wh of nominal storage, the battery allowed the system to operate beyond periods of direct solar input. This is important for rural users because charging demand may occur in the evening, during cloudy periods, or when the solar panel is not producing sufficient instantaneous power. The battery-only test confirmed that stored energy could support mobile-phone charging after the solar panel was disconnected, demonstrating the practical value of storage buffering in off-grid operation. Battery storage has similarly been identified as a key determinant of service continuity in stand-alone PV systems, especially where solar input fluctuates and user demand does not always coincide with peak generation periods (Kaldellis et al., 2009; Chaurey & Kandpal, 2010).

The DC-DC buck conversion stage also contributed significantly to system functionality. Since the battery supplied a nominal 12 V output, direct connection to mobile phones would be unsuitable and potentially unsafe. The buck converter stepped this voltage down to a regulated 5 V USB-compatible output, enabling safe and stable phone charging. This regulated output is essential for protecting connected devices, maintaining charging continuity, and improving user confidence in the system. Prototype-based solar charger studies also emphasize that voltage regulation and power-conversion circuitry are necessary for delivering stable mobile-device charging output from variable PV and battery sources (Goudar, 2019; Mamur et al., 2016).

The multi-port design increased the community relevance of the prototype. Unlike single-user portable chargers, the five USB outputs enabled simultaneous charging and improved the system's suitability for shared rural settings. The observed charging performance, approximately 50% charge for a feature phone and 25% charge for a smartphone within one hour, suggests that the prototype can deliver meaningful charging progress within practical timeframes. The slower smartphone charging rate reflects the higher energy demand of smartphones and highlights the importance of system sizing when rural phone ownership shifts from feature phones toward more energy-intensive devices. Previous work on solar-powered charging and mobile-energy systems similarly indicates that charging rate and daily service capacity depend on battery size, output current, connected load, solar irradiance, and device energy demand (Fathabadi, 2016; Rajan et al., 2018).

3.2.2 Relevance to Rural Energy Access in Uganda

The findings are directly relevant to rural Uganda, where limited grid access and unreliable electricity constrain the everyday use of mobile phones. In many off-grid communities, users rely on trading centers, commercial charging points, generators, or low-capacity solar chargers. These options can involve travel time, waiting time, recurring charging costs, and inconsistent service availability. A locally deployable solar-powered multi-port charging system can reduce these burdens by bringing charging closer to users and allowing multiple devices to be charged from a shared renewable-energy source. Uganda-based research on mobile technologies, digital financing, and micro-solar systems shows that mobile-phone use and solar energy access are closely connected in rural and peri-urban energy markets (Kato et al., 2020).

The social value of such a system extends beyond device charging. Mobile phones support communication, mobile money, trade coordination, health information, school communication, agricultural decision-making, transport arrangements, and emergency response. Improving access to phone charging can therefore strengthen rural connectivity, reduce transaction barriers, and support livelihood activities. In this sense, the prototype should be interpreted not only as an electrical device but also as an enabling energy-access technology. Rural energy-access literature increasingly recognizes decentralized solar services as important not only for lighting, but also for communication, enterprise activity, education, health services, and broader socioeconomic participation (Chaurey & Kandpal, 2010; Parikh et al., 2024).

The use of solar PV is also appropriate for Uganda's rural energy context because it reduces dependence on fuel-based generators and weak grid infrastructure. By combining PV generation with battery storage, the system provides a decentralized solution that can operate independently of the national grid. This makes it particularly suitable for households, market areas, schools, health posts, transport stages, and rural micro-enterprises where small but reliable DC power services are needed. The prototype has multiple possible deployment pathways, ranging from household-level use to shared community charging points in schools, markets, health posts, and rural kiosks (Figure 7). This interpretation is consistent with wider off-grid PV literature showing that decentralized solar systems can support basic electricity services in resource-constrained communities when technical design, affordability, maintenance, and local demand are considered together (Chaurey & Kandpal, 2010; Kato et al., 2020; Parikh et al., 2024).

