

Production of Electricity from Cocoa Pods by Gasification: Technical, Environmental, and Economic Evaluation of the CCS-180 System

Adjo Christelle Ogo¹, Yao N'Guessan², Sanwouh Élysée Yao³, Bernabé Marí Soucase⁴, Amal Bouich⁵

¹Department of Physics Applied to Industrial Technologies, Laboratory of Advanced Materials and Process Engineering, Polytechnic University of Valencia (UPV), Valencia, Spain

²Laboratory of Mechanics and Materials Science, INP-HB, Yamoussoukro, Côte d'Ivoire

³Iroko Africa, Abidjan, Côte d'Ivoire

⁴Department of Applied Physics, Institute of Design and Manufacturing (IDF), Polytechnic University of Valencia, Valencia, Spain

⁵Physics Department, Laboratory of Advanced Materials and Process Engineering, Faculty of Sciences, Ibn Tofail University, Kenitra, Morocco

Email: christogoo263@gmail.com, nguessanyaoci@gmail.com, sanwouh2@gmail.com, bmari@fis.upv.es, Bouich.amal@gmail.com

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Abstract

This study evaluates the energy valorisation of cocoa pod husks (*Theobroma cacao*) through the integration of the CCS-180 gasification system at the PEMMS cocoa-processing plant in rural Côte d'Ivoire. The analysis distinguishes two scales: one CCS-180 base module rated at 180 kWe gross output, and a 2.8-module extrapolated scenario for the PEMMS active demand of 504 kWe, obtained from 630 kVA with a power factor of 0.8. The system is based on a co-current fixed-bed gasifier fed with sun-dried cocoa pod husks characterised by a lower calorific value of 24 MJ/kg on a dry basis and a moisture content of 10% after drying. The manufacturer's specific biomass consumption of 1.5 kg/kWh is retained only as a reference for the nominal feedstock. For cocoa pod husks, a CPH-adjusted specific consumption of 1.0 kg/kWh is estimated from the reported syngas yield, syngas calorific value, and conversion efficiencies. The revised sizing yields 180 kg/h per module and approximately 1,310 tonnes/year for the 2.8-module scenario. After auxiliary consumption (<15%), one module provides about 153 kWe net; three modules provide about 459 kWe net, with the residual demand supplied by the grid or backup during peak-load periods. The Levelised Cost of Electricity (LCOE), recalculated on a net usable electricity basis after auxiliary consumption, ranges from 74.2 to 106.7 FCFA/kWh and the Investment Payback Time (TRI) from 2.98 to 17.07 years. Annual bi-

ochar co-production is estimated at approximately 85 tonnes, corresponding to about 134 tCO₂eq/year sequestered, in addition to approximately 835 tCO₂eq/year avoided through diesel substitution. The study remains a pre-feasibility assessment and recommends pilot-scale validation before full-scale deployment.

Keywords

Gasification, Cocoa Pods, Biomass, Bioenergy, CCS-180, Biochar, Rural Electrification, Specific Biomass Consumption, LCOE, West Africa, Energy Transition, Sensitivity Analysis

1. Introduction

Sustained population growth, rapid urbanisation and the intensive development of agricultural activities in West Africa have led to a sharp increase in energy demand, exacerbating pressure on fossil resources and worsening associated environmental impacts. In response, several countries in the region, notably Côte d'Ivoire, have embarked on a transition to renewable energy solutions, focusing on agricultural residues and solar energy—two strategic levers for boosting electricity access in underserved rural areas [1].

According to IRENA, Côte d'Ivoire has an average solar irradiation potential of 4 - 6 kWh/m²/day, while agricultural residues—estimated at several million tonnes per year—represent a major opportunity for decentralised, sustainable bioenergy. Among these residues, cocoa pod husks (CPH), a by-product of the country's leading export crop, are massively under-exploited despite being abundant, accessible, and energy-rich. Recent experimental work on cocoa pod biomass carbonisation has confirmed the energy potential of this residue, with measured lower calorific values ranging from 14.097 to 22.158 MJ/kg depending on the thermal treatment conditions [2]. Gasification, as a thermochemical conversion pathway for lignocellulosic biomass, has emerged as a promising solution, with cold-gas efficiencies of up to 70% reported by the World Bank and IRENA [3] [4].

Global data reveal that sub-Saharan Africa still accounts for over 80% of the world population without electricity access—approximately 567 million people in 2021, a figure virtually unchanged since 2010 [5]. Converting local agricultural waste into energy is, therefore, an appropriate response to the challenges of access, sustainability, and energy sovereignty. Combining biomass and solar resources not only reduces CO₂ emissions but also strengthens territorial resilience against disruptions in conventional energy supply.

The present study focuses on the techno-economic sizing of the CCS-180 system [6], a small-scale co-current fixed-bed gasification unit adapted for cocoa pod husks (CPH) at the PEMMS cocoa-processing plant in rural Côte d'Ivoire. CPH has a similar lower calorific value to the biomass for which the system was originally designed

(>24 MJ/kg dry basis), justifying the transfer of performance specifications, subject to the ash content difference noted in the study. Building on the cocoa-pod energy potential previously established through carbonisation, the present work examines a complementary thermochemical pathway, namely gasification for electricity production. The work aligns with the national objectives of the Electricity for All Programme (PEPT) and the National Rural Electrification Plan (PRONER) [7]. All numerical results derive from a single, fully traceable mass-and-energy balance.

2. Materials and Methods

2.1. The CCS-180 Gasification System

The CCS-180 gasifier [6] operates on the co-current (downdraft) principle with continuous biomass feed. Key system components are: i) a feed hopper with rotary airlock and bucket-elevator conveyor; ii) a cylindrical reaction vessel ($H = 5$ m, $D = 1$ m) with eight air injectors across two levels; and iii) a wet char-removal system with a rotary scraper. Raw syngas undergoes primary dry treatment (cyclone + shell-and-tube air-cooled heat exchanger) and wet scrubbing (packed tower) before entering the generator sets. The complete system specifications are described in the CCS-180 Operation and Maintenance Manual [5] (confidential technical document; available from the corresponding author upon reasonable request). **Figure 1** presents a 3D schematic view of the CCS-180 unit with all major components labelled.

