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Performance Evaluation of a Reliable Portable Solar Power System

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Abstract

The limited reliability and efficiency of existing miniature solar power systems in providing consistent AC and DC power for various applications prompted this research on the performance evaluation of a Reliable Portable Solar Power System (PSPS). To address these limitations, the Weibull analysis method was employed to estimate the reliability of individual components and ascertain the overall reliability of existing systems. This approach provided a robust framework for evaluating the system's dependability over time. A portable system was developed featuring a 266Wh capacity battery bank, bulk converters, and a mini-inverter to deliver seamless AC and DC power. The PSPS was tested for its ability to charge multiple devices and provide sustained lighting. Results indicated that the system could fully charge five laptops of varying capacities daily on a single charge, while simultaneously powering three 3W bulbs. When used exclusively for lighting, the system operated the bulbs for up to six days per charge. Additionally, a 4,000mAh phone was fully charged in just 95 minutes. The AC component demonstrated the capacity to power circuits with currents up to 13A. A comparative analysis with commercial systems revealed a 5.1% performance improvement over the Sunking 60 Home System, which was found to be more reliable than the Bee Bee Jump Solar System and the NSEL Solar Generator. In conclusion, the PSPS offers improved reliability and efficiency, making it suitable for small-scale power needs. Further enhancements are recommended, including increased battery capacity and the integration of advanced monitoring systems for real-time power management.

Keywords: Reliability, Portable Solar Power System (PSPS), Solar System, PV Electricity, PV Module, Performance Evaluation, Weibull Analysis

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1. Introduction

Unreliability and limited capacity of portable solar power systems (PSPS) in Nigeria are being observed as significant concerns, with numerous households being affected by unserviceable systems. These systems are being utilized as alternatives to the inconsistent national grid power supply.

It is estimated by the World Bank that 1.2 billion people globally are being deprived of electricity access, predominantly in rural areas. Energy accessibility is being recognized as a crucial development indicator.
Despite being the sixth largest crude oil producer globally, over 50% of Nigerians are being denied electricity access. The remaining population is being provided with merely 3-4 hours of daily supply.

Sustainable energy services are being required to be provided affordably and environmentally consciously. Portable Solar Power Systems are being considered beneficial for various applications.
Solar energy is being derived from the sun, with PV electricity production being dependent on solar radiation availability. Solar panels are being utilized to convert this energy into electricity. The power is being stored and conditioned through integrated batteries and charge controllers.

Solar power systems are being increasingly demanded globally, as traditional energy sources are being depleted and deemed environmentally harmful. Global warming legislations are being implemented worldwide. The Portable Solar Power System (PSPS) is being developed as a decentralized generation solution.

A PSPS is being designed with photovoltaic components, including solar panels, inverters, and electrical accessories. Monocrystalline solar modules are being preferred for their superior efficiency and environmental adaptability. The system is being recognized for its CO2-free, noiseless operation.

2. Literature Review

Solar energy is being provided by PV modules as a clean, renewable resource. Global warming remains Earth's paramount challenge, with the United States contributing 1.448 million metric tons of CO_2 in 2020. Legislation is being enacted worldwide to reduce fossil fuel usage, as CO_2 emissions are being linked to various health issues and environmental threats [15-17]. by Jones C. D., Totterdell I. J., Betts, R. A., Cox, P. M., & Spall, S. A. (2000).

In Nigeria, economic growth is being hindered by inadequate energy supplies, with 4,000-5,000 MW being insufficient for over 200 million people [19-20]. Portable solar systems are being considered vital for economic advancement. Projections indicate that solar alone could be generating 11,575 MW by 2030, increasing to 99,658 MW by 2050 [22]. Akinyele D.O., Rayudu R.K., Nair N. K. C(2015),

Renewable energy is being recognized as crucial for sustainable development, particularly given environmental concerns and socioeconomic benefits [23-24]. According to Kumar, E. S., & Sarkar, B. (2012).

Energy diversification is being required across all sectors to address Nigeria's power crisis. Solar charging devices are being recommended, particularly in remote locations. According to Mahmud, J. O. & Nduka A. O. (2016)

3. Materials and Methods

Materials

Materials used for the fabrication of the portable Solar Power System are discussed in the following sections.

PV Module

Monocrystalline PV modules were selected for their superior efficiency and environmental adaptability.

Balance of System (BOS) Components

The BOS components are comprised of:
i. **Battery**: Energy storage for nighttime use
ii. **Charge Controller**: Battery protection system
iii. **Inverter**: DC to AC converter

Other Components

The external components include:
i. **Nigeria plywood**: Selected for durability and non-conductivity
ii. **Screws**: Cost-effective fastening method
iii. **Concealed hinges**: For maintenance access
iv. **13Amps socket**: For laptop charging
v. **USB ports**: For small device charging
vi. **Battery display**: For voltage monitoring

The Interior Components

The PSPS's insulated interior is equipped with batteries, controllers, and converters, which were sized comprehensively.

i. **Battery**: Rechargeable 3.2V lithium batteries with 5Ah capacity were selected for their longevity and discharge capabilities.

