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RESEARCH TITLE

Techno-Economic Feasibility and Self-Recovery Model for Solar Energy Transition: A Case Study of Red Sea University, Sudan

Musab Mohamedahmed Fadul [1], Abdalla Eissa Abdelkarim[2], Mohamed Mubarak Yousif[3]

[1] M.Sc. Candidate, Faculty of Engineering, Red Sea University, Sudan
[2] Assistant Professor, Department of Civil Engineering, Faculty of Engineering, Red Sea University, Sudan
[3] Assistant Professor, Department of Mechanical Engineering, Faculty of Engineering, Red Sea University, Sudan

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Abstract

Higher education institutions in developing regions increasingly face operational and financial challenges caused by unreliable electricity grids, fuel supply disruptions, and rising fossil-fuel costs. This study examines the techno-economic feasibility of replacing diesel-based power generation with optimized hybrid solar photovoltaic systems at Red Sea University in Port Sudan, Sudan. Using the College of Engineering as a representative technical model, the study conducted an appliance-level load audit and applied a diversity factor to distinguish between theoretical peak demand and realistic daily energy consumption. The analysis reduced the estimated maximum daily load from 622 kWh/day to a calibrated operational baseline of 84.3 kWh/day per functional unit. Based on this profile, the proposed system for each unit consists of a 20 kWp photovoltaic array, a 15-kW hybrid inverter, and a 45 kWh $LiFePO_4$ battery bank. The financial analysis demonstrates strong economic viability, with an estimated capital cost of 25.9 million SDG per unit and a university-wide investment of 466.4 million SDG for 18 units. At the current local fuel price of 6,880 SDG per liter, the project is projected to achieve a simple payback period of approximately 2.5 months and a first-year return on investment of about 378%. Sensitivity analysis confirms that the model remains financially feasible even under a 50% reduction in fuel prices, maintaining a payback period of about five months. Environmentally, full implementation would eliminate the consumption of more than 328,000 liters of diesel annually and reduce carbon emissions by approximately 820 tons of CO_2 per year. The study concludes that an empirically calibrated hybrid solar transition offers a technically reliable, financially self-recovering, and environmentally sustainable model for university energy infrastructure in resource-constrained contexts.

Key Words: Solar Energy Transition, Techno-Economic Feasibility, Hybrid PV System, Energy Management, Higher Education Institutions, Diesel Replacement, Sudan.

عنوان البحث

نموذج الجدوى الفنية والاقتصادية والاسترداد الذاتي للتحول إلى الطاقة الشمسية: دراسة حالة جامعة البحر الأحمر، السودان

المستخلص

تواجه مؤسسات التعليم العالي في المناطق النامية تحديات تشغيلية ومالية متزايدة نتيجة عدم استقرار شبكات الكهرباء، واضطرابات إمدادات الوقود، وارتفاع تكاليف الوقود الأحفوري. تبحث هذه الدراسة الجدوى الفنية والاقتصادية لاستبدال أنظمة توليد الطاقة المعتمدة على الديزل بأنظمة شمسية هجينة محسّنة تعمل بالخلايا الكهروضوئية في جامعة البحر الأحمر بمدينة بورتسودان، السودان. وباستخدام كلية الهندسة نموذجًا فنيًا ممثلًا، أجرت الدراسة تدقيقًا تفصيليًا للأحمال على مستوى الأجهزة، وطبّقت معامل تنوع للتمييز بين الطلب النظري الأقصى والاستهلاك اليومي الواقعي للطاقة. وقد خفّض التحليل تقدير الحمل اليومي الأقصى من 622 كيلوواط/ساعة يوميًا إلى خط أساس تشغيلي مُعاير قدره 84.3 كيلوواط/ساعة يوميًا لكل وحدة وظيفية. وبناءً على هذا الملف التشغيلي، يتكون النظام المقترح لكل وحدة من مصفوفة ألواح كهروضوئية بقدرة 20 كيلوواط ذروة، وعاكس هجين بقدرة 15 كيلوواط، وبنك بطاريات ليثيوم فوسفات الحديد بسعة 45 كيلوواط/ساعة. وتُظهر نتائج التحليل المالي جدوى اقتصادية قوية، إذ تُقدَّر التكلفة الرأسمالية بنحو 25.9 مليون جنيه سوداني لكل وحدة، وباستثمار كلي على مستوى الجامعة قدره 466.4 مليون جنيه سوداني لعدد 18 وحدة. وعند سعر الوقود المحلي الحالي البالغ 6,880 جنيهًا سودانيًا للتر، يُتوقع أن يحقق المشروع فترة استرداد بسيطة تبلغ نحو 2.5 شهر، وعائدًا على الاستثمار في السنة الأولى يقارب 378%. كما تؤكد نتائج تحليل الحساسية أن النموذج يظل مجديًا ماليًا حتى في حال انخفاض أسعار الوقود بنسبة 50%، مع بقاء فترة الاسترداد في حدود خمسة أشهر تقريبًا. وبيئيًا، سيؤدي التنفيذ الكامل للمشروع إلى الاستغناء عن استهلاك أكثر من 328,000 لتر من الديزل سنويًا، وخفض انبعاثات الكربون بنحو 820 طنًا من ثاني أكسيد الكربون سنويًا. وتخلص الدراسة إلى أن التحول إلى نظام شمسي هجين قائم على معايرة تجريبية دقيقة يمثل نموذجًا موثوقًا فنيًا، وقابلًا للاسترداد المالي الذاتي، ومستدامًا بيئيًا لتطوير البنية التحتية للطاقة في الجامعات ضمن البيئات محدودة الموارد.

