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COMPARATIVE DESIGN, TECHNO-ECONOMIC AND ENVIRONMENTAL ANALYSIS OF DC POWERED SOLAR PV KILN WITH TES FOR SMEs POTTERY PRODUCTION VERSUS TRADITIONAL KILNS IN GHANA

Summary

This paper assesses the feasibility of substituting conventional firewood-dependent pottery kilns in Ghana with a 10 kW DC-coupled solar photovoltaic (PV) kiln. To mitigate solar intermittency and facilitate uninterrupted 72-hour operations, the system incorporates a high-temperature sensible Thermal Energy Storage (TES) unit utilizing locally sourced Basalt rock. Operating within the temperature range of 800 °C to 1000 °C, the proposed system exhibits high thermal efficiency. Additionally, an integrated Carbon finance model indicates that replacing biomass fuels not only helps prevent local deforestation but also considerably shortens the system's payback period by generating high-quality voluntary Carbon credits, thereby presenting a highly viable decarbonization pathway for rural Small and Medium Enterprises (SMEs).

Keywords: Carbon Finance, DC Solar PV, Industrial Decarbonization, Pottery SMEs, Thermal Energy Storage (TES)

Field of application for the findings: The findings provide a scalable techno-economic framework and actionable insights for decarbonising high-temperature industrial heat processes, specifically targeting rural manufacturing and Small and Medium Enterprises (SMEs) in developing economies.

Addressed audience: ***Energy system designers, environmental policymakers, SME development agencies, Academic researchers, and Carbon finance investors***

1. Introduction

Pottery production constitutes a vital livelihood for rural small and medium-sized enterprises (SMEs) in Ghana. Nevertheless, the sector predominantly depends on basic open-pit or updraft kilns fueled by biomass. These conventional techniques are characterised by low thermal efficiencies (approximately 15%) and significantly contribute to regional deforestation and greenhouse gas (GHG) emissions (Amissah & Ofori, 2021). Recent innovations in DC-coupled Solar Photovoltaic (PV) systems present a promising pathway to decarbonise high-temperature industrial heat production, circumventing the energy losses associated with DC-AC inverters (Smith & Jones, 2019). Given that ceramic firing necessitates sustained temperatures ranging from 800 °C to 1000 °C over several days, the utilization of Thermal Energy Storage (TES) becomes imperative (Kramer et al., 2020). This study offers a comparative techno-economic and environmental analysis of a 10 kW DC-coupled PV kiln utilizing Basalt rock TES, juxtaposed with traditional firewood kilns, and incorporates a carbon finance model to assess long-term viability for SMEs.

2. System Design and Methodology

2.1. System Architecture

The proposed technical architecture comprises a 10 kW Solar PV array directly interfaced with a high-temperature, high-resistance heating element within a heavily insulated kiln. The Thermal Energy Storage (TES) medium consists of crushed basalt rock, chosen for its high thermal stability, local availability, and specific heat capacity.

2.2. TES Mathematical Sizing

To provide continuous 72-hour heat retention during periods of low irradiance or night-time operation, the required mass of the TES (*m*) is derived from the total Thermal Energy demand (*Q*) of the extended cycle. This is calculated using the standard sensible heat formula:

$$Q = m \cdot cp \cdot (Tmax - Tamb) \qquad \text{(eq. 1)}$$

Where *cp* denotes the specific heat capacity of Basalt (approximately 1200 J kg-1 K-1), *Tmax* represents the target operating temperature, and *Tamb* indicates the ambient temperature. The DC direct-drive configuration ensures optimal Energy transfer directly into the thermal mass.

3. Results and Discussion

3.1. Technical Profiling

The simulation of the 10-kW photovoltaic system functioning within the Ghanaian solar regime, characterized by an average of 5.5 peak sun hours, produces approximately 55 kWh of electrical energy daily. Table 1 compares the technical profiles of the various systems. The Basalt Thermal Energy Storage (TES), with a mass of approximately 500 kg, can store approximately 160 kWh (576 MJ) of thermal energy, thereby providing adequate buffering to sustain the requisite temperatures throughout a continuous 72-hour firing and cooling cycle.

Tab. 1: Technical profiling of traditional firewood kilns versus the proposed DC-coupled PV with Basalt TES.

Parameter	**Value**	**Unit**
Solar PV Capacity (DC)	50	kW
Basalt TES Mass (72-hour autonomy)	22,000	kg
Operating Temperature Range	80 to 200	°C
Annual PV Electrical Yield	82,500	kWh
PV-to-Heat Conversion Efficiency	98	%
Annual Thermal Energy Delivered	80,850	kWh

3.2. Economic Profiling and Carbon Finance Model

Although traditional kilns necessitate minimal initial capital investment, Small and Medium-sized Enterprises (SMEs) encounter substantial operational expenditures (OPEX) attributable to rising firewood prices. Table 2 delineates the life cycle economic analysis. By eliminating approximately 100 tons of CO2 equivalent emissions annually, the PV-TES system qualifies for participation in the voluntary Carbon market. With a conservative valuation of $20 per ton of CO2 for premium, environmentally beneficial industrial-avoidance credits, the system potentially generates annual carbon finance revenue of $2,000.

Tab. 2: Economic profiling and carbon finance model for a standard Ghanaian pottery SME over a 15-year lifecycle

Economic Parameter	**Traditional Firewood Kiln**	**DC-Coupled Solar PV + Basalt TES**
Initial CAPEX	$450	$9,500
Annual Energy/Fuel Cost	$3,800	$0
Annual Maintenance Cost	$150	$250
Annual Carbon Emissions	100 tCO2e	0 tCO2e
Annual Carbon Finance	$0	$2,000 (at $20 / tCO2e)

Revenue		
Net Annual OPEX (Cost - Revenue)	$3,950	-$1,750 (Net Profit)
Levelized Cost of Heat (LCOH)	$0.025 / MJ	$0.008 / MJ
Estimated Payback Period	N/A	~1.8 years

The integration of the carbon finance model fundamentally transforms the investment landscape. The income derived from carbon credits, together with the total eradication of firewood expenses, shortens the payback period of the $9,500 initial capital expenditure to less than two years.

4. Conclusion

The comparative analysis demonstrates that substituting conventional firewood kilns with a 10 kW DC-coupled solar photovoltaic system employing basalt thermal energy storage (TES) is both technically superior and economically advantageous for small and medium-sized enterprises (SMEs) in Ghana. The locally sourced basalt efficiently supplies the 72-hour thermal storage required to sustain continuous operations at temperatures ranging from 800 °C to 1000 °C. Importantly, the adoption of a carbon finance model effectively converts the substantial initial capital expenditure (CAPEX) into a rapid return on investment, thereby supporting rural artisans and significantly reducing deforestation and greenhouse gas emissions.

5. References

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