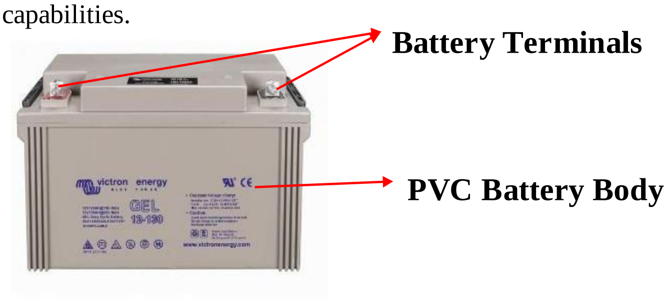

Figure 1: A typical rechargeable lithium battery

ii. **Charge Controller:** A 12V, 10A controller has been selected for implementation.

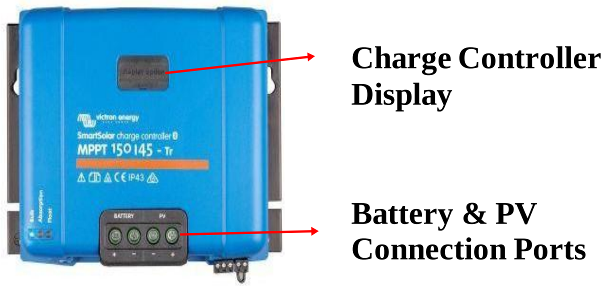

Figure 2 A charge controller

iii. **Inverter:** A 150W inverter is being utilized in the system. It is designed to be operated with laptops requiring 45W-50W power and other low-power electronics. The inverter's primary function is being executed by converting direct current (DC) to alternating current (AC). Power conditioning is being performed by chargers and controllers, which are being used to process DC from PV arrays into AC for loads.

Figure 3: A 150W Power Inverter

IV. Buck Converter: A 5V, 4A power output is provided by the buck converter for direct smartphone charging. The voltage is sufficient for phones with 3.7V batteries. A 4A current capacity is maintained to accommodate two phones simultaneously. Current adjustment is automatically performed by modern smartphones according to their requirements.

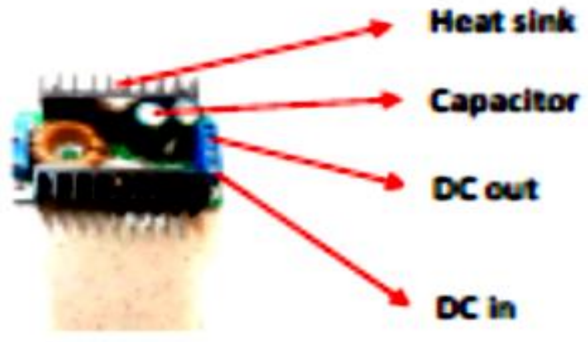

Figure 4: A bulk converter

TOOLS AND EQUIPMENT

i. Sino standard, East West Energy (EWE) Simulating Machine ii. Pyranometer for solar insulation measurement iii. Thermometer for temperature measurement iv. Voltmeter for voltage and current measurement v. Scriber, hacksaw, joining tools, and soldering equipment

METHODS

The following objectives were pursued:

- Existing PV systems reliability evaluation
- PV module characterization
- Portable Solar Power System (PSPS) design and fabrication
- PSPS performance and reliability analysis

Evaluation of the reliability of the existing PV system

Three commercial PV systems were identified and evaluated using Weibull Distribution method. Individual component reliabilities were assessed and combined for overall system reliability.

Characterization of PV module for PSPS

A monocrystalline PV module was characterized using the Sino standard EWE simulating machine. The module was positioned face-down and connected to testing probes.

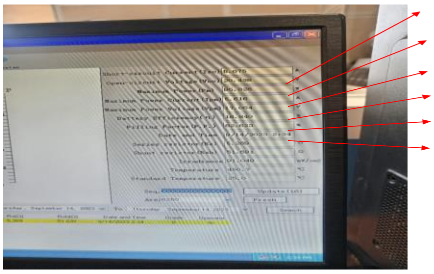

Figure 5: Screenshot of Desktop Readings

The simulating machine flashed light on the module receptive surface and the performance parameters of the module were displayed on the monitor which includes Open circuit current I_{SC}, Open circuit voltage V_{OC}, maximum power point P_m ,current at maximum power I_{pm} Voltage at maximum power V_{pm} and efficiency **%**

Figure 6: Solar Module Characteristics on Display after Simulation

PV MODULE CHARACTERIZATION

Hence, with the PV module characterized and the parameters obtained, values will subsequently be used for design and fabrication of a PV system (As shown in table 1).

Table 1: Performance parameters of a simulated 80W solar PV module

S/N	Parameter	Rate
1.	Open Circuit Voltage (**V_{OC}**)	20.60V
2.	Maximum Power Voltage (**P_m**)	18V
3.	Short Circuit Current (**I_{SC}**)	5.80 A
4.	Maximum Power (**V_{pm}**)	80 W
5	Current at maximum power (**I_{pm}**)	5.36A
6.	Efficiency (**%**)	17.8%
7.	Dimensions (*length x breadth x width*)	(1000 x 540 x 40) mm

4. Results and Discussion

Circuit Operations and Functions of the PSP

Light energy is converted into direct current by the 80W solar module of the PSPS and is transmitted to the charge controller. The battery's voltage and charge state are monitored by the controller, which regulates current flow accordingly. When the battery is depleted, current from the solar panel is directed to it; when full, power is shunted. The inverter, powered by the battery or controller, supplies 220V AC output. Battery depletion is determined by load application, as evidenced by voltage decrease when multiple devices are connected (as presented in figure 7).

