

Research Article

Benchmarking the Efficiency of Stand-Alone Solar Photovoltaic Systems in Nigeria

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Abstract

The growing demand for clean, reliable energy in off-grid and rural areas has made Solar Photovoltaic (PV) systems a viable alternative to conventional power sources; however, maximising their efficiency while balancing cost and reliability remains a significant challenge, especially in developing regions. This study presents a novel, locally engineered Pulse Width Modulation (PWM) Solar charge controller (SCC) designed to enhance energy conversion efficiency in stand-alone PV systems while maintaining affordability and ease of maintenance. Unlike existing studies that rely on imported or commercially available controllers, this research integrates indigenous design optimisation, locally sourced components, and context-specific testing under Nigerian climatic conditions. The locally constructed PWM charge controller was experimentally compared with a foreign PWM and a Maximum Power Point Tracking (MPPT) controller. Results showed that the MPPT controller achieved the highest efficiency (45-77.6%), while the PWM SCC recorded 43-66%. The inverter efficiency reached 89.7%, and the overall system efficiency was 24.4% for MPPT and 17.4% for the local PWM design. Despite its lower efficiency, the locally built PWM controller demonstrated significant potential as a cost-effective and reliable solution for rural electrification, particularly where access to advanced components is limited. The novelty of this study lies in the development and validation of a locally fabricated PWM SCC tailored to regional energy demands and environmental conditions, bridging the gap between performance optimisation and economic feasibility. It also offers a platform for standardising the overall efficiency of stand-alone Solar PV systems while providing practical insights for advancing contextualised renewable energy technologies that promote sustainable, community-driven electrification in Nigeria and similar developing regions.

Keywords

Solar Photovoltaic Systems, PWM, MPPT, Efficiency

1. Introduction

With the widening gap between electricity supply and demand and the continuous decline in fossil fuel reserves, nations worldwide are increasingly exploring alternative methods of generating electricity. Growing concerns over global warming and rapid climate change have further inten-

sified the pressure on power utilities to adopt cleaner energy sources. In recent years, distributed generation has emerged as a significant solution, enabling electricity production closer to load centres, thereby minimising transmission losses and enhancing the overall efficiency of power systems. Distrib-

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uted generation typically incorporates multiple renewable energy sources, with or without energy storage, to meet local electricity needs. Among these, photovoltaic (PV) systems have become the most widely adopted. Unlike conventional generation methods that demand constant monitoring and maintenance and are limited by geographical constraints, solar cells are highly versatile: they require minimal upkeep, can operate unattended, and, thanks to their flat-plate design, can be installed almost anywhere, including rooftops and even for charging electric or hybrid vehicles. The operation of these

solar cells is based on the PV effect [1].

Power can be extracted from solar irradiation using the PV system. The PV system converts sunlight into electrical power using the photovoltaic effect. Whenever light falls on a PV cell, the energy from a photon is transferred to the charge carriers. Then the charge carriers split into positively charged holes and negatively charged electrons due to the electric field across the junction. This results in current flow if a closed path is provided by connecting a load [2]. The basic operation of a PV cell is shown in Figure 1.

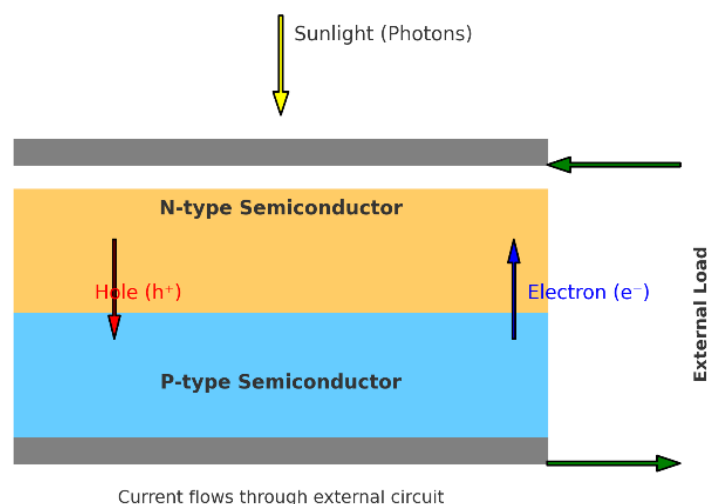


Figure 1. The basic operation of a PV cell [3].

