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Design, Performance, and Economic Implication of Solar Powered Smart Power Box

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Abstract

This paper (Design, Performance, and Economic Implications of a Solar Powered Smart Power Box) was inspired by the fact that the power outage in Nigeria has remained a troubling phenomenon that negatively impacts communication, productivity and other economic activities at the small scale. The proposed research seeks to develop and build a small, affordable, mobile, and solar-powered smart power box that could charge mobile phones, rechargeable light/fan and power banks and assess its technical and economic applicability. The questions that are answered throughout the study are whether a simple non-microcontroller based solar system can offer a reliable form of charging and whether such a system can minimize the reliance on grid electricity and commercial charging centres. Primary data were created by conducting experimental tests of a prototype system comprising of a 6V solar panel, TP4056 charging module, 3.7V lithium-ion battery and boost converter, where the performance information was recorded at different sunlight conditions during the 2024/2025 season. The quantitative analysis methods were descriptive and basic to assess the voltage stability, charging time, efficiency and operational reliability. It was found that the system provides a steady 5V output that can be used with USB, that the charging efficiency is reasonable, and that the system can be safely used in the real world. The results indicate a great economic advantage i.e. fewer expenses on energy to users, better access to power by the low-income and rural citizens and potential of small-scale entrepreneurship.

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***Related declarations are provided in the final section of this article.*

Such policy suggestions can also be the advocacy of low-cost decentralized solar technologies, the encouragement of local manufacture of renewable energy devices, and the inclusion of small solar solutions in the rural electrification plans. JEL Classification Codes: Q42, Q48, O13, O33.

1. 0 INTRODUCTION

Reliable, affordable and sustainable electricity is considered to be one of the basic controllers of economic growth, social development and technological development (Strielkowski et al., 2021) (Kumar & Rathore, 2023). Electricity forms a basis of nearly all the aspects of our current life, such as education, health care provision, communication, financial services and small-scale entrepreneurship (Kooijman-van Dijk & Clancy, 2010). In the less-developed nations like Nigeria, however, power is very limited because power outages are several, electrical generation is insufficient, transmission networks are poor, and even the area of grid distribution is very limited, especially in rural and peri-urban regions (Visagie, 2008). Such hardships are important economic and social expenses on households, students and small business operators who run their engagements and lives on electricity.

The use of mobile phones and other small handheld electronics is among the most susceptible to the use of unreliable power supply (Irnich et al., 1996). The mobile phones have also become more than mere communication tools but the digital learning mediums, mobile banking, e-commerce, healthcare information and micro-enterprise mobilization tools. To several people, a mobile phone that is charged serves as a gateway to education resources, employment prospects, emergency services and even financial inclusiveness particularly to students and the low-income earners. The reliance of these devices on routine power charges, however, implies that unreliable power has a direct negative impact on productivity, continuation of learning and income-generating activities (Irnich et al., 1996).

Due to constant power cuts, majority of users have started using other sources of energy like fuel-powered generators and business phone charging centres (Armaroli & Balzani, 2011). Although these alternatives offer a short-term solution, they are linked with high economic and social costs. The cost of fuel generators is also high because there is the need to constantly spend on petrol or diesel thereby adding a lot of weight on the power energy costs of any household particularly in the presence of an escalating fuel price (Heltberg, 2003). Moreover, generators cause pollution of the environment in terms of green-house gases, noise, and toxic fumes, which are dangerous to health (Oguntoke & Adeyemi, 2017). Commercial charging centres on the contrary are very expensive in terms of recurrent costs on users and frequently takes a lot of time to move around and wait to be attended to which lowers the overall economic efficiency.

It is based on this context that renewable energy solutions specifically, solar energy have been introduced as a potential and sustainable alternative (Kabir et al., 2018). Nigeria has the benefit of having a large amount of solar radiation throughout the year, thus photovoltaic based systems are technically viable on a large portion of the country (Akuru et al., 2017). Solar energy has many advantages since it is renewable, clean, and it is getting cheap as the cost of photovoltaic panels, and other related materials continues to reduce. Small-scale solar technologies include portable solar chargers, smart power boxes, and other systems providing decentralized access to electricity that is independent of the national grid and does not require the use of fuel (Mueller et al., 2016).

Nonetheless, although the technical viability of solar charging systems has been extensively proved, their implementation, to a large extent, depends on the aspect of economics. They rarely right at the start give much thought to technical sophistication, cost-saving, payback period, and long economic advantages: a more important considerations to potential users are affordability, cost savings, payback period, and long-term economic benefit. It is critical therefore to comprehend the economic impacts of small-scale solar solutions to promote their wide use, policymaking information, and investment decisions (Wang et al., 2020).