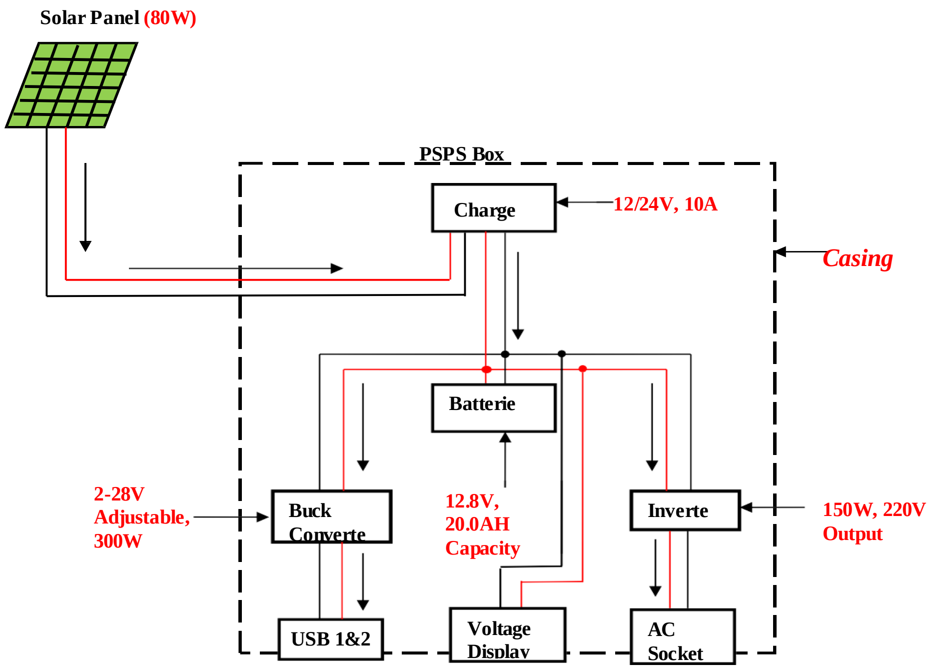

Figure 7: PSPS Circuitry

PSPS Load Evaluation

The total load on the PSPS is calculated thus:

$$Using\ the\ power\ conversion\ factor, total\ load\ on\ the\ system\ = \frac{65.05}{0.8} = 81.31VA$$

Taking into consideration, power losses due to system inefficiencies and system abuse, the overall AC power (or maximum allowable AC power) is calculated thus

$$L_{allowable\ max} = 81.31 \times F_{safety}$$

$$Total\ AC\ Load,\ L_{allowable\ max} = 81.31 \times 1.5 = 121.97VA$$

$$Therefore,\ L_{allowable\ max} = \mathbf{121.97VA}$$

Solar PV Module Requirements

The photovoltaic requirement for the PSPS is estimated

Total energy required/day, = 494.4Whr

$$No\ of\ solar\ panels\ needed\ = \frac{E_T}{Wattage_{SP} \times Hr_S}$$

$$No\ of\ solar\ panels\ needed\ = \frac{494.4\ (Whr)}{(80W \times 8hrs)} = 0.7725$$

$Therefore, no\ of\ 80W\ solar\ panels\ needed \approx \mathbf{1.0}$ ***Piece of 18V, 80W***

Buck converter power

The Total DC load is calculated thus

$$L_{DC} = 29W\ (36.25VA)$$

$$= \mathbf{54.38VA}$$

$$Buck\ converter\ size = L_{DC}\ x\ 1.5$$

$$Buck\ converter\ power = 36.25\ x\ 1.5$$

Charge controller sizing

$$Factor\ of\ safety, F_{Safety} = 1.5, therefore,$$

$$charge\ controller\ size\ = 5.3\ x\ 1.5 = 7.95A$$

The output current from the PV module = 5.3A; also the solar module has a voltage of 18V.

By market availability and comparative cost, the closest controller that is adopted has the following parameters: voltage - 12V; current - 10A. This is adopted for use.

Battery Size

Total energy required/day, E_T=494.4Whr

$$\text{Amperage capacity of 3.2V batteries required} = \frac{494.4\text{Whr}}{3.2\text{V x 8hr}} = 19.31\text{AH}$$

(Please note that four (4) nos 3.2V batteries are connected in series for each row of batteries)

Each selected battery is 3.2V, 5000mAH.

Each Row of Battery 4 no battery = 3.2 x 4 = 12.8V, 5000mAH or 12.8V, 5AH

$$Total\ no\ of\ rows\ of\ batteries\ required = \frac{19.31}{5} = 3.86\ rows$$

Approximating, total no of rows = 4

Table 2: Component Sizes: summary of the PSPS sized components is given below

S/N	Component	Quantity	Specification
1.	Inverter	1	Power = 150W
2.	Buck module converter	1	300W
3.	Solar module	1	80W; 18.0V
4.	Charge Controller	1	12/24V, 10A
5.	Lithium Battery Sizing	12 pieces	12.8V; 20,000mAH

Test results

Two tests were conducted with a fully charged PSPS and disconnected PV module. In the first test, a smartphone and laptop were simultaneously charged from 0% to 100%, with data recorded in Table 4.2 and Figure 4.3. Using remaining charge, another smartphone was charged from 0% to 100%. During peak sunlight, the PSPS effectively charged connected devices while maintaining its battery backup.

