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ASSESSMENT OF SOLAR PHOTOVOLTAIC INTEGRATION FOR RELIABLE POWER SUPPLY IN HOSPITAL LABORATORIES

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Abstract. Electrical power is critical to hospital laboratories to ensure the continuous operation of diagnostic equipment, sample maintenance, and prompt availability of results. The national grid is incapable of providing this in many developing countries. Frequent outages, voltage fluctuations, and a default fallback of a diesel generator that is budget and environment killers. Solar PV (PV) is a viable solution to this cycle. This paper performs a review of literature, technical reports and documented case studies of solar PV integration for enhancing power reliability in hospital laboratories in developing countries. The evaluation focuses on the standard laboratory energy demands, the limitations of the current power supply systems and the technical and economic benefits of a hybrid solar PV system. The assessment is based on four criteria: reliability, costs, sustainability, and implementation. The estimated energy consumed in the laboratory was 91.42kWh/day, whereas the average monthly outages were reduced from 52 hours to approximately 1 hour, the daily operating time of the generator was reduced from 18 hours to 2 hours and the monthly operating cost of the generator was reduced from ₦1,430,000 to ₦285,000. The total hybrid system also resulted in CO_2 emissions of more than 85% lower. High installation costs and weather variability continue to be significant challenges and can be overcome with careful planning and policy support. The results show that PV systems are a feasible and sustainable solution, especially in areas with limited resources where grid electricity is no longer feasible.
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Keywords: Photovoltaic, Hospital Laboratories, Energy system, Healthcare, Load profile

1. Introduction

Hospital laboratories sit at the intersection of medicine and microscopic analysis (Alruways et al., 2025). Equipment such as centrifuges, biochemistry analyzers, and cold storage units require continuous and stable electrical supply to function within acceptable parameters (Nam and Park, 2025). Power interruptions of even short duration risk compromising sample integrity, disrupting ongoing analytical procedures, and introducing errors into results that inform patient management decisions (Nam and Park, 2025).

The electricity infrastructure in many developing countries, Nigeria among them, makes this risk routine rather than exceptional (Adebayo and Ainah, 2024). The national grid in Nigeria is characterized by persistent outages, voltage instability, and load shedding that can last for hours (Adebayo and Ainah, 2024). According to the World Bank, Nigeria's power sector has long struggled to supply reliable electricity to hospitals and other essential institutions, with many facilities experiencing fewer than twelve hours of grid power per day (Yusuf, 2025). Healthcare facilities respond to this by running diesel generators almost continuously, an arrangement that works until the fuel runs out or fuel prices rises all of which happen regularly (Felice et al., 2023).

Solar photovoltaic (PV) technology has become a credible alternative to this problem (Castellano et al., 2024). When paired with battery storage and connected to the grid and generator infrastructure in a hybrid configuration, solar PV can supply a stable, continuous power source that reduces both generator dependence and grid vulnerability (Rajendran et al., 2025).

Adopting solar PV in a hospital laboratory is not simply a matter of installing panels on a roof. Energy demands vary, system sizing matters, and integrating new technology into existing infrastructure carries technical and financial implications that must be carefully assessed (Maggu et al., 2025). This paper works through those considerations systematically.

2. Materials and Method

2.1. Study Approach

This study uses a literature-based analytical approach. Rather than field installations or controlled experiments, the evaluation draws on published scholarly articles, technical reports from international energy and health organizations, and documented case studies of solar PV deployment in healthcare settings, particularly in sub-Saharan Africa and other developing regions.

The approach is deliberately practical. Complex simulation models and detailed mathematical optimization are beyond the scope of what this type of review can reliably produce, and they are not necessary for the core questions being asked. What this study can do is synthesize evidence from multiple credible sources into a structured assessment of whether solar PV integration is a viable solution for hospital laboratory power reliability.

Four evaluation criteria frame the analysis: reliability, cost implications, sustainability, and ease of implementation. These are treated as equally weighted, since each addresses a different dimension of the problem that cannot be meaningfully ranked against the others without site-specific data. The criteria allow a structured comparison between conventional power supply options and hybrid systems that incorporate solar PV.

