DEVELOPMENT OF AFFORDABLE MOBILE SOLAR POWER SYSTEMS FOR CLEAN ENERGY ACCESS

ALIREZA E. MAJD[1], FIDELINE L. TCHUENBOU-MAGAIA[1], DAVID ADEBAYO[1], PAUL BATES[1],
JAMES WILLETTS[2], DAVE NWOSU[3], ZLATKA STOEVA[4] & NDUKA N. EKERE[5]
[1]Energy and Green Technology Research Group, Centre for Engineering Innovation and Research,
University of Wolverhampton, UK
[2]AceOn Group, UK
[3]Nevadic limited, Nigeria.
[4]DZP Technologies Limited, UK
[5]Faculty of Engineering and Technology, Liverpool John Moores University, UK

ABSTRACT

The Paris Agreement and the 2030 Agenda for Sustainable Development emphasize the urgent need to fight against all forms of poverty, advance sustainable development, and achieve a low carbon future. Electricity is critical for poverty alleviation, economic growth and living standards improvement. According to the World Bank, there is some improvement in global population access to electricity, although global energy access is still a real challenge with around 675 million people without access to electricity. Moreover, the number of people without electricity in sub-Saharan Africa (SSA) has rather increased with electricity reaching only about 50% of the population. In this context, a 4 kW foldable mobile solar power system (FMSPS) with 20 kWh energy storage has been developed and used as an educational tool for school outreach as well as a demonstrator for sustainable back-up power alternative to diesel generators for clean energy access in communities with high energy poverty. The system is uniquely designed to offer easy manufacturing, cost-effectiveness, high aerodynamic stability, and reliability alongside manual operation for minimal maintenance requirement. FMSPS was designed and manufactured as part of over £1 million funding awarded by Innovate UK under the Energy Catalyst Round 8 (Clean Energy Access) Competition. The collaborative research and development project aims to develop and demonstrate the next generation sodium-ion battery energy storage integrated with solar energy generation, to provide affordable and secure access to energy in SSA.

Keywords: energy poverty, electricity access, sustainable development, mobile solar power system.

1 INTRODUCTION

Access to electricity plays a crucial role in poverty alleviation, economic growth, and improving living standards, as emphasized by the Paris Agreement and the 2030 Agenda for Sustainable Development. However, the latest data reveals that the world is falling short of achieving the SDG7 targets [1]. In 2021, approximately 675 million people still lacked access to electricity, with more than 80% of them residing in sub-Saharan Africa (SSA) [1]. Similarly, around 2.3 billion people globally lacked access to clean cooking, with significant gaps prevalent in SSA. Despite some progress, the current rate of advancement suggests that by 2030, an estimated 660 million people will still lack access to electricity, while 1.9 billion people will continue to rely on polluting cooking fuels [1]. These statistics further highlight the pressing need for effective solutions that provide clean and sustainable energy sources to bridge the energy gap, particularly in regions such as SSA. Such solutions are crucial for supporting socio-economic development and achieving the SDGs, to ensure universal access to affordable, reliable, and modern energy services. Efforts to accelerate the deployment of clean energy technologies, including the adoption of innovative systems like the foldable mobile solar power system (FMSPS), are essential to overcome the energy challenges faced by these regions and improve the livelihoods of millions of people worldwide.

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1.1 Energy challenges in SSA

Access to reliable electricity remains a significant challenge in SSA countries with hindering economic development and exacerbating existing inequalities. Only half of the population in the region has access to electricity, and frequent power cuts necessitate alternative energy sources such as fossil fuel power generators [2]. Fig. 1 illustrates the global distribution of electricity access in 2021, based on the last published records [3]. Only a third of households have access to reliable energy in Nigeria. Even those connected to the central power grid in Nigeria suffer from intermittent supply issues, impacting various aspects of daily life [4]. These limitations highlight the urgent need for innovative and sustainable energy solutions to overcome the energy challenges in Nigeria and other parts of SSA and to promote inclusive development while reducing reliance on fossil fuel-based systems.