The solar PV system comprises a PV module, Maximum Power Point Tracking (MPPT) techniques, a DC-DC converter, and an Inverter, as shown in Figure 2.

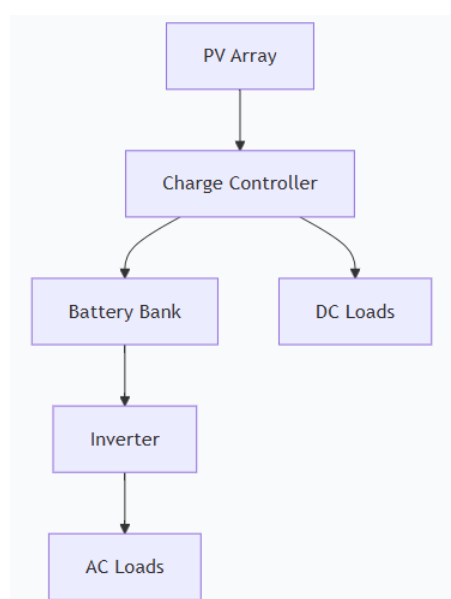


Figure 2. Main component of a Solar PV system.

A Solar PV panel absorbs the solar irradiance and converts it into electrical power. The MPPT technique is used to extract maximum power from the Solar PV panel and deliver it to the load. Under varying atmospheric conditions, MPPT always maximises power extraction from the panel [4]. A DC-DC converter serves as an interface between the PV module and the load in a PV system. Since solar power is intermittent, proper power backup is provided by utilising storage devices such as batteries and supercapacitors.

For AC loads and grids, an inverter converts DC to AC. It is estimated that 16% of the world's energy needs can be met by PV power generation by 2050. The main drawbacks of solar power generation are its low power conversion efficiency of about 9-17% and the fact that the output of a Solar PV panel depends on atmospheric conditions and temperature. The issues mentioned earlier can be mitigated by employing appropriate charge controllers. This controller exists mainly in two forms: pulse-width modulation (PWM) and MPPT controllers [5].

Moreover, recent literature reveals that more research has been carried out to increase the performance of the PV system. The efficiency can be increased by implementing highly efficient materials for manufacturing solar cells, finding appropriate controller techniques and avoiding load mismatch problems and on DC-DC converters.

This paper compares the efficiencies of MPPT and PWM under load conditions in a photovoltaic system. The structure of the paper is as follows. Section 1 presents the introduction. Section 2 provides an overview of MPPT and PWM techniques. Section 3 presents a detailed description of the materials and methods used. The test and result obtained from the experimental structure are given in Section 4. Conclusion and recommendations are presented in Section 5.

2. Study Background

With the expanding adoption of renewable energy, especially Solar PV systems, efficient battery charging is critical for system performance and longevity. Two dominant technologies manage the charging process by regulating power flow from Solar PV panels to batteries: PWM and MPPT controllers. This literature review critically examines recent studies comparing these two controller types, focusing on their operating principles, efficiencies, performance under varying conditions, economic considerations, and suitability for different applications. This assessment aids in understanding the advances and challenges each technology presents to optimize solar energy utilization.

PWM controllers regulate battery charging by gradually connecting and disconnecting the PV panel to the battery through high-frequency pulses (pulse width modulation) [6].

This method effectively reduces the panel voltage to match the battery and prevents overcharging. However, the main limitation lies in the fixed-voltage approach, which prevents the controller from extracting the maximum available power from the panels as environmental conditions vary (temperature, shading, irradiance). Consequently, PWM systems typically operate at the battery voltage, resulting in less efficient energy harvesting [7].

In contrast, MPPT controllers integrate advanced electronics and algorithms to track the PV module's maximum power point. This occurs when the voltage-current combination yields the highest power output. By dynamically adjusting the input voltage from the Solar PV panel, MPPT controllers convert excess voltage into additional current, maximising power transfer to the battery bank. The higher complexity and electronics enable MPPT systems to significantly improve charging efficiency, especially under variable environmental and load conditions [8].