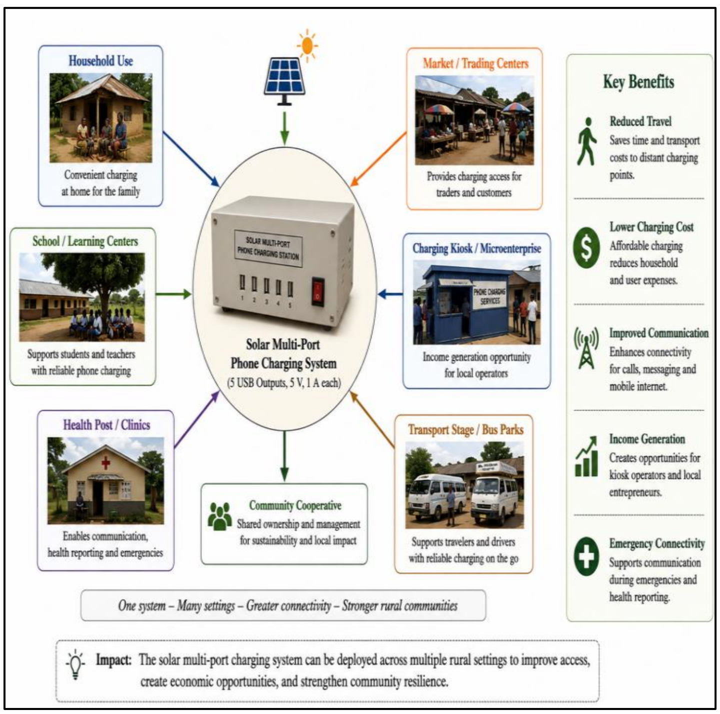


Figure 7. Potential rural deployment pathways for solar-powered multi-port phone charging in Uganda. The system can be adapted for household use, school-based charging, health-post communication support, market kiosks, transport-stage charging, or community cooperative models, depending on local demand, ownership structure, and maintenance capacity.

3.2.3 Design Strengths

A major strength of the prototype is its low-cost and locally adaptable architecture. The system uses components that are widely recognizable in small-scale solar applications, including a monocrystalline PV module, MPPT charge controller, lead-acid battery, buck converter, and USB outputs. This improves the likelihood that the system can be assembled, repaired, or modified by technicians familiar with basic solar installations and DC wiring. Studies on rural solar home systems and village-level PV systems show that technical simplicity, local maintainability, and user-accessible service models are important factors in sustaining rural solar energy interventions (Gustavsson & Ellegård, 2004; Ulsrud et al., 2015).

The use of multiple USB ports is another important design strength. It shifts the system from an individual charging device to a shared-use rural energy service. This is important because the main challenge in many rural settings is not only access to electricity, but access to charging capacity that can serve several users within a reasonable time. The multi-port arrangement increases throughput and improves the system's relevance for community-level use. This shared-service logic is consistent with village-scale solar and mini-grid studies, which emphasize that community-level systems can improve access where individual household systems are unaffordable or technically limited (Eder et al., 2015; Ulsrud et al., 2015).

Battery backup further strengthens the design by allowing charging outside direct sunlight hours. In rural settings, users may not always be available to charge phones during peak sunlight periods. Storage therefore improves flexibility and makes the system more responsive to actual user behavior. The protective casing, secure component mounting, and basic safety precautions also support practical deployment by reducing risks associated with loose wiring, mechanical vibration, accidental short circuits, and component exposure. Field assessments of rural PV systems have shown that batteries, charge controllers, wiring quality, and component protection strongly influence reliability and maintenance outcomes in stand-alone solar applications (Dunlop & Farhi, 2001; Carrasco et al., 2014).

The design is also scalable. Larger PV modules, higher-capacity batteries, additional USB outputs, or modular parallel units could be introduced depending on the intended deployment setting. A household version could prioritize affordability and compactness, while a kiosk or community version could prioritize throughput, monitoring, and durability. The scalability of decentralized PV systems has been widely recognized in rural electrification literature because PV systems can be adapted to different load sizes, ownership models, and service levels (Gustavsson & Ellegård, 2004; Eder et al., 2015; Ulsrud et al., 2015).