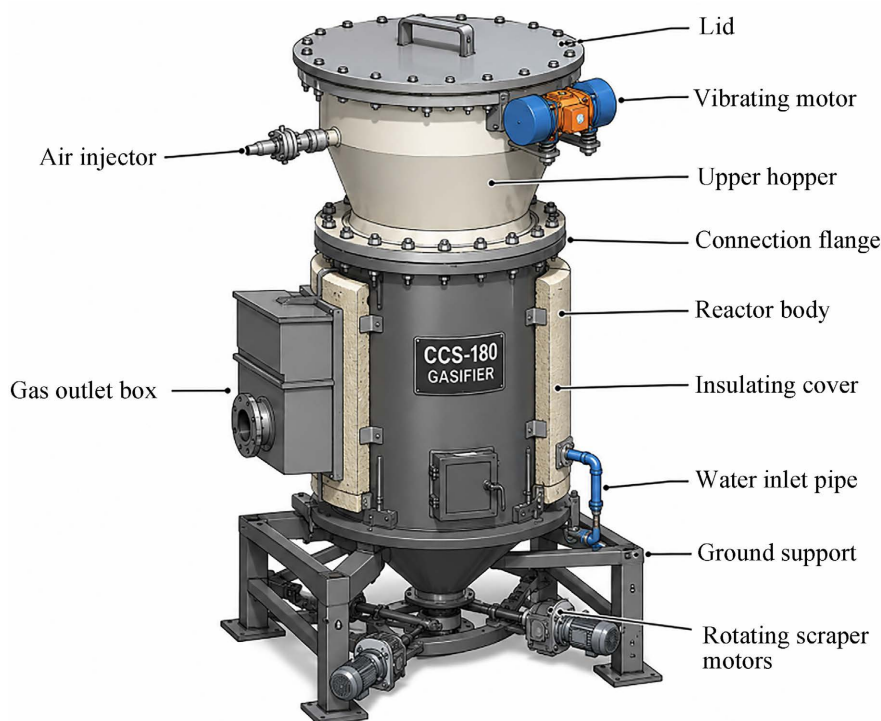


Figure 1. CCS-180 gasifier: 3D schematic view showing all major components: lid, vibrating motor, air injector, upper hopper, connection flange, reactor body, insulating cover, gas outlet box, ground support, water inlet pipe, and rotating scraper motors [5].

2.2. Methodology

2.2.1. Data Sources and Input Parameters

Consistent with the previously cited carbonisation evidence, the present gasification study considers cocoa pod husks as a technically relevant feedstock for thermochemical energy conversion. The retained CPH-adjusted specific consumption is therefore not introduced as an isolated assumption, but as part of a broader cocoa-pod valorisation pathway in which carbonisation and gasification represent complementary routes: the former mainly supports biochar and solid-fuel recovery, whereas the latter targets syngas and electricity generation [2].

Table 1 identifies the origin of every input parameter. Four source categories are used: (a) manufacturer's guaranteed performance specifications [6]; (b) biomass conditions required by the manufacturer [6]; (c) field/laboratory measurements at PEMMS and INP-HB; and (d) peer-reviewed literature for gas yield and engine benchmarks.

Table 1. Input parameters and data sources. Cat.: (a) manufacturer guarantee [6]; (b) manufacturer biomass conditions [6]; (c) field/lab measurement; (d) peer-reviewed literature.

Parameter	Value	Source/Condition	Cat.
Type of biomass (nominal)	Cashew nut shells [6] → here: CPH	Adaptation justified by similar LCV [8]	(b/c)
LCV (dry basis)	24 MJ/kg	PCS > 24 MJ/kg, Table 2 of [6]; confirmed by [8]	(b)
Moisture content (operating)	10% (post-drying)	Nominal range 8 - 12%, [6]; PEMMS confirmed	(b/c)
Bulk density	>300 kg/m ³ (400 used)	[6]; manufacturer measurement	(b)
Ash content	<3% [5]/4 - 7% CPH	[6] vs. INP-HB lab analysis (CPH)	(b/c)
Ash fusion temperature	>1200 °C	[6]	(b)
Manufacturer reference specific consumption	1.5 kg/kWh gross	Guaranteed by manufacturer for nominal feedstock; used as reference/upper bound, not as direct CPH guarantee	(a)
CPH-adjusted specific consumption	1.0 kg/kWh gross	Estimated from CPH syngas yield, syngas LCV, gas engine efficiency, and alternator efficiency; engineering rounded value retained for sizing (rounded upward from 0.91 kg/kWh to account for variability)	Calc./d
Rated output per module	180 kWe (brut)	[6]	(a)
Auxiliary consumption	<15% of gross output	[6]	(a)
Minimum operating load	50% of rated (≈90 kWe)	[6], §II.1.1	(a)

Continued

Gas engine efficiency (η_{engine})	33%	Typical for small syngas engines [9]	(d)
Alternator efficiency (η_{alt})	90%	Manufacturer datasheet [6]	(a)
Overall system efficiency (η_{global})	$\approx 17\%$ (16.7%)	Calculated from the module power ratio, $180/1,080 = 16.7\%$; rounded for design discussion	Calc.
Gas yield	1.98 Nm ³ /kg	Downdraft gasifier on CPH [8]	(d)
Installed capacity —PEMMS	630 kVA /504 kW _e	PEMMS measurement; power factor = 0.80	(c)
Operating schedule	2,600 h/year	10 h/day $\times$ 5 days/week $\times$ 52 weeks (PEMMS)	(c)
Biomass purchase price	30 FCFA/kg	Local market survey, Côte d'Ivoire, 2023	(c)
Electricity selling price	93 FCFA/kWh	PEMMS internal off-grid tariff	(c)

Table 1 summarises all input parameters and their sources. **Biomass pre-drying requirement:** The manufacturer specifies a moisture content of 8% - 12% for nominal operation (**Table 2** of [6]). PEMMS has confirmed that cocoa pod husks will be sun-dried to 10% moisture before feeding, consistent with this requirement. Maintaining moisture close to 8% - 10% is essential to improve syngas quality, stabilise reactor temperature, and reduce biomass consumption. At higher moisture levels (e.g., 15% undried), actual consumption may increase, and both energy performance and economic viability may degrade.

Ash content adaptation: The manufacturer specifies ash content $< 3\%$ for the nominal feedstock [6]. Laboratory analysis of CPH at INP-HB yields 4% - 7% ash (dry basis), approximately double the nominal value. This difference is acknowledged as a performance risk factor: higher ash may accelerate grate wear, promote clinker formation, and reduce syngas quality. Appropriate ash management procedures are recommended, and the manufacturer's performance guarantees should be understood as reference values for the nominal feedstock, not as direct guarantees for CPH operation.