Studies in Table 1, consistently show MPPT controllers outperform PWM in terms of energy harvesting and charging efficiency. For instance, MPPT systems routinely achieve peak efficiencies around 95% or higher, while PWM Solar Charge Controller (SCC)s range between 70-80% under typical conditions [9]. Research reveals that MPPT can increase harvested energy by 15-30%.

Table 1. Summary of empirical comparisons between PWM and MPPT SCC.

Research	Context	Key findings
[10]	The growing demand for affordable and reliable clean energy in off-grid areas has made Solar PV systems vital for rural electrification. This study presents a novel, locally developed PWM SCC designed for improved efficiency and cost-effectiveness using locally sourced components optimized for Nigerian conditions.	Solar charge controllers are mainly classified as Pulse Width Modulation (PWM) and Maximum Power Point Tracking (MPPT) types. The PWM controller operates as a simple switch between the solar panel and the battery, achieving 75-80% efficiency, while the MPPT controller dynamically adjusts the operating point to extract maximum power, converting excess voltage into current for higher utilization. Using the Perturb and Observe (P&O) algorithm, the MPPT controller attains 94-99% efficiency, making it a more effective solution for optimizing solar energy harvesting under varying conditions
[11]	This study presents a maximum power point tracking (MPPT)-based SCC designed for efficient battery charging in stand-alone photovoltaic systems. The proposed system enhances conventional PWM-based controllers by integrating MPPT technology with IoT-enabled monitoring for improved charging control and user interaction.	Simulation results show that the MPPT-based controller achieved 94% efficiency, significantly outperforming the PWM-based controller at 65%. The prototype also includes a Wi-Fi module for real-time monitoring of voltage, current, and battery status, with automatic disconnection and user notifications to prevent overcharging, ensuring both efficiency and safety
[12]	This study presents the design and implementation of Arduino-based PWM and MPPT SCCs using a buck converter topology for stand-alone photovoltaic systems where the PV voltage exceeds the battery voltage. The design process includes simulation in Proteus, hardware construction, and a modified Perturb-and-Observe (P&O) MPPT algorithm with	Experimental and real-time measurements show that both controllers can safely charge a 12 V battery, but the MPPT design achieved 9% higher efficiency than the PWM controller. The system, monitored using an Arduino data logger, demonstrates that the MPPT-based controller offers superior energy conversion efficiency and practical applicability for

Research	Context	Key findings
[13]	variable-duty-cycle control for improved performance.	small-scale 12 V, 100 Wp PV systems
	People in remote areas often face difficulties accessing electricity despite their regions' high solar potential, as observed in parts of Indonesia. This study investigates how variations in weather and solar irradiance affect battery output performance in Solar PV systems	Using a SEPIC converter with PI control and a P&O-based MPPT algorithm, the system achieved efficiencies ranging from 73% to 97%. Even under low solar radiation, the converter maintained an efficiency above 90%, proving its suitability for reliable solar power generation in remote locations.

These findings suggest that while MPPT controllers dominate in utility-scale and grid-connected systems, PWM controllers remain relevant in small-scale, off-grid installations where simplicity and affordability are prioritized.

Measuring system efficiency requires evaluating energy flows across the PV array, controller, battery, and load. Standard metrics include array efficiency, inverter efficiency, battery round-trip efficiency, and the performance ratio (PR) as defined by the International Electrotechnical Commission (IEC) 2021. Loss mechanisms include soiling, shading, wiring resistance, inverter conversion, and controller switching losses [14]. Studies report that overall system efficiency for small-scale solar installations typically ranges from 60% to 80%, depending on component quality and environmental conditions (Wu et al., 2020; Parida & Debbarma, 2019).

Despite abundant studies on MPPT technologies, fewer works focus specifically on PWM controller design optimization and its role in overall system efficiency. Moreover, many empirical studies fail to adhere strictly to IEC 61724-1 protocols, limiting comparability of results. Finally, limited attention has been paid to the contextual appropriateness of PWM in developing regions where cost constraints and component availability shape design decisions [15]. These gaps highlight the need for detailed PWM controller design studies coupled with rigorous system efficiency evaluation.

3. Materials and Methods

This section outlines the experimental setup, methodologies, and procedures used to evaluate the efficiencies of the Solar PV system involving the charge controllers and batteries as they are used in off-grid applications. The study utilizes a mixed-methods approach combining both qualitative and quantitative data to ensure a comprehensive understanding of the topic.