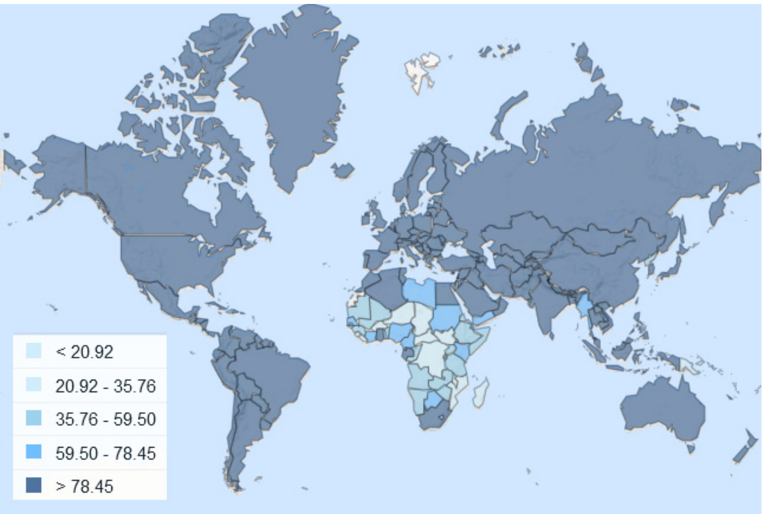


Figure 1: Global access to electricity (% of population) in 2021 [3].

1.2 FMSPS

An FMSPS presents a practical alternative to traditional and environmentally polluting mobile petrol/diesel power generators to tackle the energy access and affordability issues, particularly in areas with limited or no access to the power grid. Alongside FMSPS, small portable solar panels (PSP) have gained popularity in the market, offering a relatively lightweight, cost-effective and portable solution for urgent energy needs [5]. However, it is important to note that the power generated by PSP packages is not competitive with FMSPSs, and their efficiency is nearly half that of conventional solar photovoltaic (CSPV) panels used in FMSPSs [6].

By integrating mobile storage units and energy harvesting systems using CSPV panels, FMSPS not only reduces local emissions, including CO_2, but also minimizes fuel consumption. These innovative systems aim to provide accessible and reliable power solutions for off-grid enterprises, rural communities, and disadvantaged populations, bridging the energy access gap and promoting sustainable development. Additionally, FMSPS serves as an affordable backup power source for individuals connected to the central power grid, thus contributing to enhancing the overall energy security and reliability.

1.3 Related works

In recent years, there has been a notable surge in interest surrounding off-grid solar systems. These include solar integrated into mobile units like electric minibus taxis (eMBTs) to contribute to hybrid energy solutions [7], solar incorporated into towable solar trailers [8] and system designed as logistical transportable energy stations with high power output capabilities [9]. An illustrative case of micro-grid implementation is highlighted in the work of ZeroBase Energy with their 80 kW and 360 kWh battery-contained off-grid solar hybrid system in a refugee camp located in Lokichoggio, Kenya [9]. Several companies have brought to the market different designs of solar trailers (see Fig. 2). MPS company has developed a more compact FMSPS supplying 320 W solar power for mobile outdoor cameras [10] whereas TWT introduced a solar trailer with a relatively high energy storage capacity that offers 2.1 kW solar power generator and a 15kWh storage system [11]. OkSolar's solar trailer takes storage to the forefront with a 2.4 kW solar power system and an impressive 57 kWh storage capacity [12]. An exemplar of advanced FMSPS within the market's power range is Tesla's July 2022 solar trailer, generating 2.7 kW to power Starlink system [13].

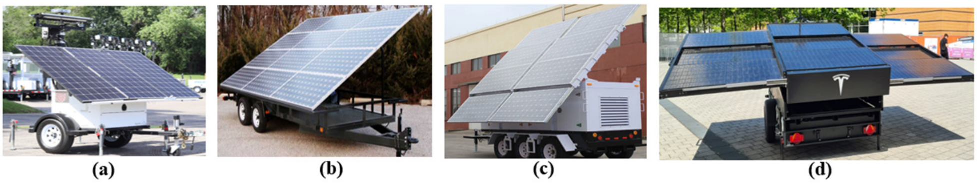


Figure 2: Examples of FMSPS available in the literature. (a) MPS: 320 W [10]; (b) TWT: 2.1 kW [11]; (c) OkSolar: 2.4 kW [12]; and (d) Tesla: 2.7 kW [13].

Most designs in the FMSPS market incorporate complex automatic folding systems, leading to elevated manufacturing expenses and increased maintenance demands, particularly in challenging regions like SSA. In contrast, this current FMSPS design emphasizes simplicity, ensuring affordability and low maintenance. It offers a robust power generation rate and storage capacity, utilizing a 4 kW solar power generator and 20 kWh energy storage. The design aims to achieve a full battery charge in 5 hours during SSA's peak sunlight and provide essential daytime electricity for various applications.

This paper aims to address the pressing need for secure, sustainable, and affordable energy solutions in SSA, with a specific focus on Nigeria. In light of these considerations, this paper explores the design, cost-effectiveness, ease of manufacture, and low maintenance aspects of a FMSPS mounted on a trailer.