Specific biomass consumption adjustment for cocoa pod husks: The manufacturer reports a guaranteed specific biomass consumption of 1.5 kg/kWh for the nominal feedstock, namely cashew nut shells or comparable lignocellulosic biomass. Since the present study focuses on cocoa pod husks, this value is not used as a direct guarantee for CPH operation. Instead, the CPH-specific consumption is estimated from the reported syngas yield of 1.98 Nm³/kg and syngas lower calorific value of 6.77 MJ/Nm³. This gives 13.40 MJ/kg, or 3.72 kWh/kg. Considering a gas engine efficiency of 33% and an alternator efficiency of 90%, the estimated gross electrical output is approximately 1.10 kWh/kg, corresponding to a

theoretical specific consumption of 0.91 kg/kWh. For conservative sizing and operational variability, a rounded value of 1.0 kg/kWh is retained for cocoa pod husks dried to approximately 10% moisture content.

Residence time and operating-value justification. The residence time is retained as a nominal solid-phase design check of approximately 10 min, not as an independent performance guarantee. In small fixed-bed downdraft gasifiers, the actual conversion time depends on particle size, bed porosity, airflow, moisture, and ash behaviour. In this study, the value is used only to confirm that the CCS-180 reactor volume and geometry provide sufficient hold-up for the drying, pyrolysis, oxidation, reduction, and ash-accumulation zones. The selected bulk density ($>300 \text{ kg/m}^3$, 400 kg/m^3 used) follows the manufacturer's admissible feedstock condition and is consistent with dried, crushed lignocellulosic residues. The 8% - 12% moisture target is taken from the manufacturer's operating conditions and retained at 10% for PEMMS because lower moisture improves gas quality and reduces tar formation; cocoa pod husk gasification studies also show that syngas quality is sensitive to moisture, air ratio, and thermal regime [10] [11]. The gas engine efficiency (33%) and alternator efficiency (90%) are used as conservative small-scale syngas-to-electricity assumptions, consistent with modular biomass gasification benchmarks [12].

2.2.2. Study Scale and Boundary

The study is structured around two complementary scales of analysis. The first scale corresponds to the base technical unit, namely one CCS-180 biomass gasification module rated at 180 kWe gross electrical output, according to the manufacturer's technical documentation [6]. This module represents the practical unit considered for initial integration into the PEMMS cocoa-processing plant.

The PEMMS plant has an installed apparent power of 630 kVA. Using a power factor of 0.8, the corresponding active electrical demand is:

$$P_{\text{active}} = S_{\text{installed}} \times \cos \varphi = 630 \text{ kVA} \times 0.80 = 504 \text{ kWe} \quad (1)$$

Therefore, 630 kVA refers to the installed apparent power of the plant, while 504 kWe represents the equivalent active power demand used for energy sizing. The value of 400 kVA mentioned in earlier project documents corresponds to a preliminary estimate of the plant load and is no longer retained as the reference value in the revised manuscript.

In the initial integration scenario, one CCS-180 module supplies part of the plant's electricity demand, while the remaining demand is covered by the national grid. Considering the manufacturer's auxiliary consumption of less than 15% of gross output [6], one module has a gross output of 180 kWe and an estimated net usable output of 153 kWe after auxiliaries:

$$P_{\text{net,module}} = P_{\text{gross,module}} \times (1 - f_{\text{aux}}) = 180 \times (1 - 0.15) = 153 \text{ kWe} \quad (2)$$

Consequently, economic and environmental indicators are reported on a net usable electricity basis, while gross production values are retained only for technical sizing.

2.2.3. Sizing Procedure

Sizing follows eight steps. The manufacturer's specific consumption of 1.5 kg/kWh is retained as a reference for the nominal feedstock only. For cocoa pod husks, a CPH-adjusted specific consumption of 1.0 kg/kWh is estimated from the reported syngas yield, syngas calorific value, gas engine efficiency, and alternator efficiency.

Step 1: Energy basis and CPH-adjusted specific consumption

Estimated active demand: $P_{\text{active}} = 504 \text{ kW}$ (from Equation (1)).

Syngas energy per kilogram of CPH:

$$E_{\text{gas}} = Y_{\text{gas}} \times \text{LCV}_{\text{gas}} = 1.98 \times 6.77 = 13.40 \text{ MJ/kg} = 3.72 \text{ kWh/kg} \quad (3)$$

Gross electrical output per kilogram:

$$E_{\text{elec,kg}} = E_{\text{gas}} \times \eta_{\text{engine}} \times \eta_{\text{alt}} = 3.72 \times 0.33 \times 0.90 = 1.10 \text{ kWh/kg} \quad (4)$$

Step 2: Calculation of biomass throughput required

$$\dot{m}_{\text{CPH,module}} = P_{\text{gross,module}} \times \text{SC}_{\text{CPH}} = 180 \times 1.0 = 180 \text{ kg/h} \quad (5)$$

$$\dot{m}_{\text{CPH,2.8}} = 2.8 \times \dot{m}_{\text{CPH,module}} = 2.8 \times 180 = 504 \text{ kg/h} \quad (6)$$

$$M_{\text{CPH,annual}} = \dot{m}_{\text{CPH,2.8}} \times t_{\text{operating}} = 504 \times 2600 = 1310400 \text{ kg/year} \approx 1310 \text{ t/year} \quad (7)$$

Step 3: Calculation of reactor volume

For the vertical cylindrical reactor geometry retained in the CCS-180 design, the useful cylinder volume is calculated as:

$$\text{LCV}_{\text{eff}} = \text{LCV}_{\text{dry}} \times (1 - w) = 24 \times (1 - 0.10) = 21.6 \text{ MJ/kg} \quad (8)$$

$$P_{\text{th,module}} = \dot{m}_{\text{CPH,module}} \times \frac{\text{LCV}_{\text{eff}}}{3.6} = 180 \times 21.6/3.6 = 1080 \text{ kW} \quad (9)$$

$$P_{\text{th,2.8}} = \dot{m}_{\text{CPH,2.8}} \times \frac{\text{LCV}_{\text{eff}}}{3.6} = 504 \times 21.6/3.6 = 3024 \text{ kW} \quad (10)$$

$$P_{\text{shaft,2.8}} = \frac{P_{\text{active}}}{\eta_{\text{alt}}} = 504/0.90 = 560 \text{ kW} \quad (11)$$

$$V_{\text{min}} = \frac{\dot{m}_{\text{CPH,2.8}} \times t_{\text{res}}}{\rho_{\text{bulk}}} = [504 \times (10/60)]/400 \approx 0.21 \text{ m}^3 \quad (12)$$

$$V_{\text{cyl}} = \frac{\pi D^2 H}{4} = \pi \times 1^2 \times 5/4 = 3.93 \text{ m}^3 \quad (13)$$

$$V_{\text{design}} = \text{SF} \times V_{\text{cyl}} = 4 \times 3.93 = 15.7 \text{ m}^3 \quad (14)$$