This paper is dedicated to economic aspects of a Solar Power Smart Box that is intended to be charged using a mobile phone and other small electronic devices. (Wang et al., 2020)It determines the cost-effectiveness of the system, the possibility of minimizing household and business energy spending, and more fundamentally, socio-economic advantages, such as work to support digital inclusion, small-scale entrepreneurship, and environmental friendliness. Placing the Solar Power Smart Box in the framework of the energy poverty and energy cost escalation, the study shows how the use of simple renewable energy technologies can provide considerable economic benefits to one individual and a community.

2.0. Materials and Methods

A) Research Design

The research took the experimental research design, where a prototype solar powered Smart Power Box was designed, built and its performance assessed. The methodology was concerned with testing the technical functionality and financial feasibility of a non-microcontroller-based solar charging, under actual environmental conditions. The experimental study was implemented in 2024/2025 season at different sunlight intensities to test the reliability of the system and the stability in voltages, charging effectiveness, and the performance of the system operation.

The design fell into four significant steps:

1. System design and components choice.
2. Construction of prototypes and integration.
3. Experiment and data gathering.
4. Economic analysis and performance.

B) Materials and Components

The prototype system was designed with the help of locally available and relatively expensive parts just to be affordable and easy to reproduce. The main materials to be utilized are:

1. 6V Solar Photovoltaic

The energy harvesting unit consists of a 6V photovoltaic (PV) solar panel that transforms incident solar energy into direct current (DC) electricity using the photovoltaic effect. The decision of a 6V panel guarantees a high-voltage to recharge a lithium-ion battery appropriately and simplicity in the system. Solar power is the core source of the input, which removes the need to use electricity or fossil fuels on the grid.

Figure 1: 6V Solar Panel

2. TP4056 Lithium-Ion Charging Module

A TP4056 charging module deals with battery charging and management. This module will control the charging operation via a constant-current / constant voltage (CC/CV) to ensure the safety and life of the lithium-ion batteries are preserved. The TP4056 eliminates overcharging, overheating and exaggerating current flow allowance, as a way of decreasing the possibilities of battery degeneration and system breakdown. On the module, visual cues give simple feedback regarding the status of the charging and enhance interaction between the user, which does not add to the complexity of the system.

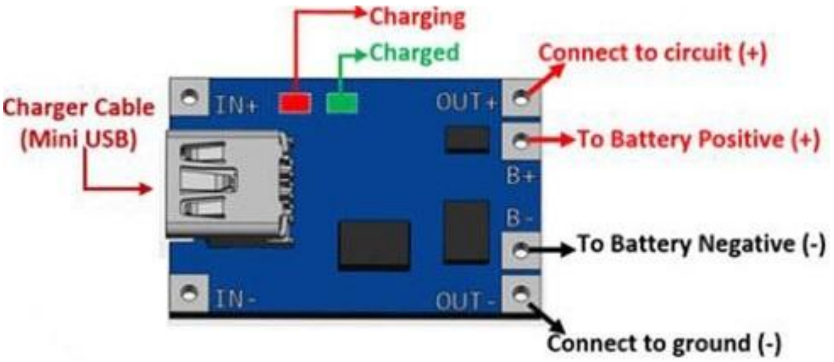

Figure 2: TP4056 Charging Module

3. 3.7V Lithium-Ion Battery

The battery also contains excess solar energy stored in the 3.7V lithium-ion battery which stores energy during the day to be utilized during dark times. The choice of lithium-ion batteries was explained by their great energy density, lightweight nature, rechargeability, as well as a high level of availability. The energy storage will make the smart box self-sufficient in provision of power in situations when there is low sunshine or even in the night, all to improve reliability and convenience of the user.

Figure 3: (3.7v Lithium-ion Battery)

4. DC-DC Boost Converter Module

A DC-DC boost converter is added to the system to supply the standard USB-powered equipment with the voltage. The battery voltage is then increased to regulated 5 V DC output by this unit to power mobile phones, power banks and other such devices. Voltage regulation is an important issue that stops the harm of the associated equipment and provides a stable performance of charging. The controlled 5 V supply is provided via a USB interface, so the system may be used with all popular charging standards.