1. Laptop: HP, 2,670mAH/10VDC (26.7Wh)
2. Phone 1: Infinix Hot5, 4,000mAH/4.7V (18.8Wh)
3. Phone 2: Infinix Hot5, 4,000mAH/4.7V (18.8Wh)
4. Bulbs: 3no, 3W DC Bulbs (9Wh)

Performance evaluation/tests of the PSPS were conducted in this sequence:

1. Simultaneous charging of the laptop and two (2) smartphones
2. Simultaneous charging of the laptop and one (1) smartphone only
3. Charging of two (2) smartphones only
4. Performance evaluation of PSPS on DC loads
5. Performance evaluation of PSPS on AC load and DC loads

Test 1: The PSPS voltage was measured at 13.3V (no-load) and 13.2V when devices were connected. The voltage was maintained at 13.2V (94% charge) after devices reached full charge. The laptop and smartphone required 130 and 120 minutes respectively for complete charging.

Table 3: Data from simultaneous charge of a laptop and a smartphone

Experimental Data on A Laptop and 2 Smartphones

S/N	Description	Initial Reading (No Load)	Initial Reading (with Load)	Reading 1	Reading 2	Reading 3	Reading 4	Reading 5
1	Laptop state of charge (%)	0	0	45	82	96	99	100
2	**Time of charge for laptop (m)**	0	0	30	60	90	120	130
3	Phone 1 state of charge (%)	0	0	22	44	65	82	100
4	**Time of Charge for phone (m)**	0	0	30	60	90	100	120
5	PSPS voltage state of charge (V)	13.3	13.2	13.1	12.9	13	13.1	13.2
6	**PSPS voltage state of charge (%)**	100	100	93	92	93	93	94

Experimental Data on 1 smartphone							
Description	**Initial Reading (No Load)**	**Initial Reading (On Load)**	**Reading 1**	**Reading 2**	**Reading 3**	**Reading 4**	**Reading 5**
Phone 2 state of charge (%)	0	0	24	45	68	96	100
PSPS voltage state of charge (V)	13.2	13.2	13.2	13.1	13.1	13	13.1
PSPS state of charge in percentage (%)	94	94	87	87	88	89	90
Charge duration (m)	0	0	30	60	90	120	140

Table 4: **Experimental Data on 1 smartphone**

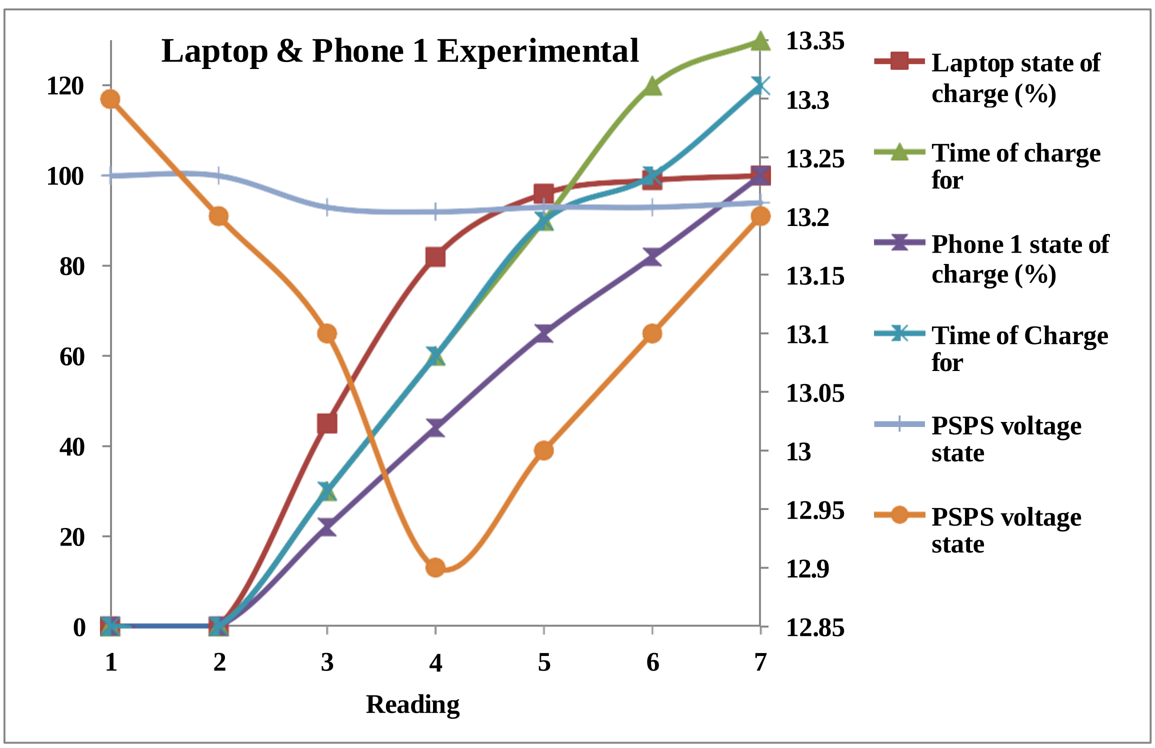

Figure 8: Chart for simultaneous charge of a laptop and a smartphone

Test 2 Simultaneous charging of the laptop and one (1) smartphone only
From Table 4 and Figure 5, it was observed that the PSPS voltage was maintained at 13.0V initially. When the second smartphone was connected, it dropped to 12.8V, and charging was completed in 140 minutes.