In this study, an experimental method was used to obtain the data. This was carried out in the power systems laboratory of the electrical & Electronic Engineering Department of the Kwara State Polytechnic, Ilorin, Nigeria. The block diagrams for the experimental connection conditions are shown in Figure 3.

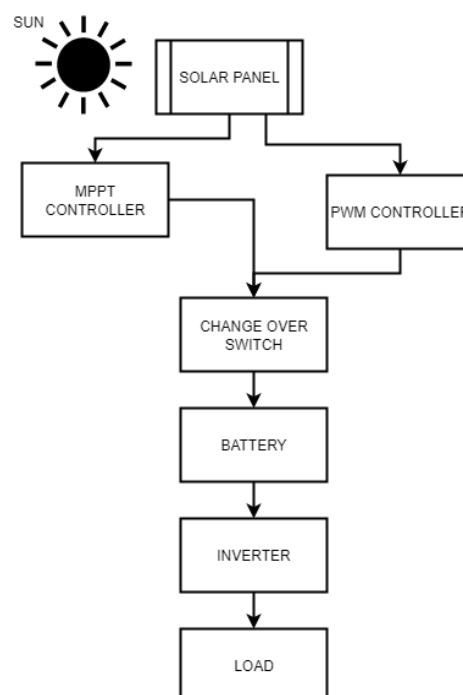


Figure 3. Block diagram of the experimental connections.

Actual experimental setups showing the device arrangements are shown in Figure 4. The connections of the SCCs were made under on-load conditions using a 100W Solar PV panel, a 12V, 1300mAh lithium-ion battery for each charge controller, and a 2-set of 5W, 12V DC bulbs connected to the inverter output terminal, as shown in Figure 4, for load assessment. The Solar PV panel was placed under the same solar intensity and angular displacement, while the panel voltage, battery charging voltage, and charging current were recorded using a digital Multimeter at 60-minute intervals. In the setup, a knife switch was used to switch the power supplied to the battery between the PWM and MPPT SCCs. Other components involved in the connection include a 500W high-frequency inverter, a 4mm DC cable and a 1.5mm AC cable for lighting ports, a 2.5mm AC cable for the socket outlet, a lampholder, and a socket outlet with a pattress. Each experimental setup used three Multimeters, with two set to a

200 Vdc range and connected across the Solar PV panel and battery to determine the Solar PV panel and battery voltages, respectively. In contrast, the third meter was set to the 20A DC range and connected in series with the battery to measure the charging current. In Figure 4, M1, M2, and M3 are measurement points for the MPPT, foreign PWM SCC, and local PWM SCC, respectively, while M4, M5, and M6 are the inverter, battery, and load segments, respectively, where the data were taken.



Figure 4. System Configuration.

4. Results

The results are analysed to address the hypotheses posed in the introduction are presented in Table 2. The experimental data shown in Table 2 show voltage, current, and power for the Solar PV panel. Table 3 shows same for the foreign MPPT charge controller. From the experiment, the overall efficiency of these parameters was determined.

Table 2. The results of voltage, current and output power of the Solar PV panel.

Time	Voltage (V)	Current (A)	Power Output (W)
10:45 am	14.50	2.08	30.16
11:45 am	15.00	2.26	33.90
12:45 pm	15.80	2.95	46.61
1:45 pm	16.30	3.59	58.52
2:45 pm	16.10	3.02	48.62
3:45 pm	15.60	2.92	45.56
4:45 pm	14.90	2.35	35.02

Choosing a value of the output power of the Solar PV panel at its peak of 58.517 in order to calculate the efficiency of the Solar PV panel at 1000w/m². The results obtained is shown below:

$$\text{Efficiency } (\eta) = \frac{\text{Power output}}{\text{power input}} \times 100$$

Where:

Power input = 100w

$$\eta_{\text{solar PV}} = \frac{58.517}{100} \times 100$$

Efficiency ($\eta_{\text{solar PV}}$) of the Solar PV panel = 58.7% at the maximum irradiance of 1000W/m².

Efficiency of the MPPT controller used ranges from (45-77.6)%.

Table 3. Performance of the MPPT charge controller.