2.2. Hospital Laboratory Energy Use

Hospital laboratories are among the most energy-intensive areas within any healthcare facility (Jovičić and Milinković, 2025). Unlike administrative offices or wards, where power demand fluctuates with the time of day, laboratory operations maintain a relatively constant load (Jovičić and Milinković, 2025). Ventilation must remain continuous to protect both samples and personnel (Jagtap et al., 2023).

The dominant energy consumers in a typical hospital laboratory include hematology and biochemistry analyzers, centrifuges, incubators, and microscopes (Jovičić and Milinković, 2025). These instruments require stable voltage; even minor fluctuations can affect measurement accuracy and, in some cases, damage sensitive components. Alongside diagnostic equipment, cold storage systems such as refrigerators, freezers, and cryogenic units represent a constant and non-negotiable load, since temperature excursions compromise reagents, blood products, and biological specimens (Jovičić and Milinković, 2025).

Lighting, air conditioning, and ventilation add to the base load. In laboratories that operate around the clock, these systems must be sized for continuous rather than intermittent use (McQuiston et al., 2023). The combined effect is a facility that is, in energy terms, always on, with very little tolerance for interruption.

2.3. Solar PV System Overview

A solar PV system converts sunlight into direct current (DC) electricity through photovoltaic modules (Gusev et al., 2024). The amount of power generated depends on the intensity of solar radiation, panel efficiency, orientation, and local shading conditions. Because most laboratory equipment operates on alternating current (AC), an inverter converts the DC output into usable power (Gusev et al., 2024). For sensitive medical equipment, pure sine wave inverters are recommended, as they replicate the smooth AC waveform that grid-electricity provides and avoid the harmonic distortion that can affect instrument performance (Ojo et al., 2025).

Battery storage is a key component in settings where grid reliability is low. Batteries store surplus energy generated during peak sunlight hours and discharge it during periods of low generation or at night, ensuring that critical loads remain powered regardless of conditions outside (Aslam et al., 2022). A charge controller sits between the panels and the battery bank, regulating charge rates to prevent overcharging and extend battery life a component that is easy to overlook in system design but critical to long-term performance (Aslam et al., 2022).

In hybrid configurations, the solar PV system operates alongside the grid and a backup generator as shown in fig. 1. During daylight hours with adequate solar radiation, PV generation handles a significant portion of the load, reducing grid draw and generator run time (Maitra et al., 2024). When solar output drops below what the load requires, the system draws from battery storage first, then switches automatically to grid or generator supply. This layered approach is what gives hybrid systems their reliability advantage over any single power source used alone.

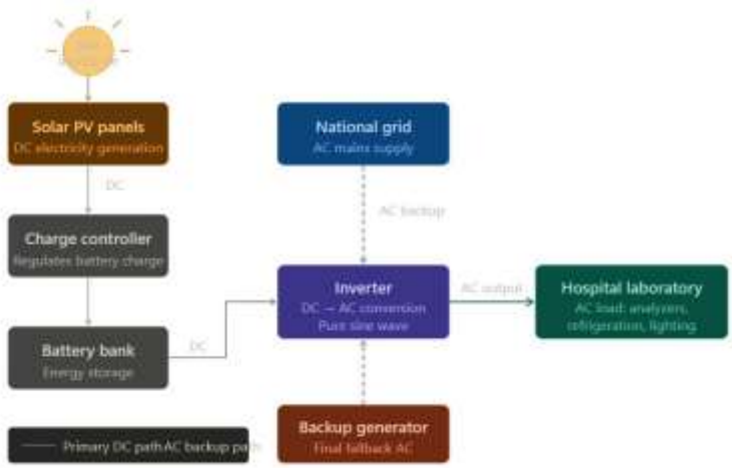

Figure 1: Schematic diagram of a hybrid solar PV system for hospital laboratory power supply

2.4. Evaluation Criteria

Four criteria guide the comparative assessment of power supply options for hospital laboratories. Each is treated qualitatively, consistent with the literature-based nature of the study.

2.4.1 Reliability

Reliability refers to the ability of a power system to deliver continuous, stable electricity without interruptions or dangerous voltage fluctuations. For a hospital laboratory, this is the primary requirement; all other considerations are secondary to it (Lazaroiu et al., 2023).