2 SYSTEM SPECIFICATION AND COMPONENTS

The design of the FMSPS encompasses various key aspects to ensure its effectiveness, portability, and ease of use. This section provides an overview of the system design considerations, including the components, construction, and functionality. The FMSPS consists of several essential components that work together to enable efficient solar energy generation and storage. These components typically include a battery storage system, conventional solar PV panels, power management units, a foldable frame structure (FFS), and a trailer.

2.1 Battery storage system

Our proposed affordable solar power generator, specifically designed for operation in Nigeria, incorporates a trailer-mounted system with a 4 kW solar PV generator system and a 20 kWh battery storage capacity to provide reliable and continuous power supply. This system stores excess energy generated by the solar panels during peak sunlight hours and releases it when demand arises or during periods of low solar irradiation. The battery storage system ensures a stable power output and allows for off-grid operation.

2.2 Conventional solar PV panels

To maximize solar energy capture, the system is designed to securely hold nine solar panels. Each panel measures 2.1 m in length and 1.05 m in width, with a power-generating capacity of 445 W, an open circuit voltage of 49 V, and a maximum module efficiency of 21%.

2.3 Power management units

Power management units include solar charge controllers, a battery management system, and 5 kW DC-to-AC power inverter. These play a crucial role in the FMSPS by regulating and optimizing the flow of energy between the solar panels, battery storage system, and connected devices or appliances. For example, these units monitor the system’s energy production, battery charge levels, and power consumption, ensuring efficient energy utilization and preventing overcharging or discharging of the battery.

2.4 FFS

The proposed FMSPS incorporates a FFS that provides both mechanical support and portability. This frame allows for easy setup and dismantling, making the system highly portable and convenient for transportation to different locations and ensuring long-term reliability. The foldable design also ensures efficient space utilization during storage and transportation, making it suitable for different environmental conditions and deployment scenarios. This feature allows the solar panels to be positioned at an optimal angle relative to the sun’s position, capturing the maximum amount of sunlight and maximizing the system’s overall performance.

2.5 Trailer

The FMSPS is designed to be lightweight and portable for easy transportation. A trailer (Brenderup 3251STB) weighing 250 kg with a loading capacity of 750 kg was selected, allowing for a total weight of 1 ton when fully loaded. The internal dimensions of trailer, 2.5 m in length and 1.42 m in width, provide ample space to accommodate the FMSPS components. This design ensures that the system can be towed by common vehicles and deployed to various locations. Table 1 presents a summary of the main components for the system, along with their respective weights. The total weight of the listed items, excluding the FFS is 490 kg. Hence, an FFS with a maximum weight capacity of 260 kg can be deployed to support the operation of the system. This additional weight allowance accounts for the weight of the FFS itself, as well as any necessary attachments.

Table 1: Summary of component weights for the FMSPS.

Item	**Weight (kg)**	**Quantity**	**Total weight (kg)**
Panel (W:104 cm, L: 210 cm)	24.3	9	218.7
Inverter (5 kW)	66	1	66
Solar charge controller (3 kW)	5	2	10
Wiring with connectors	20	1	20
Battery (4.2 kWh)	22.1	5	110.5
Battery casing	15	2	30
Joints and connections			5
Trailer cover and fastening belts			10
Margin			20
Total			**490**

3 FFS DESIGN

The proposed FMSPS was designed according to the specifications outlined earlier. The design process considered factors including (a) easy manufacturing, (b) manual operation, (c) minimum maintenance, (d) cost-effectiveness, (f) high stability, (g) reliability, (h) safety, and (i) low weight.

The optimized design for the FFS was obtained through an interactive design process with several conceptual designs examined and evaluated (see Fig. 3). This visual representation showcases the steps involved in assessing and refining the different conceptual designs, ultimately leading to the selection of the most optimized design solution for the FMSPS.

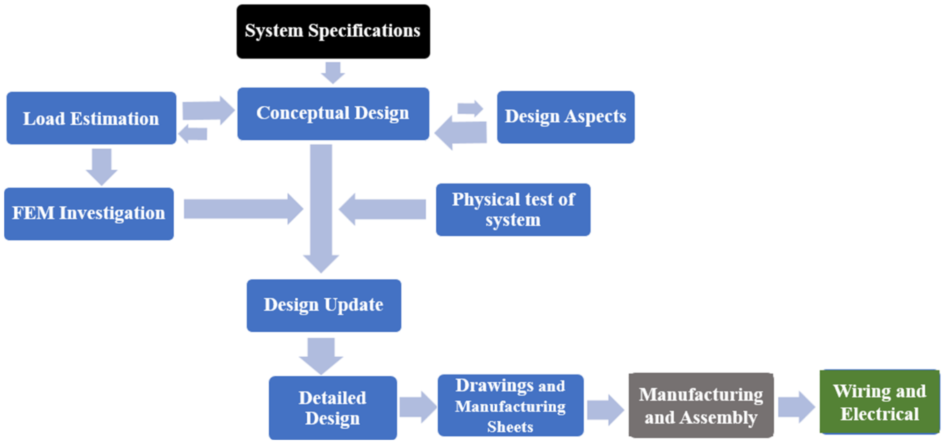


Figure 3: Chart illustrating the applied design process for the FFS.