Time	Power input (W)	Power output (W)	Efficiency (%)
10:45am	30.16	13.79	45.7
11:45am	33.90	20.28	61.3
12:45pm	46.61	33.25	71.3
1:45pm	58.57	45.44	77.6
2:45pm	48.62	38.08	65.0
3:45pm	45.52	29.04	49.6
4:45pm	35.05	20.80	35.6

For the PPT

$$\eta_{SCC} = \frac{\text{Power output to the battery from the MPPT SCC}}{\text{power input from the Solar PV panel}} \times 100$$

Figure 5 describes the graph representation of the power input, power output and efficiency of the MPPT SCC.

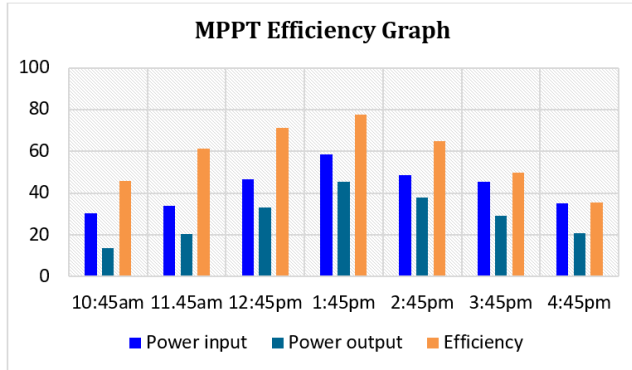


Figure 5. The graph shows the MPPT SCC power input, power output, and efficiency over time.

Table 4 shows the readings taken for the foreign PWM charge controller which is same as the locally made PWM charge controller.

Table 4. Power input, power output and efficiency of the PWM SCC.

Time	Power input (W)	Power output (W)	Efficiency (%)
10:45am	30.16	12.72	42.10
11:45am	33.9	16.63	49.06
12:45pm	46.61	24.70	52.90
1:45pm	58.52	23.76	40.60
2:45pm	48.62	20.25	41.64
3:45pm	45.56	21.93	37.40
4:45pm	35.02	14.88	25.30

For the PWM SCC

$$\eta = \frac{\text{Power output to the battery from the PWM SCC}}{\text{power input from the Solar PV panel}} \times 100$$

Efficiency of foreign PWM controller ranges from (42-55)%

Figure 6 describes the graph representation of the power input, power output and efficiency of the PWM SCC.

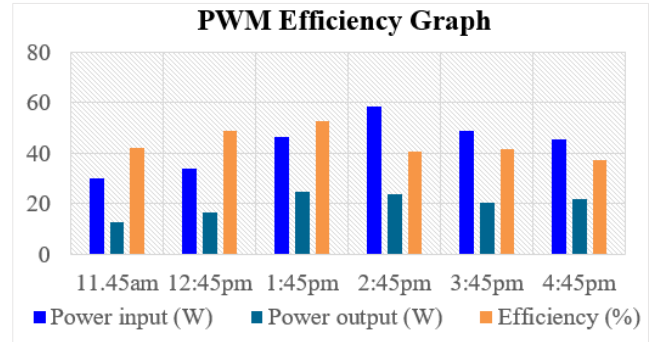


Figure 6. The graph shows the power input, power output, and efficiency of the foreign PWM SCC over time.

The charging current for 1300mAh battery was calculated. As we know that charging current should be 10% of the Ah rating of battery.

Therefore,

Charging current for 1300mAh Battery

$$I = 1300mAh \times (10/100)$$

$$I = 0.13Amps.$$

But due to some losses, 0.13 - 0.15 Amperes for batteries charging purpose instead of 0.13Amps was considered.

Battery Charging Time:

Taking 0.13 Amp for charging purpose,

Then,

$$\text{Charging time for 1300mAh battery} = \frac{1300mAh}{0.13} = 10 \text{ hours}$$

Practically, it has been noted that 40% of losses occurs in case of battery charging.

Then:

$$1300mAh \times (40/100) = 0.52mAh$$

Therefore, 1300 + 0.52 = 1300.52mAh (1300mAh + Losses)

Now Charging Time of battery = Ah ÷ Charging Current

Putting the values;

$$1300.52mAh \div 0.13 = 10.004hrs$$

Therefore, the 1300mAh battery would take 10 Hours to fully charge in case of the required 0.13A charging current.