2.4.2 Cost implications

Cost implications cover the full economic picture initial installation expenditure, ongoing operation and maintenance costs, fuel consumption, and the long-term savings that accrue from reduced generator use (Akangbe and Sharifi, 2025). In resource-constrained settings, the balance between upfront investment and lifecycle cost is often the deciding factor in whether a system gets adopted.

2.4.3 Sustainability

Sustainability examines the environmental impact, principally, whether a system reduces greenhouse gas emissions and dependence on fossil fuels. This matters both for global climate goals and for the immediate working environment within and around a healthcare facility (Lazaroiu et al., 2023).

2.4.4 Ease of implementation

Ease of implementation addresses the practical side of adoption: whether a system can be scaled to match available resources, how compatible it is with existing infrastructure, what space it requires, and what level of technical expertise it demands to install and maintain (Vodapally and Ali, 2022).

3. Results and Discussion

For all quantitative results given in the results section, the values are only simulated quantities based upon literature reported values, and are only given as a means to illustrate comparative system performance.

3.1. Simulated Operational Datasheet

Hospital laboratories operate under electrical demands that are both continuous and highly sensitive to interruptions. Due to the literature-based nature of this study, representative operational values were synthesized from published healthcare energy studies and typical laboratory load characteristics reported in comparable developing-country healthcare facilities (Jovičić and Milinković, 2025; Lawal et al., 2022). The simulated dataset was used to evaluate the technical and economic performance of different power supply configurations for hospital laboratory applications.

The selected equipment represents the major electrical loads commonly found in medium-scale hospital laboratories, including diagnostic systems, refrigeration units, ventilation systems, and supporting infrastructure as seen in table 1. Estimated daily energy consumption was calculated using equipment power ratings and average operational durations under normal laboratory operating conditions (Brown et al., 2023).

Table 1: Daily Energy Consumption of Hospital Laboratory Equipment (Alghamdi and Krarti, 2025; van Lierde, 2024).

Equipment	Quantity	Power Rating (W)	Operating Hours/Day	Daily Energy Consumption (kWh/day)
Hematology Analyzer	1	450	10	4.50
Biochemistry Analyzer	1	600	10	6.00
Centrifuge	2	300	5	3.00
PCR Machine	1	1000	4	4.00
Laboratory Refrigerator	2	250	24	12.00
Deep Freezer	1	400	24	9.60
Incubator	1	350	24	8.40
Air Conditioning Unit	2	1500	10	30.00
Lighting System	12	20	12	2.88
Ventilation System	2	150	24	7.20
Computers and Accessories	4	120	8	3.84

The simulated load assessment indicates that cooling and environmental control systems account for the largest proportion of total energy consumption within the laboratory environment (Alghamdi and Krarti, 2025). Air conditioning systems alone contribute approximately 32.8% of the estimated daily demand, reflecting the continuous thermal regulation requirements necessary for equipment stability and personnel comfort (van Lierde, 2024). Refrigeration and cold storage systems also represent a significant base load due to their uninterrupted operating cycles (Alghamdi and Krarti, 2025).

Diagnostic and analytical equipment such as hematology analyzers, biochemistry analyzers, centrifuges, and PCR systems collectively contribute a substantial portion of the remaining demand and require stable voltage conditions for accurate operation (Badnjević et al., 2026). The resulting load profile demonstrates that hospital laboratories maintain a relatively constant energy demand throughout the day, making them highly dependent on reliable and uninterrupted electricity supply.

The estimated daily energy demand of 91.42 kWh/day provides a realistic basis for evaluating the suitability of hybrid solar photovoltaic systems for hospital laboratory applications under developing-country operating conditions (Gesteira et al., 2021).

3.2. Comparative Reliability Analysis

Reliable electricity supply remains the most critical operational requirement in hospital laboratories due to the sensitivity of diagnostic equipment and the continuous nature of laboratory activities (Lazaroiu et al., 2023). To evaluate the effect of solar photovoltaic integration on laboratory power reliability, a comparative assessment of four power supply configurations was conducted using simulated operational performance indicators. The evaluated configurations include grid-only supply, generator-only supply, solar PV combined with grid supply, and a full hybrid configuration consisting of solar PV, battery storage, grid connection, and generator backup (Lazaroiu et al., 2023).