3.2.4 Design Limitations

Despite its promising performance, the study has several limitations that should be acknowledged. First, the prototype was tested using a limited number of mobile phones. Although the selected feature phone and smartphone provided useful early performance evidence, broader testing across different phone brands, battery capacities, charging protocols, and states of charge would be needed to establish generalizable charging performance. Previous field-performance studies of stand-alone PV systems emphasize that broader testing under different load profiles and operating conditions is necessary before drawing strong conclusions about system reliability and service capacity (Dunlop & Farhi, 2001; Carrasco et al., 2014).

Second, long-term durability was not assessed. The prototype was evaluated at the functional testing stage, but the effects of repeated charge-discharge cycles, prolonged outdoor exposure, dust accumulation, humidity, heat, vibration, and user handling were not systematically measured. These factors are important because rural deployment conditions can significantly affect system reliability and maintenance needs. Long-term assessments of rural PV systems show that outdoor exposure, component quality, battery performance, and maintenance practices can strongly influence system lifetime and user satisfaction (Carrasco et al., 2014; Gustavsson & Ellegård, 2004).

Third, battery degradation was not evaluated over multiple cycles. The lead-acid battery was selected for affordability and local availability, but lead-acid storage is sensitive to depth of discharge, charging practices, temperature, and maintenance. Without long-term cycling data, it is not possible to determine battery life, replacement frequency, or life-cycle cost. Battery-focused studies in PV systems identify the battery as one of the most failure-prone and cost-sensitive components, particularly where charge-discharge behavior, temperature, and maintenance are poorly controlled (Dunlop & Farhi, 2001; Carrasco et al., 2014; Sauer & Wenzl, 2008).

Fourth, weather variability was not fully tested. The energy balance was based on an assumed six peak sun hours, and the prototype was tested under favorable sunlight conditions. Performance during cloudy days, rainy seasons, low irradiance, or partial shading may be lower. Seasonal field testing is therefore required before wider deployment recommendations can be made. PV performance literature shows that solar irradiance, module temperature, shading, and seasonal resource variation can significantly affect energy yield and system output (Skoplaki & Palyvos, 2009; Mondol et al., 2007).

Fifth, the study did not conduct a full economic analysis. Although the design was intended to be low-cost, cost per charge, payback period, maintenance cost, replacement cost, and affordability for different user groups were not quantitatively assessed. Similarly, user satisfaction, willingness to pay, community ownership preferences, and social acceptance were not formally measured. These dimensions are important for translating the prototype into a sustainable rural energy service. Rural solar studies show that affordability, payment models, service reliability, ownership structure, and user acceptance are as important as technical performance in determining long-term adoption (Gustavsson & Ellegård, 2004; Eder et al., 2015; Branker et al., 2011).

3.2.5 Implications for Design Improvement and Future Deployment

The findings point to several opportunities for technical refinement and field-scale development. Battery storage is a priority area for improvement. Although lead-acid batteries are affordable, future versions should evaluate lithium-ion or lithium iron phosphate storage because of their higher energy density, longer cycle life, deeper usable discharge, and lower maintenance requirements. The trade-off between higher upfront cost and lower life-cycle replacement cost should be assessed through techno-economic analysis. This is important because battery replacement and degradation can contribute substantially to the long-term cost of stand-alone PV systems (Sauer & Wenzl, 2008; Carrasco et al., 2014).

Increasing the PV module capacity could improve daily energy throughput and enhance performance under cloudy or high-demand conditions. A larger PV module would allow faster battery recharge, support more smartphones, and improve resilience during periods of reduced irradiance. However, PV oversizing should be balanced against cost, portability, and enclosure design. Techno-economic PV studies emphasize that PV sizing should balance capital cost, energy demand, storage capacity, reliability targets, and expected operating conditions (Branker et al., 2011; Mondol et al., 2007).