الكلمات المفتاحية: التحول إلى الطاقة الشمسية، الجدوى الفنية والاقتصادية، النظام الكهروضوئي الهجين، إدارة الطاقة، مؤسسات التعليم العالي، استبدال الديزل، السودان.

1. Introduction

The transition from decentralized diesel power generation to renewable solar energy is no longer merely an optional environmental upgrade for institutions in Sub-Saharan Africa [12]; it has become a strict financial and operational imperative [11], [13]. The Red Sea University in Port Sudan currently faces severe operational constraints due to extreme fossil fuel price volatility, frequent supply chain disruptions, and inherent national grid instability [21]. With local gasoline prices reaching 6,880 SDG/liter, traditional power generation has become financially untenable, threatening the continuity of critical academic operations [22].

This study introduces an engineering-validated, self-recovering solar transition strategy for 18 faculties and administrative units across the university campus. The primary objectives of this initiative are to: (1) achieve energy independence by deploying hybrid off-grid solar systems to ensure 24/7 operational continuity [14]; (2) optimize capital efficiency by right-sizing systems based on empirically validated load profiles rather than theoretical maximums [16], [17]; (3) ensure financial self-recovery by leveraging current fuel displacement to achieve rapid payback periods [15]; and (4) support broader climate commitments by contributing to Sudan’s 2030 renewable energy targets and the Paris Agreement Nationally Determined Contributions (NDCs) [23],[29].

2. Methodology and Technical Analysis

To establish a standardized, replicable system design for all university units, a detailed study was conducted at the College of Engineering (November 2024) to serve as the institutional blueprint.

2.1 Load Auditing and Power Assumptions

Accurate energy modeling requires precise baseline data. An appliance-level audit was performed across academic and administrative zones. Standard power ratings applied included: Ceiling Fans (70 W), LED Lights (15 W), Desktop Computers (250 W), Display Screens (100 W), Projectors (250 W), Water Coolers (500 W), Refrigerators (200 W), Printers (400 W), and Photocopiers (1,000 W) [19], [20]. Heavy workshop equipment and HVAC systems were documented as separate add-ons requiring independent scaling.

2.2 Operational Load Profile

The connected load distribution across key operational zones within the College of Engineering yielded a total connected load of 97,140 W (~97.1 kW). The breakdown included:

- **Administrative Offices (Dean, Registry, Departments):** ~14.1 kW
- **Professors & Admin Offices (24 units):** ~27.4 kW
- **Lecture Halls (17 units):** ~17.5 kW
- **Labs & Workshops (12 units):** ~38.2 kW

2.3 Diversity Factor and Energy Calibration

In academic environments, non-simultaneous operation, duty cycling, and staggered scheduling must be accounted for to prevent capital waste [18]. Applying an engineering-standard Diversity Factor of 0.8 (80%) [4], the Theoretical Peak Load was calculated as 77.7 kW. Assuming a standard 8-hour operational day, the Maximum Theoretical Daily Consumption was estimated at 621.6 kWh/day.

However, after factoring in actual usage patterns and part-time facility utilization, the realistic average daily consumption was calibrated down to **84.3 kWh/day**. This engineering calibration prevents costly system oversizing while guaranteeing reliable coverage of critical daily loads.

2.4 System Design Optimization

Two sizing scenarios were evaluated to demonstrate engineering rigor. Designing for the theoretical maximum (622 kWh/day) would have required a massive 130 kWp PV array and a 400-kWh battery bank, demanding ~650 m² of installation space.