The assessment considered three major reliability indicators: average monthly outage duration, voltage stability, and average generator runtime as seen in table 2. These indicators were selected because they directly influence laboratory operational continuity, equipment protection, and long-term system sustainability.

Table 2: Comparative Reliability Performance of Power Supply Configurations (Lazaroiu et al., 2023; (Mapfumo, 2022).

Power System	Average Monthly Outage Duration (hrs/month)	Voltage Sustainability (%)	Generator Runtime (hrs/day)
Grid Only	52	68	0
Generator Only	14	82	18
Solar PV + Grid	6	92	5
Solar PV + Grid + Generator	1	98	2

The results indicate that the grid-only configuration provides the lowest reliability due to frequent outages and unstable voltage conditions, consistent with reported electricity challenges in Nigeria (Adebayo and Ainah, 2024). Generator-only systems improve continuity but require extended operating periods, resulting in higher fuel consumption and maintenance demands (Ekeriance and Barididum, 2025).

Integrating solar PV with grid supply significantly improves reliability by reducing outage duration and generator dependence. The full hybrid configuration achieved the best performance, reducing outage duration to approximately 1 hour per month while maintaining high voltage stability. Generator runtime also decreased substantially from 18 hours/day in generator-only systems to approximately 2 hours/day in the hybrid configuration (Mapfumo, 2022).

These results demonstrate that hybrid solar PV systems provide a more reliable and operationally sustainable solution for hospital laboratory power supply in grid-unstable environments as shown in fig. 2.

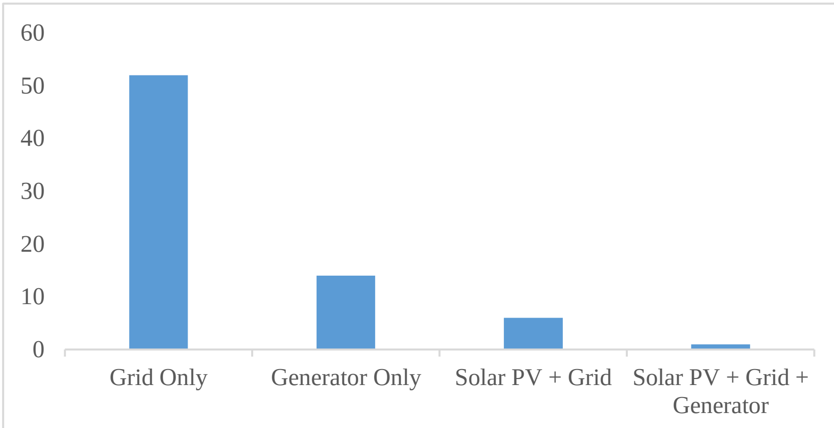

Figure 2: Average Monthly Outage Duration for Different Power Supply Configurations

3.3. *Economic Performance Analysis*

The economic performance of each power supply configuration was evaluated using estimated monthly fuel, maintenance, and electricity costs from literature reported data. The assessment focused on the long-term operational expenditure associated with each system, particularly the impact of generator runtime reduction achieved through solar PV integration as shown below in table 3.

Table 3: Table showing Monthly Operational Cost Comparison (Ekeriance and Barididum, 2025; Kahwash et al., 2021; Maggu et al., 2025)

Power System	Fuel Cost (₦/month)	Maintenance Cost (₦/month)	Electricity Cost (₦/month)	Total Monthly Cost (₦/month)
Grid Only	0	20,000	450,000	470,000
Generator Only	1,250,000	180,000	0	1,430,000
Solar PV + Grid	250,000	50,000	180,000	480,000
Solar PV + Grid + Generator	120,000	45,000	120,000	285,000

The simulated results show that generator-only systems have the highest operational cost due to continuous fuel consumption and increased maintenance requirements associated with prolonged engine operation. Fuel expenses alone account for a significant portion of the monthly expenditure, making generator dependence economically unsustainable for many healthcare facilities over extended periods (Ekeriance and Barididum, 2025).

Although the grid-only configuration presents lower maintenance costs, unreliable electricity supply limits its practical suitability for hospital laboratory operations (Kahwash et al., 2021). Frequent outages and voltage instability often require additional protective equipment and operational interruptions, which may indirectly increase laboratory operating costs.