This geometric volume represents the cylindrical basis. The design volume retained in this study is 15.7 m³ to account for the drying, pyrolysis, oxidation, reduction, and ash zones, as well as operational margins for semi-industrial use. A safety factor of approximately 4 (SF = 15.7/3.93) is applied, consistent with published design practice for fixed-bed gasifiers at this scale [12], to accommodate the four reaction zones, ash accumulation space, and operational margins for semi-industrial use.

Step 4: Overall energy losses

Heat losses are estimated from the external surface area of the reactor and the temperature difference between the reactor and the ambient air. The model is used to quantify the expected order of magnitude and to identify insulation or heat-

recovery opportunities.

Using the revised CPH scenario, losses are reported as approximately 86 kW per module, corresponding to about 8% of the module feedstock thermal input. For the 2.8-module extrapolated scenario, the same proportional assumption gives approximately 241 kW:

$$P_{\text{loss,module}} = 0.08 \times P_{\text{th,module}} = 0.08 \times 1080 \approx 86 \text{ kW} \quad (15)$$

$$P_{\text{loss,2.8}} = 2.8 \times P_{\text{loss,module}} = 2.8 \times 86 \approx 241 \text{ kW} \quad (16)$$

Step 5: Product gas flow

For the 2.8-module extrapolated scenario, the CPH biomass feed rate is 504 kg/h. With a syngas yield of 1.98 Nm³/kg, the syngas flow rate is:

$$\dot{V}_{\text{gas}} = \dot{m}_{\text{CPH,2.8}} \times Y_{\text{gas}} = 504 \times 1.98 \approx 998 \text{ N} \cdot \text{m}^3/\text{h} \quad (17)$$

A 20% safety margin is retained for fan sizing:

$$Q_{\text{fan}} = 1.20 \times \dot{V}_{\text{gas}} = 1.20 \times 998 \approx 1198 \text{ N} \cdot \text{m}^3/\text{h} \quad (18)$$

Step 6: Energy production

For cocoa pod husks, the retained syngas lower calorific value is 6.77 MJ/Nm³. The thermal energy contained in the syngas for the extrapolated scenario is:

$$P_{\text{th,gas,LCV}} = 5 = \frac{\dot{V}_{\text{gas}} \times 5}{3.6} = 998 \times 5/3.6 \approx 1386 \text{ kW} \quad (19)$$

$$P_{\text{th,gas,LCV}} = 6.77 = \frac{\dot{V}_{\text{gas}} \times 6.77}{3.6} = 998 \times 6.77/3.6 \approx 1877 \text{ kW} \quad (20)$$

Considering the gas engine efficiency of 33% and alternator efficiency of 90%, the theoretical gross electrical output is approximately:

$$P_{\text{elec,theoretical}} = P_{\text{th,gas}} \times \eta_{\text{engine}} \times \eta_{\text{alt}} = 1877 \times 0.33 \times 0.90 \approx 557 \text{ kWe} \quad (21)$$

For conservative plant integration, the scenario is limited to the 504 kWe active demand and to the CCS-180 modular rating.

Stage 7: Annual energy production

Annual gross electricity production is calculated from the rated gross output and the operating schedule:

$$E_{\text{gross,module}} = P_{\text{gross,module}} \times t_{\text{operating}} = 180 \times 2600 = 468000 \text{ kWh/year} \quad (22)$$

$$E_{\text{net,module}} = P_{\text{net,module}} \times t_{\text{operating}} = 153 \times 2600 = 397800 \text{ kWh/year} \quad (23)$$

$$E_{\text{gross,2.8}} = P_{\text{active}} \times t_{\text{operating}} = 504 \times 2600 = 1310400 \text{ kWh/year} \quad (24)$$

$$E_{\text{net,2.8}} = E_{\text{gross,2.8}} \times (1 - f_{\text{aux}}) = 1310400 \times 0.85 = 1113840 \text{ kWh/year} \quad (25)$$

These net values are used for LCOE, revenue, TRI, and avoided-emissions calculations.

Step 8: Coverage rate

One module covers approximately 30.4% of PEMMS active demand. Three modules provide approximately 91.1% net coverage after auxiliary consumption:

$$\text{Coverage}_{\text{module}} = \frac{P_{\text{net,module}}}{P_{\text{active}}} \times 100 = 153/504 \times 100 \approx 30.4\% \quad (26)$$

$$\text{Coverage}_{3\text{ modules}} = (3 \times 153)/504 \times 100 = 459/504 \times 100 \approx 91.1\% \quad (27)$$

The remaining demand is supplied by the grid or by backup during peak-load periods.

2.3. Technical Analysis of Key Components

The cyclone separator reduces particulate loading before the shell-and-tube heat exchanger and wet scrubbing tower. Syngas is cooled by indirect air contact to 50°C - 60°C; condensate (water and tars) is collected in two tanks beneath the exchanger and redirected to the condensate treatment unit. This two-stage treatment ensures syngas quality compatible with the generator sets. Auxiliary consumption is guaranteed below 15% of gross output at full load [6], consistent with benchmarks from comparable systems in Benin [11]. **Figure 2** presents the complete syngas treatment flowchart from gasifier to electricity production.