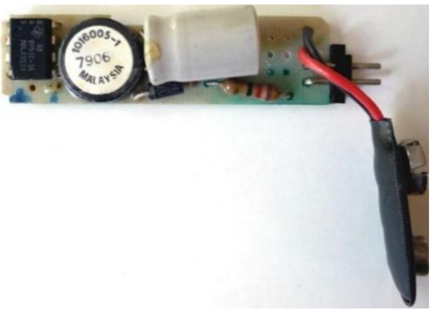

Figure 4: A DC boost converter

5. USB Output Port

It offers standardized output point where mobile phones and other small electronics can be charged.

Figure 5: USB Output Port

6. Protection Circuit

The protection circuit built in to avoid any overcharging, deep discharge and short-circuit situation.

Figure 6: Protection Circuit

7. Connecting Wires, Casing (Smart Box Enclosure), Switches, and Mounting Accessories

The choice of all the components was determined by their availability, affordability, efficiency and compatibility with low-power applications.

C) System Architecture and Circuit Configuration.

The architecture of this system is sequential model of energy flow:

(i) Solar Panel
(ii) Charging Module (TP4056)
(iii) Lithium-Ion Battery
(iv) Boost Converter
(v) USB Output

- When the solar panel has access to sunlight it forms DC voltages.
- The output of the panel is connected to the TP4056 charging component which controls the charging current and provides a safe way of charging the battery.
- The controlled energy is stored in the lithium-ion battery.
- The accumulated energy is fed to a DC-DC boost converter that raises the voltage to consist of a constant 5V.

- The controlled 5V power supply is provided through a USB on which devices can be charged.
- A digital multimeter was used to test electrical connections before the whole system was deployed to ensure that they were correctly poled, of the correct voltage level, and continuous.

This arrangement removes the use of the microcontroller, makes the system less complex and cheap, but still operational.

D) Prototype Construction

The smart power box consisted of the components joined together on a small mounting environment and encasing them in a portable casing. Correct insulation, and safe soldering methods were utilized to have a secure and safe procedure. The solar panel was directly outwardly mounted to allow it to receive more sunlight and internal modules were put in such a way that they can receive minimal energy loss and heat.

Figure 7: Solar power smart power box

E) Operational Reliability

The repeated cycles of test provided the stability of performance of the system during different days of work and different environmental conditions. It was not a disadvantage of lack of microcontroller-based control on reliability. Rather, the simplified design minimized possible failure points and helped to make the operation robust.

The built-in circuitry on protection was effective to avoid short-circuit operationalities and connect the battery to deep discharge. This increases the safety as well as the life-span. This is also due to the ease of service and fix using local technical expertise as the system architecture is simple.

Such findings indicate that the performance of low-complexity solar charging systems is reliable and can be guaranteed in case they are designed and assembled correctly.