The integration of solar PV significantly reduces operational expenditure by lowering generator runtime and minimizing dependence on unstable grid supply (Kahwash et al., 2021).

The solar PV + grid configuration demonstrates considerable reductions in fuel and maintenance costs compared to generator-only systems as shown in fig. 3. However, the full hybrid configuration achieved the best overall economic performance, with an estimated monthly operating cost of approximately ₦285,000/month (Maggu et al., 2025).

These findings indicate that despite the relatively high initial installation cost associated with hybrid solar PV systems, the reduction in fuel consumption, maintenance frequency, and generator operating hours provides substantial long-term economic benefits. The results therefore support the growing adoption of hybrid renewable energy systems for healthcare facilities in developing countries (Maggu et al., 2025).

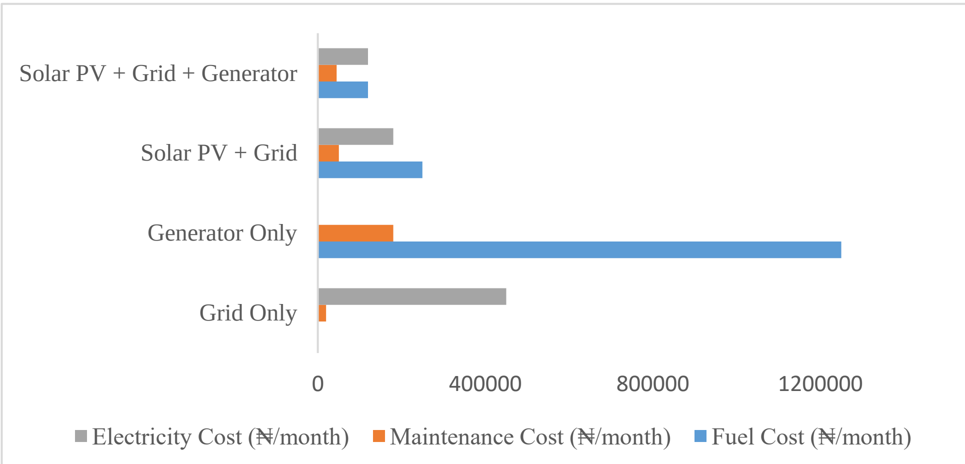

Figure 3: Estimated Monthly Operational Cost for Different Power Supply Configurations

3.4. *Environmental Impact Assessment*

The environmental impact of different power supply configurations was evaluated based on estimated diesel consumption and associated carbon dioxide (CO_2) emissions (Felice et al., 2023). This analysis is particularly important in hospital laboratory settings, where continuous generator use contributes significantly to greenhouse gas emissions and local air pollution.

Diesel consumption values were estimated based on typical generator efficiency under hospital laboratory load conditions, while CO_2 emissions were calculated using a standard emission factor of approximately 2.68 kg CO_2 per liter of diesel consumed as seen in table 4 (Felice et al., 2023).

Table 4: Comparative Analysis of Power Supply Configurations for Hospital Laboratories (Felice et al., 2023; Matragi, 2025; Bošnjaković et al., 2023)

Power System	Diesel Consumption (Liters/month)	Estimated CO_2 Emission (kg/month)
Generator Only	2100	5630
Solar PV + Grid	620	1660
Solar PV + Grid + Generator	300	804

The results indicate that generator-only systems have the highest environmental impact due to continuous diesel combustion, resulting in significantly higher CO_2 emissions (Matragi, 2025). This aligns with studies highlighting the environmental burden of diesel-based power generation in healthcare facilities across developing regions.

The integration of solar photovoltaic systems leads to a substantial reduction in diesel consumption and associated emissions (Bošnjaković et al., 2023). The full hybrid configuration demonstrates the lowest environmental impact, achieving an estimated reduction of more than 85% in CO_2 emissions compared to generator-only systems. This reduction is primarily due to reduced generator runtime and increased reliance on renewable energy sources (Bošnjaković et al., 2023).

These findings highlight the environmental advantages of hybrid solar PV systems, particularly in sensitive facilities such as hospital laboratories where sustainability and operational reliability must be balanced as shown in fig. 4.