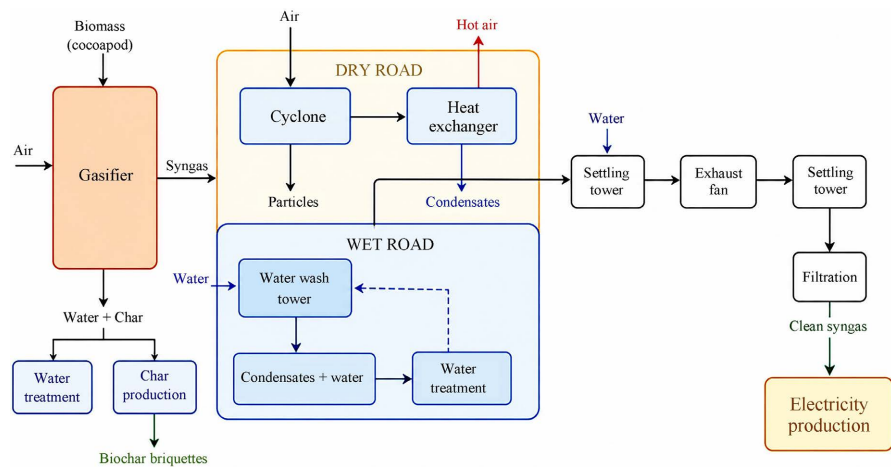


Figure 2. Schematic diagram of the CCS-180 gas treatment system.

The co-current (downdraft) configuration is scientifically justified by its tar-cracking advantage: pyrolysis volatiles traverse the high-temperature combustion zone before reaching the reduction zone, producing lower-tar syngas than updraft designs [9]. The CCS-180 gasifier is rated for biomass feed rates up to 500 - 1,000 kg/h before flow instability [6], well above the 504 kg/h calculated here. **Figure 3** provides a general view and R-R section cut of the heat exchanger.

2.4. Financial and Economic Analysis

2.4.1. CAPEX Estimation

Total capital expenditure covers major equipment and installation costs. All cost ranges are sourced from supplier quotes and comparable West African projects [13] [14]. **Table 2** presents the costs of major equipment, and **Table 3** lists auxiliary equipment costs.

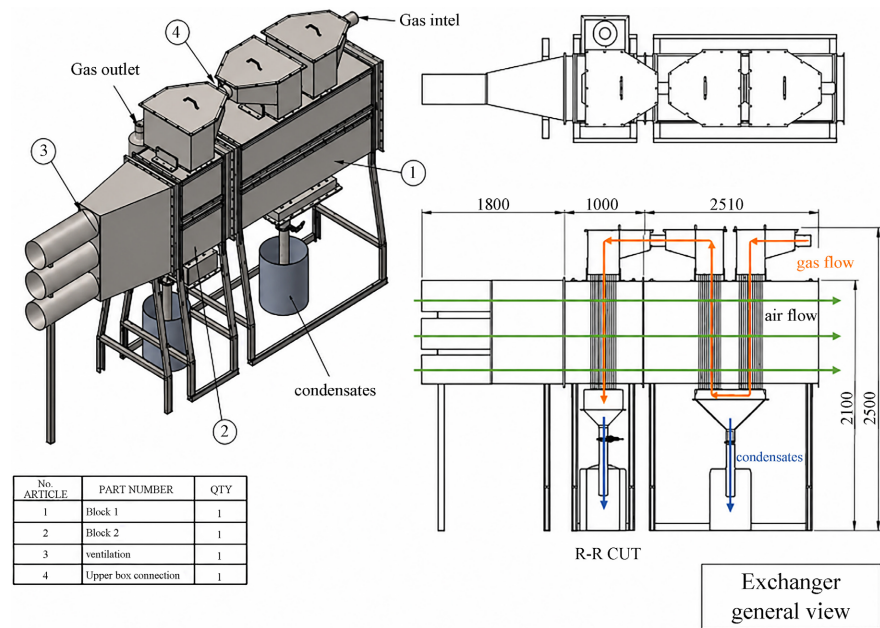


Figure 3. CCS-180 syngas/air shell-and-tube heat exchanger: 3D perspective view (left) and R-R section cut (right) showing orange gas-flow arrows descending through tube bundles, green airflow arrows passing horizontally through the shell side, and blue condensate drainage paths to collection tanks [6].

Table 2. CAPEX—major equipment (180 kWe module).

Equipment	Cost (USD)	Cost (FCFA)	Source
200 kW thermal downdraft gasifier	8,000 - 12,000	4,800,000 - 7,200,000	[14]
Syngas generator set, 200 kW	25,000 - 35,000	15,000,000 - 21,000,000	Supplier quote
Installation and commissioning	15,000 - 20,000	9,000,000 - 12,000,000	[13] [15]

Subtotal: 28,800,000 - 40,200,000 FCFA.

Table 3. CAPEX—auxiliary equipment.

Equipment	Cost (USD)	Cost (FCFA)	Source
Tubular heat exchanger (200 kW)	500 - 1,500	300,000 - 900,000	[16]
Cyclone separator	100 - 500	60,000 - 300,000	[17]
Sand/gravel filter (tar reduction)	480 - 1,200	288,000 - 7 20,000	[18]
Gas cooler	1,100 - 67,750	660,000 - 40,650,000	[19]
Feed hopper with conveyor	1,999 - 7,800	1,199,400 - 4,680,000	[20]
Ash collection bin	39 - 70	23,400 - 42,000	[21]
PLC control system and sensors	5,000 - 10,000	3,000,000 - 6,000,000	[12] [22]

Subtotal: 5,530,800 - 53,292,000 FCFA.; Total CAPEX: 34,330,800 - 93,492,000 FCFA.

2.4.2. OPEX Estimation

Annual OPEX for the base module covers five items (Table 4). Biomass supply uses the CPH-adjusted feed rate from Equation (6):

$$\begin{aligned}\text{OPEX}_{\text{biomass}} &= \dot{m}_{\text{CPH,module}} \times t_{\text{operating}} \times C_{\text{biomass}} \\ &= 180 \times 2600 \times 30 = 14040000 \text{ FCFA/year}\end{aligned}\quad (28)$$

Table 4. Annual OPEX summary—180 kWe base module.