Calculating Discharge Time:

$$\text{Discharge time(hours)} = \frac{\text{battery capacity}}{\text{current drawn}}.$$

A 1300mAh battery with an 800mAh load:

$$\text{discharge time (hours)} = \frac{1300\text{mAh}}{800\text{mAh}} = 1.625\text{hrs}$$

Calculating Depth of Discharge (DoD):

$$\text{DoD} = \frac{\text{discharge capacity}}{\text{total capacity}} \times 100$$

1300mAh battery discharges 800mAh:

$$\text{DoD} = \frac{800\text{mAh}}{1300\text{mAh}} \times 100$$

$$\text{DoD (\%)} = 61.54$$

Taking the DoD as the efficiency of the lithium battery used,
 $\eta_{\text{battery}} = 61.54\%$

EFFICIENCY OF THE INVERTER

The experimental data shown below are for the inverter;
 from these results, the inverter's efficiency was determined.

In determining the efficiency of the inverter:

$$\text{Energy of the battery (Wh)} = \frac{1300 \times 12}{1000}$$

$$\text{Energy of the battery (Wh)} = 15.6\text{Wh}$$

Energy Supplied to Load

The load of 28W was powered for 30 minutes = 0.5 hours,

so:

$$\text{Energy Supplied} = 28\text{W} \times 0.5\text{h} = 14\text{Wh}$$

$$\eta_{\text{inverter}} = \frac{14\text{Wh}}{15.6\text{Wh}} \times 100$$

$$\eta_{\text{inverter}} = 89.7\%.$$

Overall Efficiency of The Solar System

$$\eta_{\text{total}} = \eta_{\text{solar PV}} + \eta_{\text{SCC}} + \eta_{\text{battery}} \times \eta_{\text{inverter}}$$

Efficiency of the system with the MPPT controller

$$\eta_{\text{MPPT SCC}} = 0.58 \times 0.77 \times 0.6154 \times 0.897$$

$$\eta_{\text{MPPT SCC}} = 24.4\%.$$

Efficiency of the system with the PWM controller

$$\eta_{\text{PWM SCC}} = 0.58 \times 0.55 \times 0.6154 \times 0.89$$

$$\eta_{\text{PWM SCC}} = 17.4\%$$

5. Conclusion

This study designed and tested a locally constructed PWM SCC and compared its performance with a foreign PWM and an MPPT controller in a stand-alone PV system. The results confirmed that the MPPT controller consistently achieved

higher efficiency, particularly under varying irradiance conditions, with overall system efficiency reaching 24.4%, compared to 17.4% for the PWM-based systems. Nonetheless, the locally developed PWM SCC demonstrated stable operation, acceptable efficiency (up to 66%), and cost-effectiveness, making it suitable for basic off-grid applications where affordability is a priority. These findings highlight the trade-off between performance and cost, suggesting that while MPPT technology remains the superior option for maximizing energy utilization, improved local PWM designs can provide a reliable and economically viable solution for rural and resource-constrained settings.

In the future, AI-based MPPTs using neural networks, fuzzy logic, or genetic algorithms that learn and adapt to changing irradiance and temperature should be researched to achieve faster, more stable power tracking than traditional methods. Hybrid MPPTs, which combine classical and intelligent algorithms such as P&O and Fuzzy Logic, offer improved convergence speed and performance under partial shading. These advances enable smarter, more efficient, and reliable Solar charge control, ideal for remote and stand-alone PV systems.

Abbreviations

AC	Alternating Current
DC	Direct Current
IEC	International Electrotechnical Commission
MPPT	Maximum Power Point Tracking
P&O	Perturb and Observe
PI	Proportional-Integral
PWM	Pulse Width Modulation
PV	Photovoltaic
SCC	Solar Charge Controller
SEPIC	Single-Ended Primary Inductor Converter

Author Contributions

Olatunji Ahmed Lawal: Conceptualization, Funding Acquisition, Investigation, Methodology, Project Administration, Supervision

Mustapha Zubair Oba: Data curation, Resources, Validation

Kabiru Lateef: Formal Analysis, Writing – review & editing

Abdulhameed Adeyemi Jimoh: Investigation, Software, Visualization

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Data Availability Statement

The data is available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare no conflicts of interest.

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