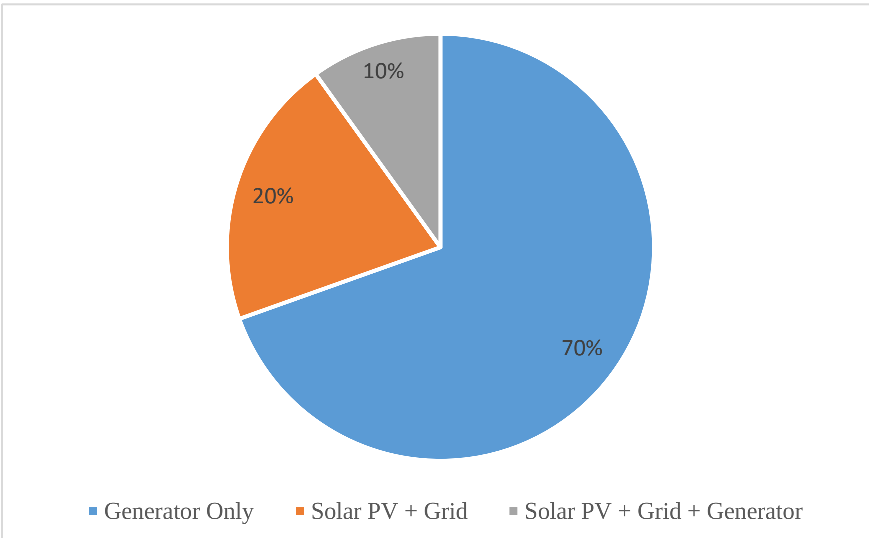

Figure 4: Estimated CO_2 Emissions for Different Power Supply Configurations

3.5. Comparative Analysis of Power Supply Options

A comparison of the evaluated power supply configurations is necessary to identify the most suitable option for hospital laboratory applications (Giwa et al., 2023). This comparison is based on the combined outcomes of reliability, economic performance, and environmental impact assessments presented in the previous subsections (Arowolo et al., 2025).

Across all performance indicators, the full hybrid system (solar PV, grid, battery storage, and generator backup) demonstrates superior performance compared to other configurations (Njoku et al., 2026). It consistently achieves the lowest outage duration, highest voltage stability, lowest operational cost among renewable-integrated systems, and the lowest environmental impact in terms of CO_2 emissions (Njoku et al., 2026).

The grid-only configuration performs poorly in terms of reliability due to frequent power interruptions, despite relatively moderate cost implications. This makes it unsuitable for critical laboratory operations where uninterrupted power supply is essential. The generator-only configuration, while offering improved continuity, is associated with significantly higher operational costs and environmental burden, making it economically and environmentally unsustainable over long-term operation (Ibegbulam et al., 2023).

The solar PV + grid configuration presents a balanced improvement, particularly in reducing generator dependency and improving voltage stability (Atawi et al., 2022). However, its performance is still limited by grid instability and partial reliance on non-renewable energy sources.

Overall, the results indicate that hybridization of energy sources provides the most effective strategy for achieving reliable, cost-efficient, and environmentally sustainable power supply in hospital laboratories, particularly in regions with unstable grid infrastructure.

4. Conclusion

This study assessed the integration of solar photovoltaic systems into hospital laboratory power supply infrastructure, with a focus on improving reliability, reducing operational costs, and minimizing environmental impact. A comparative evaluation of four power supply configurations was conducted using a simulated operational dataset derived from literature-based load characteristics and standard energy performance assumptions.

The results indicate that hospital laboratories exhibit relatively high and continuous energy demand, primarily driven by diagnostic equipment, refrigeration systems, and environmental control units. Reliability analysis showed that grid-only systems are highly vulnerable to frequent outages, while generator-only systems, although more reliable in continuity, are associated with high fuel consumption and operational inefficiencies.

The integration of solar photovoltaic systems significantly improves system performance across all evaluated metrics. In particular, the full hybrid configuration demonstrated the best overall performance, achieving the lowest outage duration, highest voltage stability, reduced generator runtime, lower operational costs, and significantly reduced carbon emissions compared to conventional systems.

The findings suggest that hybrid solar PV systems provide a technically viable and economically sustainable solution for hospital laboratory power supply in regions with unstable grid infrastructure. However, successful implementation requires careful system sizing, adequate financial planning, and technical capacity for maintenance and operation.

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