Item	Specification	Hypothesis	Cost (FCFA/year)
Biomass supply	Dried CPH, 180 kg/h (Equation (6))	$180 \times 2,600 \text{ h} \times 30 \text{ FCFA/kg}$	14,040,000
Maintenance & spare parts	Full system	8% of CAPEX/year	2,746,464 - 7,479,360
Labour 2 operators	Qualified staff	$2 \times 250,000 \times 12 \text{ months}$	6,000,000
Auxiliary energy	Fans, pumps, conveyors	1 - 2% of capacity $\times$ tariff	1,200,000 - 2,000,000
Insurance & miscellaneous	Contingencies	Annual lump sum	1,500,000 - 2,000,000
Total annual OPEX	—	—	25,486,464 - 31,519,360

2.4.3. LCOE and Investment Payback Time (TRI)

The Levelised Cost of Electricity (LCOE) is calculated over a 15-year project life-time using a discount rate $r = 8\%$:

$$\text{CRF} = \frac{r(1+r)^N}{(1+r)^{N-1}} \quad \text{with } r = 8\% \text{ and } N = 15 \text{ years} \quad (29)$$

$$\text{LCOE} = \frac{\text{CAPEX} \times \text{CRF} + \text{Annual OPEX}}{E_{\text{net,module}}} \quad (30)$$

The Investment Payback Time (TRI, Temps de Retour sur Investissement) is an undiscounted metric. In this study, TRI does not refer to the Internal Rate of Return. It is calculated as:

$$\text{TRI} = \frac{\text{CAPEX}}{\text{Annual net cash-flow}} \quad (31)$$

$$\begin{aligned}\text{Annual revenue} &= E_{\text{net,module}} \times \text{Selling price} \\ &= 397800 \times 93 = 36995400 \text{ FCFA/year}\end{aligned}\quad (32)$$

2.4.4. Sensitivity Analysis

A one-factor-at-a-time (OFAT) sensitivity analysis was conducted for four key variables: i) biomass moisture post-drying (8% - 15%), ii) biomass purchase price (20 - 50 FCFA/kg), iii) CAPEX deviation (−20% to +50%), and iv) electricity selling price (70 - 120 FCFA/kWh). Base values are those of **Table 1**.

3. Results and Discussion

3.1. Sizing Results

The sizing parameters of the CCS-180 system were determined based on the CPH-adjusted specific consumption, $\text{SC}_{\text{CPH}} = 1.0 \text{ kg/kWh}$ as well as on the mass and

energy balance defined by Equations (1) - (21). As shown in **Table 5**, these results summarize the main sizing values used to evaluate the operational requirements and performance of the CCS-180 system.

Table 5. Sizing results for the CCS-180 system. All values are based on the CPH-adjusted specific consumption $SC_{CPH} = 1.0 \text{ kg/kWh}$ and the mass-and-energy balance of Equations (1) - (21).

Parameter	Value	Unit/Reference
Biomass moisture (post-drying, nominal)	10	% (Table 2 , [6])
CPH-adjusted specific consumption, SC_{CPH}	1.0	kg/kWh (Equation (5))
LCV effective (dry, $w = 10\%$)	21.6	MJ/kg (Equation (9))
Syngas energy per kg of CPH	13.40 (3.72)	MJ/kg (kWh/kg) (Equation (3))
Biomass feed rate module (Equation (1))	180	kg/h (Equation (6))
Biomass feed rate 2.8-module extrapolation (Equation (2))	504	kg/h (Equation (7))
Annual biomass consumption 2.8-module extrapolation (Equation (3))	1,310	t/year (Equation (8))
P_{th} input module (Equation (5))	1,080	kW (Equation (10))
P_{th} input 2.8-module extrapolation (Equation (6))	3,024	kW (Equation (11))
Mechanical shaft power—2.8-module scenario (Equation (7))	560	kW (Equation (12))
Min. reactor volume, V_{min} (Equation (8))	0.21	m ³ (Equation (13))
Cylinder volume, V_{cyl} (Equation (9))	3.93	m ³ (Equation (14))
Design reactor volume ($SF = 4\times$)	15.7	m ³ (Equation (15))
Reactor geometry	$H = 5 \text{ m}, D = 1 \text{ m}$	
Wall heat losses ($\approx 8\%$ of P_{th} input)	86	kW/module (Equation (16))
Syngas flow rate, $\dot{V}_{gas}$ (Equation (11))	998	Nm ³ /h (Equation (18))
Fan flow, Q_{fan} (Equation (21))	1,198	Nm ³ /h (Equation (19))
$P_{th,gas}$ conservative LCV = 5 (Equation (12))	1,386	kW (Equation (20))
$P_{th,gas}$ design LCV = 6.77 (Equation (13))	1,877	kW (Equation (21))
$P_{elec,net}$, three modules after auxiliaries	459	kWe
Annual net usable production three-module practical configuration	1,193,400	kWh/year
Residual demand covered by grid/backup	45	kWe
Annual gross production module (Equation (16))	468,000	kWh/year (Equation (23))
Annual net usable production module	397,800	kWh/year (Equation (24))
Annual gross production 2.8-module extrapolation (Equation (17))	1,310,400	kWh/year (Equation (25))

Continued

Annual net usable production 2.8-module extrapolation	1,113,840	kWh/year (Equation (26))
Coverage one module net vs active demand	30.4	% (Equation (27))
Coverage three modules vs active demand after auxiliaries	91.1	% (Equation (28))

These sizing results extend the cocoa-pod valorisation pathway introduced above by shifting from carbonisation and biochar recovery toward gasification-based electricity generation. Both approaches support the use of cocoa pod residues as local energy resources, while the present study specifically quantifies the electrical performance, biomass demand, and operational requirements of the CCS-180 system [2].

3.2. Economic Feasibility

3.2.1. Base Module (180 kWe)

Using the OPEX from **Table 4** (biomass at 180 kg/h, Equation (22)) and the net usable annual electricity production after auxiliaries (397,800 kWh/year), the financial results are:

$$\begin{aligned} \text{Annual net cash-flow} &= 36995400 - [25486464 \text{ to } 31519360] \\ &= 5476040 - 11508936 \text{ FCFA/year} \end{aligned} \quad (33)$$

$$\text{TRI}_{\min} = 34330800/11508936 = 2.98 \text{ years (minimum CAPEX)} \quad (34)$$

$$\text{TRI}_{\max} = 93492000/5476040 = 17.07 \text{ years (maximum CAPEX)} \quad (35)$$

Table 6 summarises the financial assumptions and results for the 180 kWe base module.

Table 6. Financial results—180 kWe base module.