Conversely, the final optimized proposal [35], based on the calibrated 84.3 kWh/day baseline, resulted in the following specifications per unit:

- **PV Array:** 20 kWp total capacity (32 × 625W monocrystalline modules), requiring only ~90 m² of installation footprint. High-efficiency monocrystalline panels were selected to withstand high-temperature desert conditions [6].
- **Inverter:** 15 kW industrial-grade hybrid inverter (MPPT-integrated) to cover the realistic peak load (~10.54 kW) with sufficient headroom for startup surges.
- **Battery Storage:** 45 kWh LiFePO4 battery bank [10]. LiFePO4 chemistry was chosen for its superior thermal stability and safety against thermal runaway in hot climates [8], [9].

3. Financial Analysis and Environmental Impact

The financial viability of the project was assessed using a Self-Recovery Model, which calculates payback strictly through operational fuel displacement [15].

3.1 Capital Expenditure (CAPEX) and Operational Savings

The estimated cost per customized solar unit is 25,911,000 SDG. Expanding this model to all 18 faculties and units requires a total capital investment of 466,398,000 SDG (factoring in bulk procurement discounts).

Based on an estimated conservative daily fuel displacement of 50 liters per unit (900 liters/day across 18 units), the system yields the savings outlined in Table 1.

Table 1. Operational Savings and Return on Investment (ROI)

Financial Metric	Estimated Value	Unit / Timeframe
Daily Cost Avoidance	6,192,000	SDG / Day
Monthly Savings	185,760,000	SDG / Month
Annual Savings	2,229,120,000	SDG / Year
Simple Payback Period	**2.51**	**Months**
Year 1 ROI	**~378**	**%**

3.2 Sensitivity Analysis

To assess financial resilience against market fluctuations, a sensitivity analysis was conducted on fuel prices (Table 2). Even under a severe 50% drop in fuel prices, the project retains a highly viable payback period of just 5.0 months.

Table 2. Fuel Price Sensitivity Analysis and Project Viability

Market Scenario	Fuel Price (SDG / Liter)	Projected Monthly Savings (SDG)	Simple Payback Period (Months)
+20% Price Increase	8,256	222,912,000	2.1
Current Baseline	6,880	185,760,000	2.5
-20% Price Drop	5,504	148,608,000	3.1
-50% Price Drop	3,440	92,880,000	5.0

3.3 Environmental and Social Impact

Implementing the 18-unit transition will eliminate the localized burning of over 328,000 liters of diesel annually, avoiding approximately **820 tons of CO_2 emissions per year** [24]. Socially, the project ensures uninterrupted educational continuity and includes a localized capacity-building program to certify university technicians in hybrid PV-BMS maintenance [36].

4. Implementation Strategy and Risk Management

4.1 Phased Rollout

To maximize cash flow efficiency, a three-phase rollout is proposed:

- **Phase 1 (Months 1–2):** Deployment in 4 priority faculties. Validates performance via FAT/SAT and simulated modeling [35] to generate immediate savings.
- **Phase 2 (Months 3–5):** Expansion to 8 additional faculties, funded largely by Phase 1 savings and external financing.
- **Phase 3 (Months 6–7):** Completion of 6 administrative units, achieving full university coverage.

4.2 Risk Mitigation

Key technical and environmental risks have been systematically addressed:

- *Coastal Corrosion:* Mitigated via hot-dip galvanized mounting and IP65+ marine-grade cabling to withstand Red Sea coastal salinity [26].
- *Equipment Protection:* System compliance aligned with IEC and NFPA 70 standards for surge protection and rapid shutdown [1], [3].
- *Heavy Equipment Inrush:* Managed through separate auditing and soft-starter integration for workshops.
- *Theft/Vandalism:* Prevented via secure structural mounting, perimeter fencing, and community engagement.

5. Conclusion

The Red Sea University Solar Transition Project presents a technically precise, financially compelling, and environmentally critical framework. By sizing systems to realistic operational consumption rather than theoretical maximums, the university avoids capital overcommitment while guaranteeing academic continuity. With a payback period of under three months at current fuel prices, this project sets a new benchmark for sustainable higher education infrastructure in Sudan.

It is highly recommended that funding entities approve phased financing starting with priority faculties. Furthermore, the verified carbon reduction heavily qualifies the institution for international climate finance grants (e.g., Green Climate Fund) [30], [32]. The adoption of this validated standardized template is recommended for immediate deployment.

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