3.1 Load estimation

The impact of wind forces on the FFS was evaluated through an aerodynamic investigation using analytical formulations. The lift and drag forces acting on the solar PV panels can be mathematically described using eqn (1):

$$F_{L,D} = \frac{1}{2} A\rho C_{L,D} V^2, \tag{1}$$

where F_L and F_D are lift and drag forces (N), respectively, A is the area (m^2) of the panel subjected to the air flow, ρ is the mass density (kg/m^3) of the air flow, and V is the velocity (m/s) of wind relative to the panel. C_L and C_D are also lift and drag coefficients, respectively.

For the framed panels, specific values of C_L and C_D were used for a rectangular solar PV panel tilted at 30° and 15°. Based on literature sources, the reported values for C_L and C_D are as follows: for a panel tilted at 30°, C_L = 1.2 and C_D= 0.71, while for a panel tilted at 15°, C_L= 0.16 and C_D= 0.48 [14].

For the proposed FFS design, the annual wind pattern in Nigeria and utilizing a maximum wind velocity of 10 m/s was considered based on relevant literature sources [15], [16]. This implies that the system is designed to operate within weather conditions where the wind velocity does not exceed 10 m/s, and if the wind velocity surpasses this threshold, the system's operation should be halted temporarily to ensure safety.

Considering a maximum wind velocity of 10 m/s, the panel area of 2.184 m^2 (as specified in Table 1), and an air density of 1.221 kg/m^3, the lift and drag forces for the panel tilted at 30°were calculated as 160 N and 94.6 N, respectively. Similarly, for the panel tilted at 15°, the lift and drag forces were determined as 64 N and 21.3 N, respectively. The design incorporates the calculated values for the panel tilted at 30°, as it experiences higher and more significant forces that are critical for the system's performance under service loads.

3.2 FFS conceptual designs

During the conceptual design phase of the FFS, several design options were explored to achieve an effective and practical folding system. Mild steel has been chosen as the preferred material for the FFS due to its favourable characteristics and compatibility with the design objectives including high strength, durability, and maintaining cost-effectiveness and ease of fabrication availability of the material for easy fabrication in Nigeria. In order to ensure structural integrity and performance, the structural components of the FFS were carefully selected to provide sufficient strength while keeping the elements within the elastic zone of mild steel, which has a yield strength of approximately 240 MPa. This ensures that the FFS can withstand the anticipated loads and stresses during operation without exceeding the material's elastic limits.

The initial concept involved using parliament hinges to connect sets of three solar panels together, which were then connected to each other using larger hinges (see Fig. 4). Although this concept had the advantages of low maintenance needs, easy manufacturing and cost-effectiveness, it posed challenges during the unfolding process due to the weight of the panel sets and limitations in hinge strength for handling bending loads in cantilever positioning.

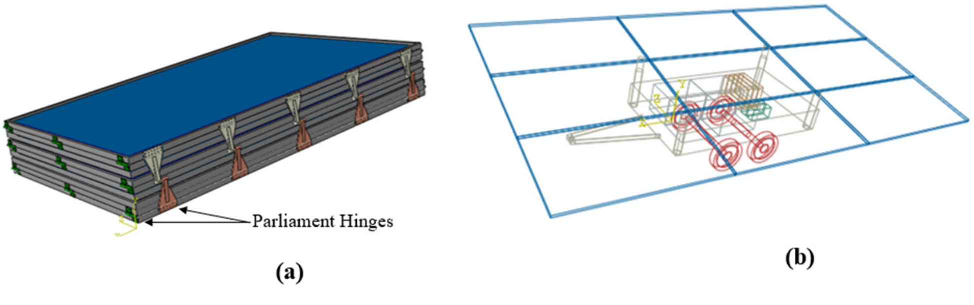


Figure 4: Computer-aided design (CAD) views for the FFS concept using parliament hinges. (a) Folded state; and (b) Unfolded state mounted on the trailer.