Financial Item	Value
CAPEX (total)	34,330,800 - 93,492,000 FCFA
Annual OPEX	25,486,464 - 31,519,360 FCFA/year
Annual gross energy production	468,000 kWh/year
Annual net usable energy after auxiliaries	397,800 kWh/year
Electricity selling price	93 FCFA/kWh (PEMMS off-grid tariff)
Annual revenue	36,995,400 FCFA/year (net usable electricity basis)
Annual net cash flow	5,476,040 - 11,508,936 FCFA/year
Investment Payback Time (TRI)	2.98 - 17.07 years
LCOE (net usable electricity basis)	74.2 - 106.7 FCFA/kWh
National grid tariff (reference)	80 - 100 FCFA/kWh
Diesel generation (reference)	150 - 250 FCFA/kWh

3.2.2. Extrapolation to Near-Full Plant Coverage (504 kWe)

Linear scalability is assumed. The same 15-year LCOE basis, discount rate, and unit cost structure are applied to the single-module and extrapolated scenarios. Gross production values are reported for technical sizing, while net usable electricity after auxiliary consumption is used for revenue, TRI, LCOE, and avoided-emissions calculations. Consequently, the LCOE and TRI remain unchanged under proportional scaling. Multi-unit procurement may reduce CAPEX per module in a real deployment (**Table 7**).

Table 7. Extrapolated results near-full plant coverage scenario (504 kWe $\times$ 2.8).

Item	Extrapolated value ($\times 2.8$)
CAPEX ($\times 2.8$)	96,126,240 - 261,777,600 FCFA
Annual OPEX ($\times 2.8$)	71,362,099 - 88,254,208 FCFA/year
Annual gross energy production	1,310,400 kWh/year
Annual net usable energy	1,113,840 kWh/year
Annual revenue	103,587,120 FCFA/year
Annual net cash flow	15,332,912 - 32,225,021 FCFA/year
TRI (payback time, same ratio)	2.98 - 17.07 years
LCOE	74.2 - 106.7 FCFA/kWh

3.2.3. LCOE Analysis and Benchmarking

The LCOE range (74.2 - 106.7 FCFA/kWh), calculated on a net usable electricity basis after auxiliary consumption, requires careful interpretation. Under the minimum CAPEX scenario, the LCOE (74.2 FCFA/kWh) remains below the lower bound of the grid tariff (80 FCFA/kWh), confirming economic competitiveness for the best-case investment. Under the maximum CAPEX scenario, the LCOE (106.7 FCFA/kWh) exceeds the upper bound of the national grid tariff by about 6.7% and is therefore not grid-competitive unless CAPEX is reduced or additional revenues are captured. It nevertheless remains well below diesel generation (150 - 250 FCFA/kWh), maintaining value relative to the most common rural energy alternative.

It should be noted that the maximum TRI (17.07 years) exceeds the assumed project lifetime of 15 years. This worst-case result is attributable mainly to the high-end gas cooler cost range ([18]: factor 62 $\times$) and should be interpreted as a conservative boundary case rather than as the target investment scenario. Obtaining a firm supplier quote, excluding unrealistic outlier quotations, or adopting a low-cost/local procurement strategy would be expected to bring the maximum payback time within the project lifetime.

The large CAPEX spread (34.3 M to 93.5 M FCFA, factor 2.7 $\times$) is driven primarily by the gas cooler cost range ([18]: 660,000 - 40,650,000 FCFA, factor 62 $\times$). Obtaining firm quotes for this component before the final investment decision would substantially narrow the uncertainty and likely yield an LCOE closer to the competitive minimum scenario.

3.2.4. Sensitivity Analysis Results

The sensitivity analysis (**Table 8**) is conducted on the minimum CAPEX scenario, where economic viability is strongest. Key findings: i) moisture has a moderate impact, confirming that pre-drying to 8% - 10% is important; ii) biomass price is the most influential operating variable and may push the TRI up to 22.9 years at 50 FCFA/kg, confirming the need to secure low-cost or waste-stream biomass; iii) CAPEX deviation remains critical because of the wide equipment cost range; and iv) a higher electricity selling price reduces the payback time. Under all tested single-factor scenarios, the system remains competitive with diesel generation in terms of LCOE, but the payback criterion becomes unfavourable when biomass price or CAPEX reaches the upper conservative bound.

Table 8. Sensitivity analysis minimum CAPEX scenario (34,330,800 FCFA), 180 kW_e module.

Variable	Range Tested	LCOE (Net Basis, FCFA/kWh)	TRI (Years)
Biomass moisture (post-drying)	8% → 15%	72 - 78	2.8 - 3.4
Biomass price (FCFA/kg)	20 → 50	62 - 98	2.1 - 22.9
CAPEX deviation	-20% → +50%	71 - 83	2.3 - 5.1
Selling price (FCFA/kWh)	70 → 120	Unchanged	14.6 - 1.5

The upper TRI value of 22.9 years corresponds to an extreme unfavourable sensitivity case, where the biomass purchase price reaches 50 FCFA/kg under the conservative economic assumptions used in the analysis. It should not be interpreted as the central project result, but rather as a risk indicator showing that project viability strongly depends on securing a low-cost cocoa pod husk supply. Under the base biomass price of 30 FCFA/kg, the payback time remains in the range reported in **Table 6**.

3.3. Scientific Discussion

3.3.1. Sizing Consistency and Validation

The revised sizing is anchored to a CPH-adjusted specific consumption rather than directly applying the manufacturer's nominal feedstock value. The manufacturer reports 1.5 kg/kWh for the nominal biomass, while the present study estimates 1.0 kg/kWh for cocoa pod husks from syngas yield, syngas calorific value, and conversion efficiencies. This approach distinguishes the single-module integration scenario from the 2.8-module extrapolated scenario and clarifies the relationship between 630 kVA, 504 kW_e, 180 kW_e, and the 200 kW equipment class used for cost estimation.

The ash content of CPH (4% - 7%, INP-HB laboratory) exceeds the manufacturer's nominal specification (<3% for the nominal feedstock, **Table 2**, [6]). This is the most significant technical difference between the nominal feedstock and CPH and must be managed proactively: higher ash accelerates grate wear, may promote clinker formation at combustion temperatures, and could slightly reduce

calorific value. Recommended mitigation measures include: i) more frequent ash evacuation cycles; ii) monitoring of combustion zone temperature to detect clinker risk; iii) periodic sieve analysis of incoming biomass. These measures do not invalidate the performance data from [6] but should be incorporated into the site-specific Operation and Maintenance Plan.