Table 5: Data from the charge of second smartphone only

Description	**Initial Reading (No Load)**	**Initial Reading (On Load)**	**Reading 1**	**Reading 2**	**Reading 3**	**Reading 4**	**Reading 5**
Phone 2 state of charge (%)	0	0	24	45	68	96	100
PSPS voltage state of charge (V)	13.2	13.2	13.2	13.1	13.1	13	13.1
PSPS state of charge in percentage (%)	94	94	87	87	88	89	90
Charge duration (m)	0	0	30	60	90	120	140

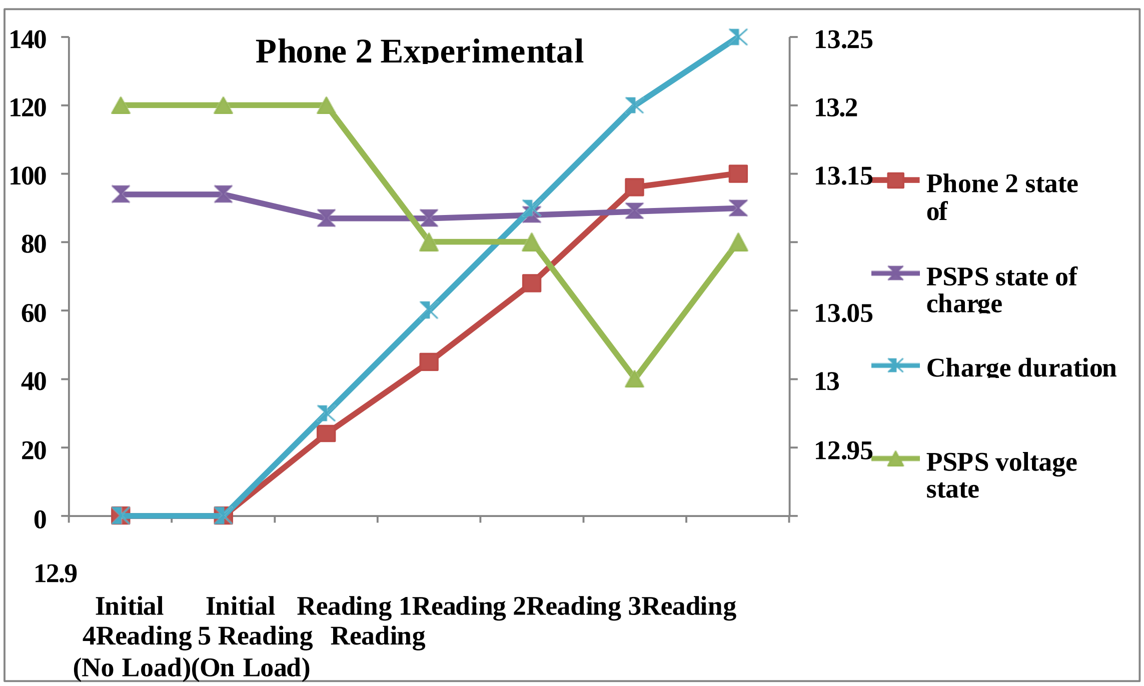

Figure 9: Phone 2 Experimental Charging Results

Test 3 Charging of two (2) smartphones only

Three DC bulbs were connected to the PSPS system, which had a state of charge of 98% at 13.4V. The system was monitored hourly throughout the night, and voltage and charge percentages were recorded.

Table 6: Data from the use of 3nos 3W Bulbs for 7hour

3 DC Bulbs/Lights working for 7 hours (Dusk to Dawn)								
Description	**Initial Reading**	**1 Hour**	**2 Hours**	**3 Hours**	**4 Hours**	**5 Hours**	**6 Hours**	**7 Hours**
PSPS voltage state of charge (V)	13.3	13.1	13	12.8	12.7	12.7	12.6	12.6
PSPS voltage state of charge (%)	98	98	95	93	86	80	74	71