To address the challenges encountered with the initial design concepts, a rail system was considered to replace large parliament hinges. This rail system allowed for smooth sliding of each panel set in and out, facilitating the folding and unfolding process of the system. Two options were evaluated for assembling the rails: (i) on the frame structure itself, or (ii) on the trailer's bed. For the concept where the rails were assembled on the structure, hydraulic or motorized telescopic columns were initially used to adjust the leg height on each side of the trailer. This allowed for easy tilting of the system. While this configuration demonstrated reliable operation, it also came with higher maintenance requirements and increased manufacturing costs. Fig. 5 provides a visual representation of this concept, showcasing the integration of the telescopic columns and the rail system on the frame structure.

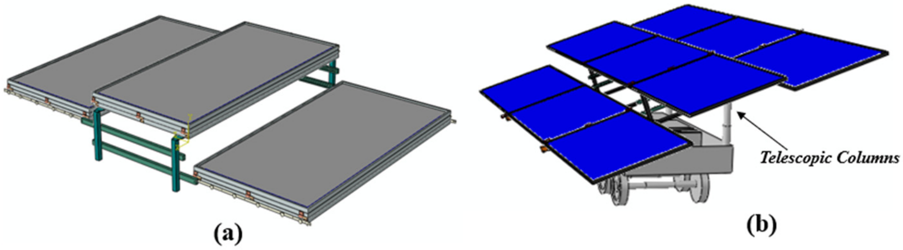


Figure 5: CAD views for the FFS concept using rails assembled on the structure, and telescopic columns. (a) Folded state; and (b) Unfolded state mounted on the trailer.

The challenges associated with the use of telescopic columns were overcome by replacing two heavy-duty hinges and a saddle to tilt the system. However, this modification led to an increased height of the system, which presented difficulties during the unfolding process of the panels. Additionally, there was a potential risk of instability during towing the trailer due to the higher centre of gravity (see Fig. 6).

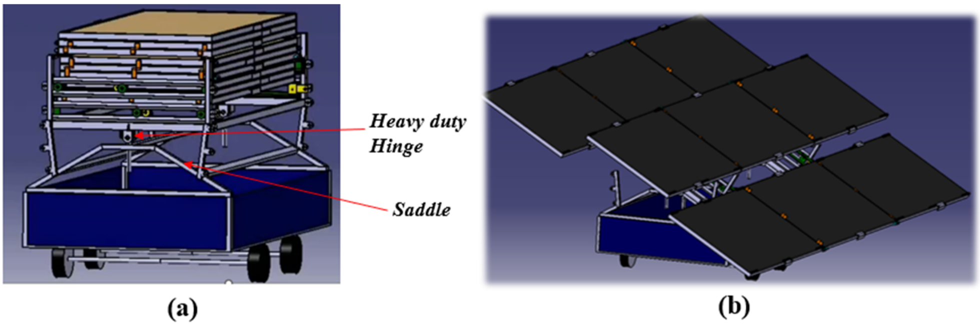


Figure 6: CAD views for the FFS concept using rails assembled on the structure, heavy duty hinges and saddle. (a) Folded state; and (b) Unfolded state mounted on the trailer.

The concept of using rails assembled on the trailer's bed emerged as the most suitable solution, meeting all the design requirements for the proposed FFS. This concept offered exceptional stability for the unfolded panels, benefiting from the wide span of external legs (see Fig. 7). One limitation of this concept is its ability to only tilt six panels, which may result in slightly less light harvesting optimization compared to other concepts. However, this limitation is offset by the significant reduction in shadowing, resulting in improved power generation by the panels. Additionally, this design required lighter structural components and with a rail system using simple V-grooved wheels.

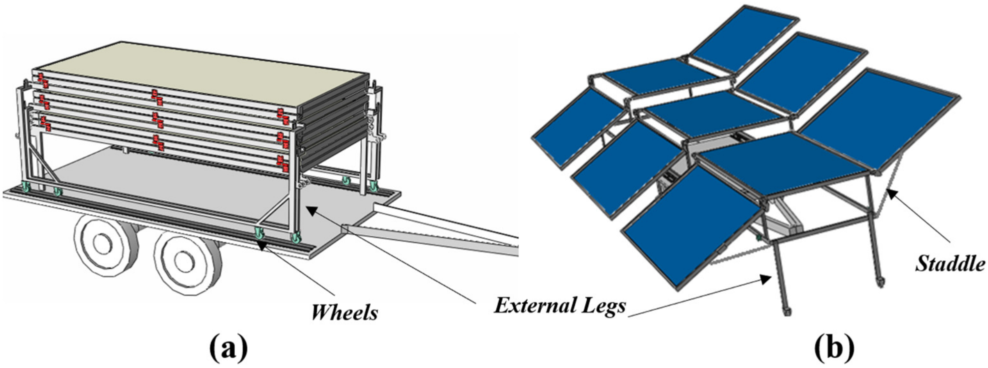


Figure 7: CAD views for the FFS concept using rails assembled on the trailer's bed, heavy duty hinges and saddle. (a) Folded state; and (b) Unfolded state mounted on the trailer.