3.3.2. Economic Nuances

The LCOE range (74.2 - 106.7 FCFA/kWh) reflects investment uncertainty and operational assumptions rather than methodological weakness. The dominant source of CAPEX uncertainty remains the gas cooler cost range ([19]), which alone spans a factor of 62×. Three actions can substantially reduce this range before the final investment decision: i) obtain firm supplier quotes for the gas cooler; ii) explore multi-unit procurement discounts for the three-module installation; iii) investigate locally sourced alternatives for auxiliary equipment.

Biomass cost (30 FCFA/kg) remains the largest single OPEX item (14.04 M FCFA/year for one module). Securing a long-term biomass supply agreement with PEMMS's cocoa suppliers or recovering post-processing husks at near-zero cost as a waste stream could reduce biomass cost to 5 - 15 FCFA/kg and dramatically improve economics. At 10 FCFA/kg, OPEX_{bio} drops to 4.68 M FCFA/year for one module, shifting the LCOE downward in all CAPEX scenarios.

3.3.3. Study Limitations and Environmental Quantification

This study is a pre-feasibility analysis. Results rely on manufacturer reference data [6], secondary literature, engineering models, and a CPH-adjusted consumption scenario derived from syngas yield and calorific value data. The revised value of 1.0 kg/kWh should be interpreted as an engineering estimate rather than as an experimentally guaranteed value. No full-scale pilot has been commissioned at PEMMS; results should be regarded as preliminary pending experimental validation.

Several factors may affect the actual CPH consumption under real operating conditions: seasonal variability of cocoa pod husk composition, residual moisture after drying, particle size distribution, ash content, tar formation, gas cleaning efficiency, engine derating when operated with low-calorific syngas, and partial-load operation. The revised scenario is therefore technically plausible and economically promising, but it should be validated through pilot-scale testing before an investment decision or full-scale deployment.

Quantified environmental indicators (pre-feasibility level):

CO₂ avoidance: Replacing diesel (0.85 kgCO₂/kWh [5]) with biomass gasification (net ≈ 0.10 kgCO₂/kWh) is calculated using the net usable electricity output of the 2.8-module scenario:

$$\Delta\text{CO}_2 = 1113840 \times (0.85 - 0.10) / 1000 \approx 835 \text{ t CO}_2\text{eq/year} \quad (36)$$

Biochar sequestration: Char yield 6.5% by mass [5] on annual biomass feed:

$$M_{\text{char}} = 0.065 \times 1310 \text{ t} \approx 85 \text{ t/year} \quad (37)$$

$$\text{CO}_{2\text{seq}} = 85 \times 1.57 \approx 134 \text{ t CO}_2\text{eq/year} \quad [23] \quad (38)$$

Combined climate benefit: $835 + 134 \approx 969$ tCO₂eq/year for the near-full-coverage scenario. A formal LCA is recommended as the next step.

3.4. Risks and Environmental Management

Operation involves risks of syngas leaks, fire, and operator exposure to CO and H₂. Passive and active safety devices in the CCS-180 design include droplet separators, water seals, pressure-relief valves, activated-carbon filters, non-return valves, and controlled-purge systems [6]. Fire safety measures comprise heat detectors, automatic cut-off devices, and biomass-rated extinguishers. Research on agricultural gasifiers in West Africa confirms the effectiveness of these devices [24]. These measures ensure compliance with applicable industrial safety standards.

3.5. Biochar Production and Recovery

The char recovery system [6] comprises: a grate retaining the char bed; a rotary scraper discharging char through lateral openings; a water-flushed closed-circuit conveyor; and a separation screen at the gasifier outlet. A water seal prevents gas ingress into the char circuit. The recovered biochar (≈ 85 t/year) is free of hazardous materials and can be converted into briquettes as a cooking fuel substitute or applied as a soil amendment. Studies on cashew nutshell biochar confirm significant agromonic benefits [25] [26], and recent research validates that biochar addition improves soil microbial stability and reduces nutrient leaching [23]. With a sequestration potential of ≈ 134 tCO₂eq/year, systematic biochar recovery creates both environmental value and a secondary revenue stream for local farmers. **Figure 4** illustrates the char emptying operation from the cyclone particle recovery tank.



Figure 4. Emptying the cyclone particle recovery tank: charcoal powder (biochar) discharged through the coal powder exit door into a collection container.

4. Conclusions

This study presents a coherent pre-feasibility techno-economic evaluation of the CCS-180 gasification system applied to cocoa pod husks at the PEMMS plant in rural Côte d'Ivoire. The analysis distinguishes two scales: one CCS-180 module rated at 180 kWe gross output for partial integration, and a 2.8-module extrapolated scenario for near-full coverage of the 504 kWe active plant demand. The manufacturer's 1.5 kg/kWh value is retained as a nominal-feedstock reference, while a CPH-adjusted value of 1.0 kg/kWh is used for the revised cocoa pod husk scenario.

Economic analysis reveals a more cautious but still relevant picture when net usable electricity after auxiliary consumption is used. Under the minimum CAPEX scenario, the LCOE (74.2 FCFA/kWh) remains below the national grid tariff (80 - 100 FCFA/kWh) with a TRI of 2.98 years, demonstrating strong financial viability. Under the maximum CAPEX scenario, the LCOE (106.7 FCFA/kWh) exceeds the upper bound of the grid tariff, and the TRI reaches 17.07 years, which is above the 15-year project lifetime. This maximum scenario should therefore be interpreted as a non-attractive conservative boundary case, mainly driven by high auxiliary-equipment quotations, especially the gas cooler. The project should privilege a low-CAPEX/low-cost procurement scenario, firm supplier quotations, local fabrication where feasible, biomass supply agreements, heat recovery, and biochar valorisation to keep the payback time within the project lifetime.

Environmental benefits are quantified at ≈ 835 tCO₂eq/year avoided through diesel substitution and ≈ 134 tCO₂eq/year sequestered via biochar co-production (≈ 85 t/year), totaling ≈ 969 tCO₂eq/year. The higher ash content of CPH (4% - 7% vs. <3% for the nominal feedstock [5]) remains the primary technical difference from the manufacturer's nominal specification, requiring enhanced ash management procedures. Experimental commissioning, long-term performance monitoring, and pilot-scale validation using real cocoa pod husks are therefore recommended before full-scale deployment.

CCS-180 is positioned as a credible, modular technology for sustainable rural electrification in West Africa, contributing to energy accessibility, circular valorisation of agricultural waste, and decarbonisation of rural territories.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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