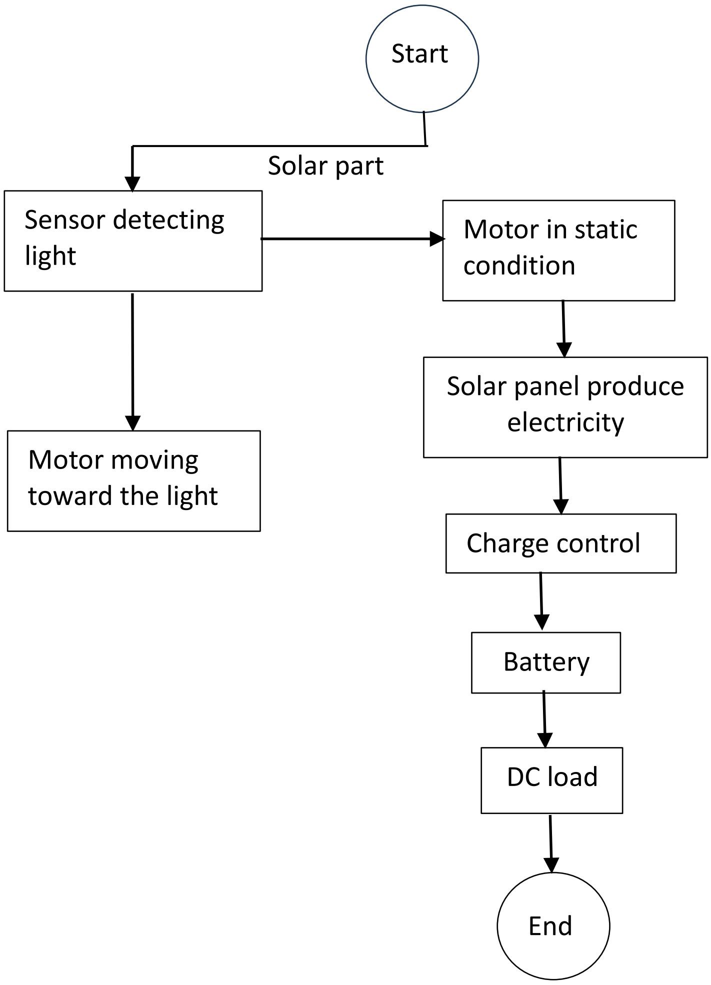

Figure 7: Flow chart

1. PERFORMANCE EVALUATION

To test the consistency and effectiveness of the system in real life scenarios, the performance testing was performed. Important parameters to be measured were the stability of output voltages of the system when subjected to different sunlight intensities, the charging time as well as system response. The digital multimeter was used to record voltage at the solar panel output, battery terminals and USB output. The process of charging tests was carried out on mobile phones and power banks that connected to the system and measured the time that mobile phones and power banks needed to reach small battery levels of charge under the varying conditions.

The stability of the system was evaluated in terms of voltage changes and thermal characteristics at long-term operation. Effectiveness of energy storage was also checked through the capacity of the battery to provide backup power when there was low or absent sunlight.

2. ECONOMIC ANALYSIS

In the economic analysis, they were able to gather data on the initial expenditure of the system components including solar panel, battery, charging module, boost converter, and enclosure. Long term cost implications were estimated by taking into account estimated component life and replacement. Potential cost saving was estimated by the number of devices charged per day to determine how much the smart box would be used.

The economic performance of Solar Power Smart Box would be compared alongside other charging alternatives that are widely applicable in Nigeria like fuel-powered generators and commercial phone charging centres. The parameters on cost were fuel used, the charges, cost on maintenance and the opportunity costs in the time. An analysis of cost-benefits framework was also used to understand net savings in the long term.

A simple payback period analysis was undertaken to find out the financial feasibility by comparing the initial investment cost with the cumulative savings computed with regard to avoided charges. This would give a precise and practical measure of the affordability and attractiveness of investment by would-be users. Combining technical and economical approaches to assessment, the paper provides a detailed analysis of the Solar Power Smart Box as a viable and economically viable energy solution i.e. sustainable energy.

3. TECHNICAL PERFORMANCE

It was tested in an experiment that the Solar Power Smart Box can provide a steady and constant output of 5V DC that can be used to charge mobile phones, power banks, and other devices that can be charged using a USB connection. In a typical sun environment, 6V photovoltaic panel was able to power everything within the essential lithium-ion battery with the help of the TP4056 charging module as well as to charge devices as needed. Voltage readings at the USB outlet demonstrated little voltage variation, which is an indication of successive voltage regulation by the boost converter.

The safety of battery and stability of the system were observed during the time it was tested. TP4056 charging module was able to regulate the charging current and charge voltage effectively and eliminate the possibility of overcharging and overheating of the lithium-ion battery. In the conditions of long-term operation, a significant accumulation of heat did not occur, which evidenced the fact that the system can be safely used during continuous operation. Moreover, the battery had the benefit of reliable backup power in case the sunlight intensity was lowered or even unavailable hence assured constant charging capabilities. These findings confirm that the smart box can be widely applied in real-life situations where there is a problem with uneven electricity supply.

4. COST ANALYSIS

The cost analysis indicated that the Solar Power Smart Box could be built at fairly low capital cost as simple components are used and those are locally available. Some of the significant cost components are the photovoltaic panel, the lithium-ion battery, the charging module, the boost converter, and the enclosure. The total system cost is relatively low enough since it can be purchased by the students, low-income families, and small business owners by not relying on the use of complex control systems and imported components.

The smart box is nearly free of charge to run once it is installed. The system does not consume fuel and the routine maintenance is minimal mostly consisting of cleaning the solar panel occasionally and replacing batteries after the service life of the battery. Compared to this, the generators that use fuel consume unending fuel cost, maintenance charges, and regular repair costs, whereas commercial charging stations accrue a recurring fee every time a generation is done. With large savings in terms of long-term energy bills by eradicating these redundant costs, the Solar Power Smart Box saves the user on a large measure of financial expenditure.

5. PAYBACK PERIOD AND SAVINGS

Economic analysis indicates that the investment, made in the Solar Power Smart Box to start with, is repaid in a comparatively short time frame by the sums saved on costs. To the users who used to rely on charged charging services or generators, the fact that this does not require them to cover daily charging fees and to buy fuel leads to immediate financial gains. When these shunned costs are tallied up at duration of time, the measure of the payback period is usually in months and not years.