3.3 Detailed design

The selected concept for the FFS utilizes a rail system assembled on the trailer's bed, consisting of nine solar panels arranged into three quadpods: Lower, Middle, and Upper quadpods (see Fig. 8). The Middle quadpod is securely fixed to the trailer's bed using bolt connections, while the other two quadpods can slide out in the front and back directions of the trailer. The space underneath the middle quadpod is utilized to accommodate all electrical accessories, including battery cases, inverters, and solar charge controllers.

Each slidable quadpod is equipped with four wheels at the bottom frame, enabling smooth sliding along the rails. The quadpods are equipped with stoppers and removable pin connections to the Middle quadpod, ensuring stability in both folded and unfolded states. To further enhance stability when unfolded, each slidable quadpod is supported by two wheeled legs positioned on rail pairs connected to the trailer's bed.

Within each quadpod, there are three framed solar panels. The lowest panel is fixed to the quadpod structure, while the other two panels are hinged to the quadpod corners and stabilized using adjustable staddles removable pins with 10 mm diameter. This design allows for tilting the panels at various angles between −30 and 30°, ensuring optimal solar exposure throughout the day and maximizing energy generation. The FFS in its folded state has dimensions of 2,250 mm in length, 1,420 mm in width, and 990 mm in height. Taking into account the 660 mm height of the trailer bed, the overall height of the FMSPS is 1,650 mm. When unfolded, the system requires a larger space, with dimensions of 6.7 m in length and 3.7 m in width.

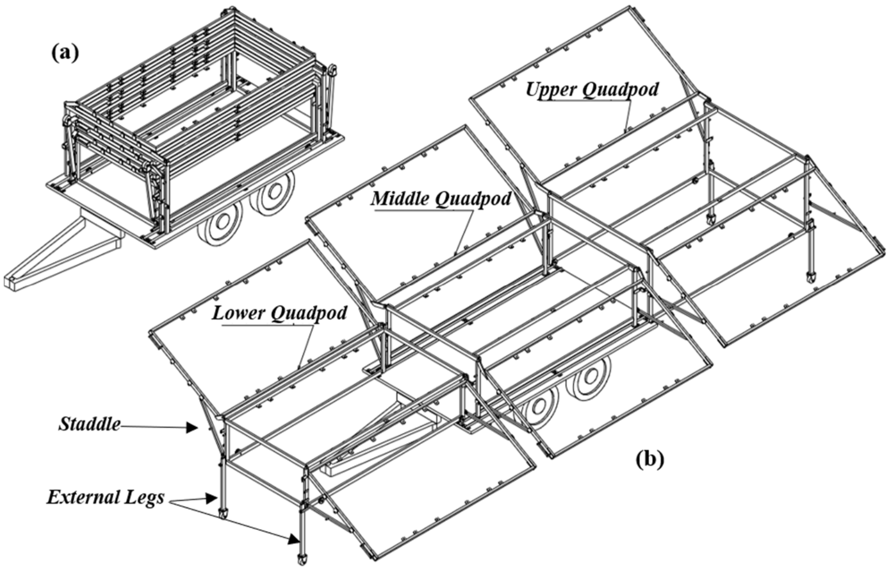


Figure 8: CAD views showcasing the final design of the FFS mounted on the trailer, illustrating the system in both (a) the folded state; and (b) the unfolded state.