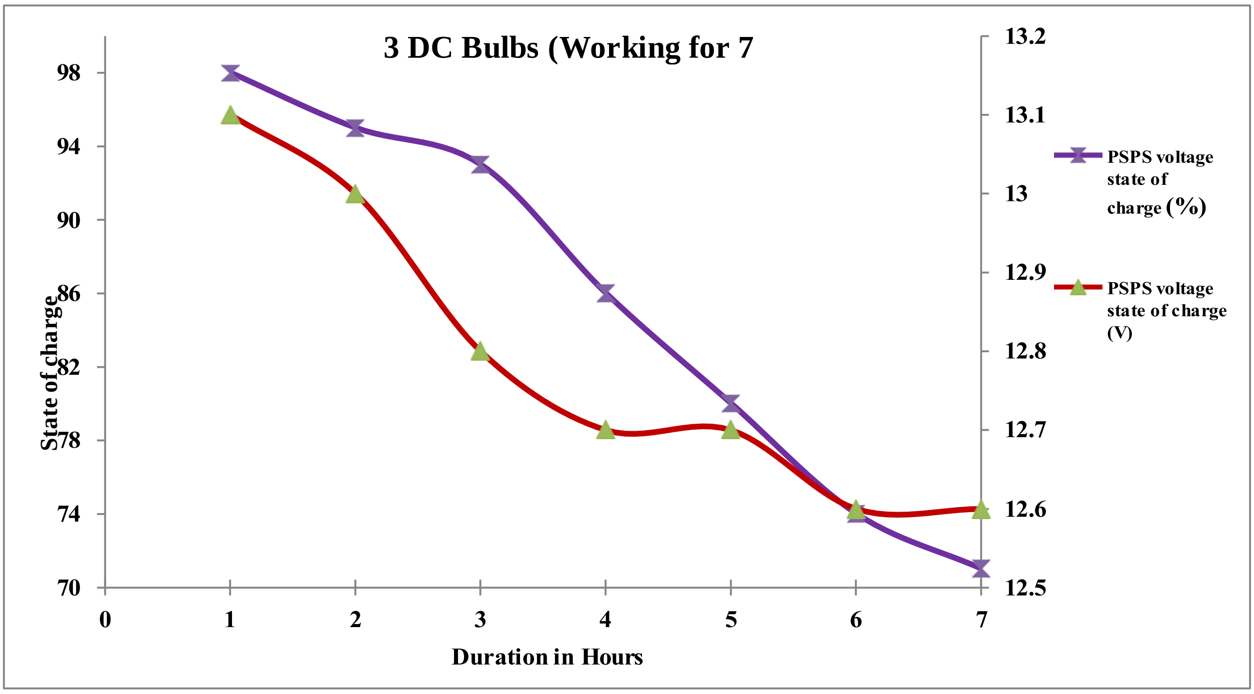

Figure 10: Performance chart of the three bulbs

Table 7: Experimental data for simultaneous use of laptop, 3 smartphones and 3 Bulbs

Experimental Data for Simultaneous Use of Laptop, 2 Smartphones & 3 Bulbs							
Description	Initial Reading (No Load)	Initial Reading (with Load)	Reading 1	Reading 2	Reading 3	Reading 4	Reading 5
Laptop state of charge (%)	0	0	25	45	70	89	100
Time of charge for Laptop (min)	0	0	20	50	70	90	110
Average state of charge for 2 phones (%)	0	0	25	48	65	88	100
Time of charge for 2 phones (min)	0	0	35	65	90	110	130
3 Bulbs time of use (hrs)	0	0	1	2	3	4	5
PSPS voltage state of charge (V)	13	12.9	12.7	12.6	12.5	12.4	12.4
PSPS voltage state of charge (%)	94	90	83	75	70	65	64