System monitoring should also be incorporated in future designs. A simple digital display showing battery state of charge, output voltage, current, and charging status would improve usability and maintenance. Such monitoring could help users avoid excessive battery discharge, identify faults early, and manage charging demand more effectively. Output voltage and current indicators would also support more rigorous performance evaluation. Monitoring is especially important in stand-alone PV systems because battery condition, charge-controller behavior, and load consumption affect reliability and maintenance decisions (Dunlop & Farhi, 2001; Carrasco et al., 2014).

The enclosure should be upgraded for weather resistance if the system is intended for outdoor or semi-outdoor use. Improved casing materials, sealed cable entry points, dust protection, ventilation, and heat management would increase durability. Thermal management is particularly important where multiple phones are charged simultaneously, because converters, wiring, and battery components may generate heat during sustained operation. PV performance studies show that temperature and environmental exposure affect solar module output, while field studies show that component protection and maintenance influence long-term system reliability (Skoplaki & Palyvos, 2009; Carrasco et al., 2014).

Finally, future work should move from prototype testing to structured field validation. The system should be evaluated across dry and rainy seasons, different rural locations, diverse phone models, and realistic user-demand patterns. Community deployment models should also be tested, including household ownership, school-based charging points, health-post charging stations, market-based kiosks, and micro-enterprise models. Combining technical performance data with user acceptance and cost-effectiveness analysis would provide stronger evidence for scaling solar-powered multi-port phone charging as a rural energy-access solution in Uganda. This combined technical and socio-economic validation approach is consistent with rural electrification literature, which shows that successful decentralized solar systems require reliable engineering performance, suitable ownership models, affordable tariffs, local maintenance capacity, and user acceptance (Gustavsson & Ellegård, 2004; Eder et al., 2015; Ulsrud et al., 2015).

4.0 Conclusions

This study designed, constructed, and evaluated a low-cost solar-powered multi-port phone charging system for rural energy access in Uganda. The prototype integrated a 17 W monocrystalline photovoltaic panel, a 12/24 V MPPT charge controller, a 12 V/12 Ah lead-acid battery, DC-DC buck conversion, and five regulated 5 V USB charging outputs. The system was developed to address a specific rural energy-service need: reliable mobile-phone charging in off-grid communities where phones support communication, mobile money, trade, education, health information, transport coordination, and emergency response.

The energy-balance analysis showed that the 17 W PV module could generate approximately 102 Wh/day under favorable six peak-sun-hour conditions, while the 12 V/12 Ah battery provided 144 Wh of nominal storage. This storage capacity allowed charging to continue when direct solar input was unavailable, improving the system's usefulness during cloudy periods, evening hours, and battery-supported operation. The estimated daily PV output was sufficient to meet the calculated energy requirement for five feature phones and could theoretically support five smartphones under favorable sunlight conditions.

Prototype testing confirmed the functional viability of the system. During battery-supported operation, a feature phone reached approximately 50% charge within one hour, while a smartphone reached approximately 25% charge within the same period. These results correspond to estimated full-charge times of approximately two hours for a feature phone and four hours for a smartphone. The five-port USB configuration also demonstrated the practical potential of the system for shared rural use, where multiple users may require charging access at the same time.

Overall, the findings suggest that a compact, affordable, and locally adaptable solar-powered multi-port charging system can contribute to rural energy access by reducing dependence on distant charging points, lowering recurring charging burdens, and improving mobile connectivity in off-grid communities. The system is best interpreted as a small-scale community energy-access prototype rather than a fully optimized commercial charging kiosk. Its contribution lies in demonstrating how modest PV capacity, battery storage, charge control, regulated DC conversion, and multi-port output can be integrated into a practical rural charging solution.

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Declaration of conflict of interest

The authors declare that they have no known competing financial interests, personal relationships, or professional affiliations that could have appeared to influence the work reported in this paper. The research was conducted independently, and all findings, analyses, and conclusions presented in this study are solely those of the authors.

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