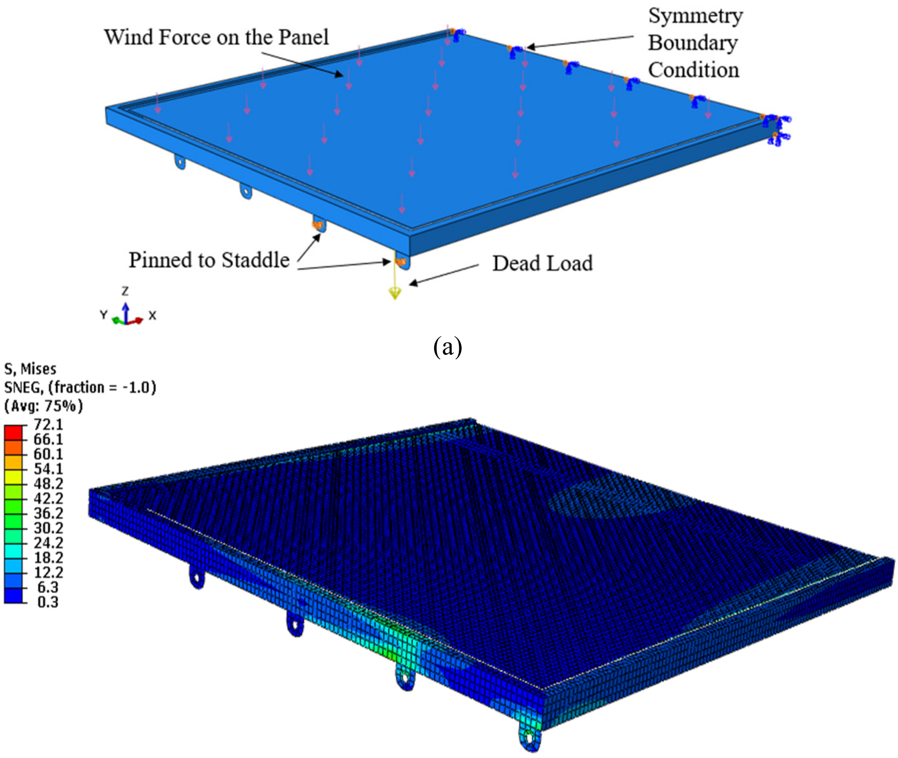
The fabrication of FFS utilized simple structural components made of mild steel. These include:

1. Brackets and connections: Flat parts with thickness ranging from 3 mm to 10 mm.
2. Rods: 10 mm diameter rods.
3. Staddles: Box tubes with dimensions of 20 mm × 20 mm × 2 mm.
4. Structure components: Box tubes with dimensions of 40 mm × 20 mm × 1.5 mm. These components are used for various parts of the FFS, including panel frames, legs, and columns.

The selection of the mentioned structural components was based on a thorough evaluation of various options, considering factors such as availability, manufacturing cost, and most importantly, high strength. The structural components were analysed using analytical calculations to assess their performance in bending, buckling, and shear force. Additionally, to ensure accuracy, the main structural parts were simulated using finite element method (FEM) software. This comprehensive analysis and simulation process ensured that the selected structural components meet the necessary strength requirements for the FFS. Furthermore, the overall weight of the FFS structure, which is 155 kg, demonstrates a favourable weight-to-strength ratio, further validating the design and ensuring an optimal balance between weight and structural integrity.

3.4 FEM investigation

To finalize the design of structural elements and the connection between the parts including flat brackets, joints, and the structural stability of the frames, the framed panel was simulated in Standard ABAQUS/CAE 2022 [17]. Static step was used to examine the framed panel against the boundary conditions and applied service loads including the elements' weight load (dead load) and the wind force on the panel as introduced in Section 3.1. For this, a symmetry boundary condition was used for the panel to simplify the calculation and pinned (free to rotate) boundary conditions were used for hinge connections. Fig. 9(a) shows the FEM view of the framed panel showing the applied loads and boundary conditions.



(a)

(b)

Figure 9: FEM simulation view of the framed panel in ABAQUS 2022, showing (a) the boundary conditions and applied loads; and (b) the Von mises stress distribution on the framed panel used in the FMSPS.

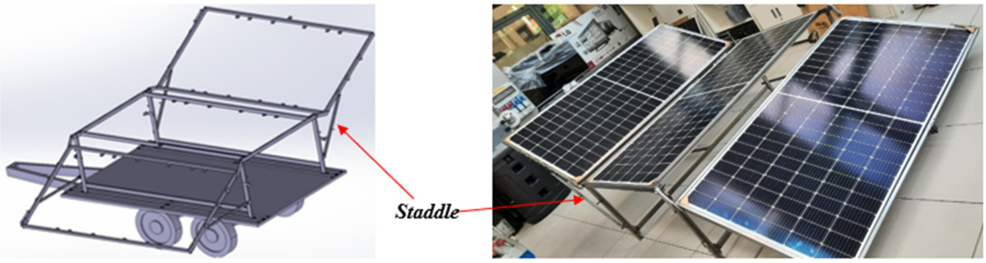
The solar PV panel was modelled as a coated tempered glass with a thickness of 3.2 mm, assuming it behaves as a perfectly elastic material. The mechanical properties considered for the panel were a Young's modulus of 70 GPa and a Poisson's ratio of 0.23 [18].