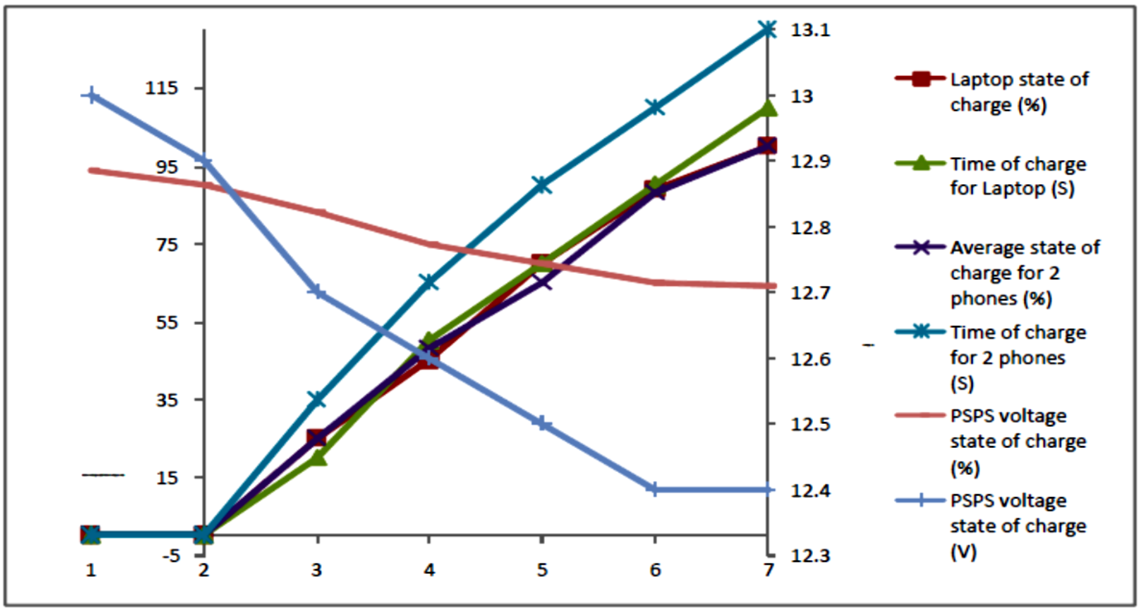

Figure 11: Performance Chart for Laptop, 2 Smartphone and 3 Bulbs

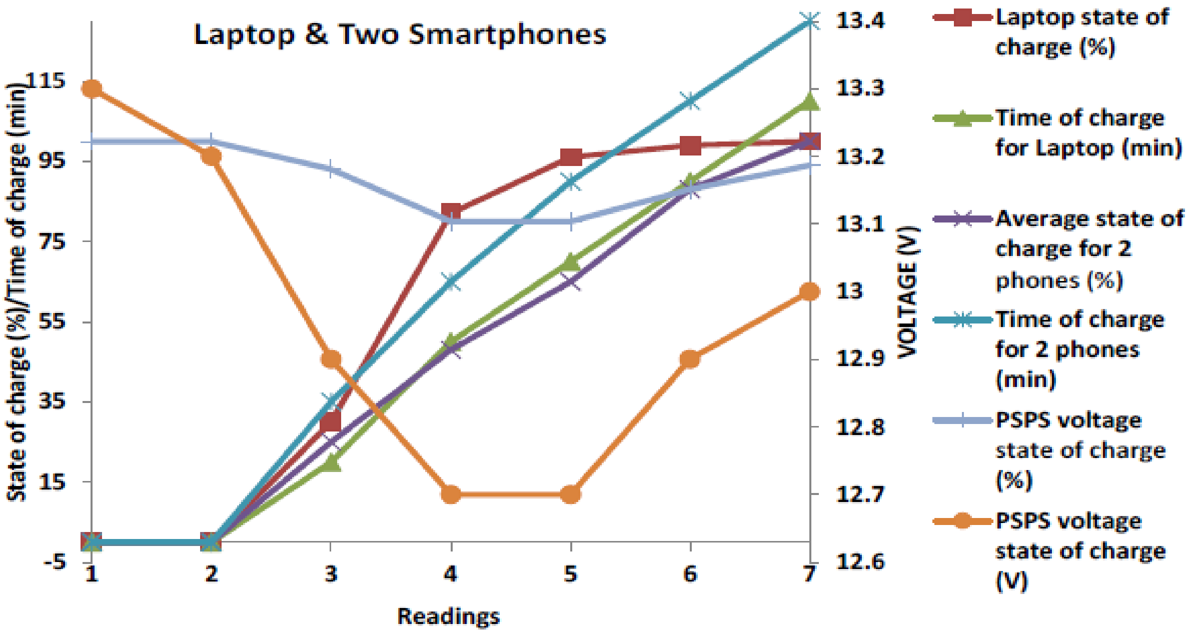

Figure 12: Performance chart for laptop and 2 smartphones

Table 8: Experimental data for 2 smartphones

Data for Laptop & 2 Smartphones							
Description	Initial Reading (No Load)	Initial Reading (with Load)	Reading 1	Reading 2	Reading 3	Reading 4	Reading 5
Laptop state of charge (%)	0	0	30	82	96	99	100
Time of charge for Laptop (min)	0	0	20	50	70	90	110
Average state of charge for 2 phones (%)	0	0	25	48	65	88	100
Time of charge for 2 phones (min)	0	0	35	65	90	110	130
PSPS voltage state of charge (V)	13.3	13.2	12.9	12.7	12.7	12.9	13
PSPS voltage state of charge (%)	100	100	93	80	80	88	94

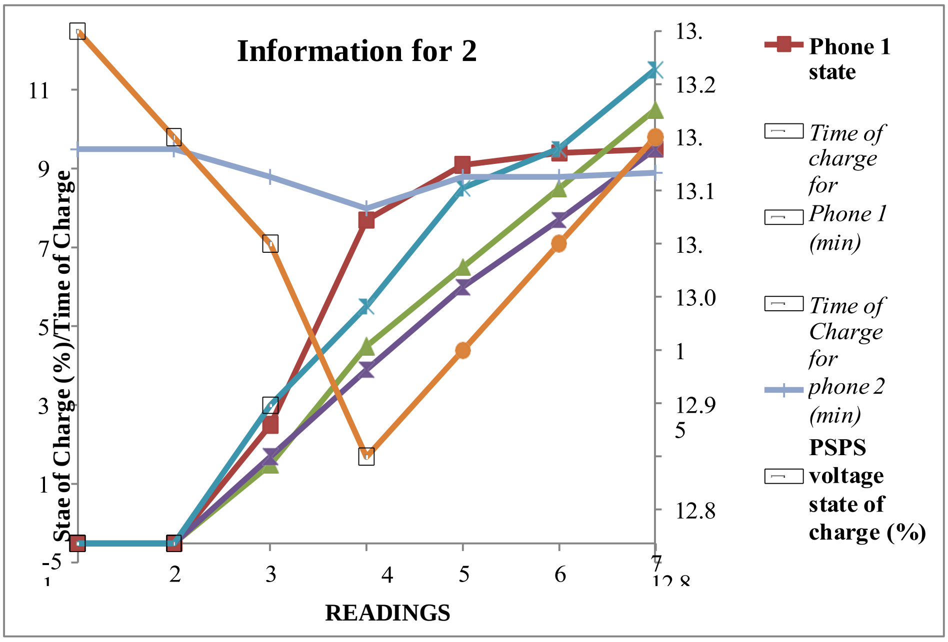

Figure 13: Performance chart for 2 smartphones

System Performance under Full Loading

The PSPS was charged fully by a solar module. After disconnection, both AC and DC loads were powered simultaneously for eight hours and twenty minutes.