The net savings provided by the smart box in the limits of the anticipated service life of the system of a number of years based on replacement periods of the battery packs. Such savings are especially substantial to the students and small business owners who are highly dependent on mobile devices in education, communication and income-generating processes. The system is also an economically viable investment that is affordable and easily cost recoverable even where the user has a limited budget.

6. GENERAL ECONOMIC IMPLICATIONS

The Solar Power Smart Box creates broader economic effects on households and communities in addition to direct savings of costs. On a household level, low spending on energy service will lead to more disposable income that can be used by users to invest in other basic needs such as education, healthcare, and food. Access to medical care and ability to afford it is also a factor to perform better in digital services, such as online learning, mobile banking, and the possibility to work remotely.

At the community level, the smart box facilitates the development of micro-enterprises whereby small-scale phone charging enterprises can be supported using the solar powered smart box. These businesses are able to run without fuel expenses and they become profitable and more sustainable. It is also possible to minimize the dependence on commercial charging centres and generators by the deployment of several smart boxes within a community, retaining financial resources in the local economy.

Regarding the environment and the health of populations, the decline in the use of fuel-powered generators will decrease the use of fossil fuel, gas emission, and noise pollution. These environmental benefits do translate into indirect economic benefits such as less spending in health care and a better life. All these facts combined prove that the Solar Power Smart Box will not only be technically viable, but also possess a significant economic potential, which will contribute to sustainable growth and universal access to power.

3.0 RESULTS AND DISCUSSION

The findings of this paper prove that Solar Power Smart Box is not only technically sound but also economically beneficial, which supports its appropriateness as a feasible proposal to address the energy access issue in developing economies. The consistent electrical performance seen at testing confirms the observing that simple and low-cost system architecture does have the capability to serve the requirements of mobile phones and small electronic devices in charging without sacrificing the safety or dependability of the system. The result matches other previous studies that underscore suitability of technology, where solutions are had to be designed to match the local need, income, and technical ability, and not excess complexity in technology.

On the economic side, affordability of Solar Power Smart Box is one of the greatest strengths of this gadget. High cost of entry in the face of low-income households and students is directly tackled by the low entry capital, along with the reasonably insignificant operating and maintenance expenses. The payback period as revealed is less in this research meaning that it takes the user a few months to make up their investment by saving on phone charging fee as well as fuel bill. This high rate of cost return makes the system economically viable even to individuals who have small disposable income and perceived risk of investment is minimized.

The Solar Power Smart Box helps to reduce productivity and economic efficiency through low cost of accessing energy in small machines. Quality access to chargeable mobile devices will make users to contribute more in digital life routine, including online learning, mobile banking, e-commerce and communication businesses. To the students, this can be translated to a continuity of learning and access to learning materials whereas to small business owners and informal sector workers it can be translated to efficiency in operations and the potential to earn income. By so doing, the system enables digital inclusion and aids in bridging the digital divide that is linked to energy poverty.

The results also indicate the participation of the smart box in the reduction of poverty and livelihood. This will help the households to spend a scarce resource on other vital needs like food, healthcare, and education by breaking the cycle of spending money on commercial charging services and reliance on generators that consume fuel. The system will provide micro-entrepreneurship at the community level, especially with small-scale phone charging stations which may run on solar power. The advantage of such businesses is the zero fuel costs and the low cost of operations which enhances profitability and long-term sustainability of the business.

The other significance of this study is on the scalability and replicability of Solar Power Smart Box. Its design is simple, and its arrangement depends on the availability of common components, which makes it locally assembleable, serviceable, and possibly to do mass production of them. This increases the chances of local production and skill base, which may trigger employment and empower the local economies. Localized production also minimizes reliance on technologies that are imported as well as provision of domestic value chain in the renewable energy sector.

The system also makes economic sense considering environmental considerations. The decreased application of fuel run generators results in decreased greenhouse emissions, noise pollution and spending on harmful exhaust fumes. These environmental returns have international economic benefits such as lowered medical bills and quality of life. The Solar Power Smart Box can also be considered the convergence of technical functionality, economic efficiency, social inclusion and environmental sustainability when looked at as a whole.

In general, the discussion shows that under certain conditions of affordability and consideration of the context of use, small-scale renewable energy technologies can bring significant economic and social value. The Solar Power Smart Box is one example of how one simple engineering solution can be useful in resolving energy poverty and sustainable development and conducting inclusive access to modern energy services.

4.0 CONCLUSION

This paper has examined the economic implications of a Solar Power Smart Box designed for charging mobile devices in areas with unreliable electricity supply. The results confirm that the system provides significant cost savings, rapid payback, and long-term economic benefits compared with conventional charging alternatives.

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