For the structural parts, mild steel was chosen as the material, considering its mechanical properties of a yield stress of 240 MPa, a Young's modulus of 210 GPa, and a Poisson's ratio of 0.3. It is important to note that the design aimed to keep the structural elements within the elastic region, disregarding the plastic region, in order to achieve higher reliability and durability. To discretize the model, a combination of quadrilateral and triangular continuum shell elements was used, considering the high ratio of the panel surface area to its thickness. Fig. 9(b) depicts the distribution of maximum von Mises stress on both the solar PV panel and its holding frame, along with the meshing system used for analysis. The maximum von Mises stress observed on the solar PV panel, located at its centre, is approximately 12 MPa. On the other hand, the holding frame experiences a maximum von Mises stress of up to

72 MPa. By considering the ultimate limit state design and comparing the yield strength of the material to the maximum von Mises stress obtained, a load safety factor of 3 was determined for the framed panel. This demonstrates a high level of reliability and ensures the structural integrity of the FFS.

4 FFS FABRICATION

Prior to commencing the full fabrication of the FFS, a prototype of the Middle quadpod, which represents the mid-section of the system, was created. The main objective of this prototype was to assess the performance and functionality of the folding mechanism and verify the stability of the structure under real-world conditions. As anticipated, the folding mechanism functioned successfully, and the prototype exhibited good level of stability. Fig. 10 showcases the CAD view of the detailed design of the Middle quadpod, as well as an image of the physical prototype fabricated based on this design. The whole structure was then built followed by the assembly of the electrical components, as well as the wiring for the FMSPS as illustrated by Fig. 11. The developed FMSPS has been used as an educational tool for school and community outreach (see Fig. 12) as well demonstrator for sustainable back-up power alternative to diesel generators for clean energy access in communities with high energy poverty.



(a) (b)

Figure 10: (a) CAD design; and (b) Prototype of the Middle quadpod, validating folding mechanism and stability.

(a) (b)

Figure 11: Final output of the FMSPS showing the system in both (a) the folded state; and (b) the unfolded state.

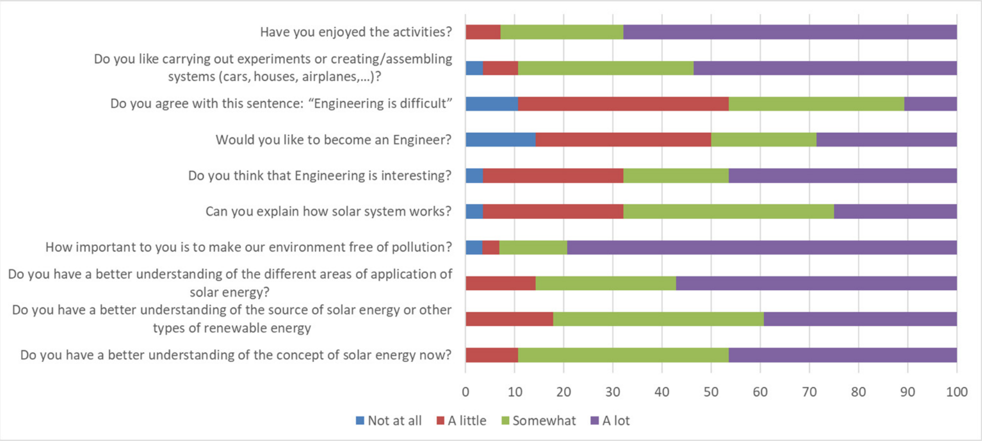


Figure 12: Typical feedback by pupils from an outreach event.

5 CONCLUSION

A 4 kW FMSPS with a 20 kWh energy capacity has designed and built to address the challenges faced in areas with limited access to electricity. While the FMSPS is designed for global applicability, it is specifically tailored to meet the needs of SSA, with a focus on Nigeria. Through a thorough review of conceptual designs, the FFS was developed to incorporate essential design aspects such as ease of manufacturing, manual operation, minimal maintenance, cost-effectiveness, high stability, reliability, safety, and lightweight construction. FEM simulations using ABAQUS 2022 validated the structural integrity of the FFS, ensuring its durability and reliability. The calculated load safety factor of 3 further confirmed its robustness.

Prototype of the FFS, demonstrated the ease of operation for folding and unfolding the framed panels, as well as high structural stability.

The full system, including the FFS and electrical components, was successfully fabricated and mounted on a trailer. By adopting the FMSPS, communities and businesses can access clean and affordable energy solutions, reducing dependence on fossil fuels and enhancing energy resilience. The completion of the FMSPS's final production demonstrates its viability as a practical and efficient solution for off-grid areas.

6 RECOMMENDATIONS FOR FUTURE RESEARCH

Further research focusing on investigation of the vibration effects caused by towing of the trailer, wind forces during operation, as well as the impact of high environmental temperatures in SSA on the reliability of the solar PV panels are suggested. The proposed research recommendation will provide insights into potential structural issues and particularly cell interconnection failures, allowing for design modifications and strategies to enhance the system's durability and longevity.

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