Product Reliability Determination

PSPS' Reliability Determination

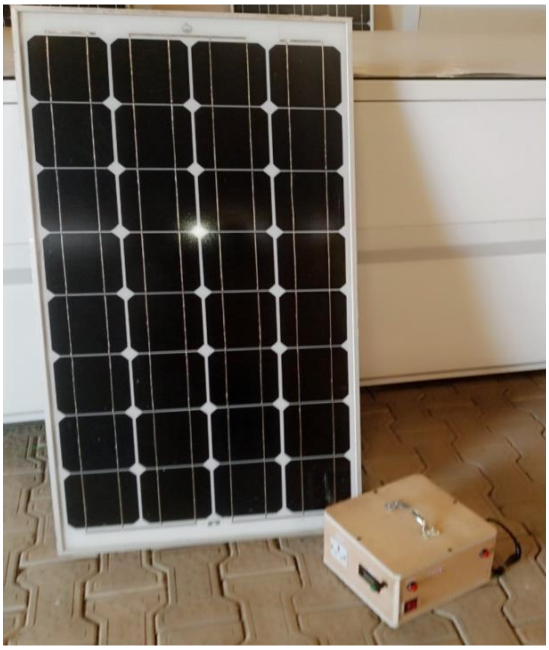

Figure 13: The PSPS

i. For a PV module designed for 25years, cycles to failure =13,688 [35].
ii. For a Lithium-ion battery designed for 5years, cycles to failure = 2,738 [30 & 31].
iii. For an inverter designed for 15years, cycles to failure =8,213 [32].

iv. For a charge controller designed for 10year, cycles to failure =5,475 [29].

For a commercial PV system, A (Sun King 60 Home system) PV module designed for 20years:

i. Cycles to failure =10,950 [35].
ii. For a Lead acid battery designed for 3years, cycles to failure = 1,643 [37].
iii. For an inverter designed for 10years, cycles to failure =5,475 [32].
iv. For a charge controller designed for 10year, cycles to failure =5,475 [29].

For commercial PV system, B (NSEL Mini Solar Generator) Using equations 2.0 and 2.1 above for a PV module designed for 25years:

i. Cycles to failure =13,688 [53].
ii. For a Lead acid battery designed for 3years, cycles to failure = 1,643 [31 & 32].
iii. For an inverter designed for 15years, cycles to failure =8,213 [32].
iv. For a charge controller designed for 12year, cycles to failure =6,570 [29].

Commercial PV system, C (Beebee jump solar)
For a PV module designed for 20years,

i. Cycles to failure =10,950 [35].

- For a Lead acid battery designed for 3years, cycles to failure = 1,643 [36].
- For an inverter designed for 15years, cycles to failure =8,213 [32].
- For a charge controller designed for 10year, cycles to failure =5,475 [29].

Therefore, the reliability of the PV system of the three commercial products A, B, C and the new design PSPS Newly designed PSPS =0.9237

i. Commercial product A = 0.8785
ii. Commercial product B = 0.8770
iii. Commercial product C = 0.8703

5. Result and Discussion

Reliability of Components in PV systems

Reliability evaluation of different solar power systems for electrical power supply to domestic appliances was done. The solar power system products evaluated for reliability includes; Sunking 60 power system, NSEL Mini solar generator, Beebeejump Solar system (S1 Plus) and the designed PSPS. The tables below shows a comparison of the reliability of each components in the various PV systems.

Table 9: Comparison of Reliability of Components of the PV Systems

Product	Component	Type	Rating	Cycle to failure	Reliability	Reliability Summary
	PV module	Poly crystalline	60	10,950	0.9939	
	Storage battery	Lead Acid	12V	1,643	0.9006	
Comm. A	Inverter	NA				**0.8785**
	Charge controller	PWM	12V/7A	5,475	0.9814	
	PV module	Mono crystalline	80	13,688	0.9959	
	Storage battery	Lead Acid	40	1,643	0.9006	
Comm. B	Inverter	Square wave	300	8,213	0.9907	**0.8770**
	Charge controller	PWM	12V/10A	6,570	0.9870	
	PV module	Poly crystalline	160	10,950	0.9939	

	Storage battery	Lead Acid	12	1,643	0,9006	
	Inverter	Square wave	150	8,213	0.9907	**0.8703**
Comm. C	Charge controller	PWM	12V/10Ah	5,475	0.9814	
	PV module	Mono crystalline	80W	13,688	0,9959	
	Storage battery	Lithium-ion	20Ah	2,738	0.9525	
	Inverter	Modified sine wave	150W	8,213	0.9907	**0.9237**
New design						
	Charge controller	MPPT	12/24V	5,475	0.9829	
PERCENTA	**GE RELIABILITY IMPROVEMENT OVER**			**COMM. A**		**0.051(5.1%)**

Comparison of Reliability of the System Components in Series

Table 10 below presents the comparison of the reliability of each PV system as well as the percentage reliability improvement of the new design over the best commercial A PV system.

Table 10: Comparison of Reliability of the PV Systems

Product	Reliability
Commercial A	0.8785
Commercial B	0.8770
Commercial C	0.8703
New Design	0.9237
Percentage Reliability improvement over commercial A	0.9237- 0.8785 /0.8785 0.051 =5.1%

From table 4.9 above, the new design PSPS has an improvement of 5.1% over commercial A PV system in the market currently which has the best reliability among the other commercial products. This is as a result of standard design and sizing of the PV components and also usage of standard components in fabricating the new design PSPS.

6. Conclusion and Recommendation

Commercial portable PV systems were evaluated and determined to be unreliable. The PV module parameters were verified using NASENI sun simulator. A Portable Solar Power System (PSPS) was designed and fabricated according to specifications. The system was tested successfully with various devices and demonstrated 5.1% improved reliability compared to existing systems.

Recommendations

The following recommendations were made:

1. Aluminum casing should be utilized instead of wood for better heat dissipation.
2. Hybridization with grid/generator charging capabilities should be explored.

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Author Contributions

All the authors contributed to the development of the work. All authors read and approved the final manuscript.

Competing interests

The authors declare no competing interests.

Data Availability

The authors confirm that the data supporting the findings of this study are available within the article.

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