

Assessing the Energy Penalty and Carbon Capture Efficiency of Renewable-Gas-Battery Hybrid Power Systems: Insights from Urban and Rural Nigerian Case Studies

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Abstract: This study evaluates the parasitic electrical burden and carbon dioxide capture performance of post-combustion capture integrated into renewable-gas-battery hybrid power systems in Nigeria. Two contrasting cases are examined: Port Harcourt, representing an urban-industrial load centre, and Lafia, representing a rural-agricultural load centre. Aspen HYSYS was used for process-level modelling of flue-gas conditioning, amine absorption, solvent regeneration, carbon dioxide separation and compression, while HOMER Pro was used for system-level optimisation of solar photovoltaic generation, wind turbines, gas turbines and battery storage. The system boundary extends from capture to compression and excludes downstream transport and geological storage. Lafia achieved a higher carbon dioxide capture efficiency of 97.88%, but required 0.057 kWh kg⁻¹ CO₂ and incurred a parasitic load of 2.56%, equivalent to 0.512 MW. Port Harcourt achieved 93.78% capture efficiency, but required only 0.0185 kWh kg⁻¹ CO₂ and incurred a parasitic load of 0.79%, equivalent to 1.109 MW. Both optimised systems maintained renewable penetration above 90%. The results demonstrate that percentage capture efficiency alone is an incomplete indicator of technical performance: specific electrical intensity and the parasitic share of demand are essential for interpreting scale effects. Carbon capture can be integrated into renewable-rich hybrid systems without undermining reliability, but smaller systems face proportionally higher energy penalties. The paper provides scale-sensitive guidance for designing carbon-capture-enabled hybrid power systems in developing economies.

Keywords: carbon capture; parasitic load; hybrid energy systems; post-combustion CO₂ capture; renewable-gas-battery systems; Aspen HYSYS; HOMER Pro; Nigeria; off-grid power systems; energy penalty.

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I. INTRODUCTION

The transition to reliable and low-carbon electricity remains difficult in developing economies where demand is rising, central grids are unstable, and fossil-fuelled generation continues to provide balancing capacity. Global mitigation assessments identify renewable electricity, storage, efficiency and carbon capture, utilisation and storage as complementary options for deep decarbonisation rather than mutually exclusive technologies [1]-[4]. In Nigeria, this systems perspective is particularly relevant because energy access, industrial competitiveness and emissions reduction must be pursued simultaneously. The national energy transition strategy recognises the continuing near-term role of natural gas while targeting net-zero emissions by 2060 [5].

Hybrid energy systems offer a practical response to this tension. Solar photovoltaic generation and wind power can reduce fuel use, batteries can shift electricity across time and smooth short-duration variability, and gas turbines can provide firm capacity during renewable shortfalls. A substantial literature shows that well-sized hybrid systems can improve reliability and reduce lifecycle emissions in remote and grid-constrained applications [6]-[10]. However, where natural gas remains part of the architecture, residual carbon dioxide emissions persist. Retrofitting or integrating post-combustion capture with the dispatchable component can reduce these emissions while preserving system adequacy.

Post-combustion chemical absorption is technically mature, but it is not energetically neutral. Electricity and heat are required for flue-gas handling, solvent circulation, solvent regeneration, cooling, carbon dioxide drying and compression. This internal consumption reduces the power available to serve external demand and is commonly described as the energy penalty or parasitic burden [11]-[15]. The burden can affect

generation sizing, storage dispatch, fuel consumption, reserve margins and cost. In a stand-alone thermal plant, the penalty is usually discussed as a reduction in net efficiency. In a renewable-rich hybrid system, it operates as an additional flexible or semi-flexible load that competes with consumer demand and battery charging.

The key research problem is therefore not simply whether capture can remove carbon dioxide, but whether the associated energy requirement can be absorbed without compromising reliability or imposing disproportionate system expansion. Scale is central to this question. Larger installations may spread fixed auxiliary loads over greater gas throughput, use compressors closer to design capacity and support more effective heat integration. Smaller systems may achieve high percentage removal while consuming a larger share of available electricity per unit of carbon dioxide captured [16]-[19].

This paper compares Port Harcourt and Lafía using a common modelling framework. Port Harcourt represents an urban-industrial centre with high demand and concentrated energy use; Lafía represents a smaller rural-agricultural system. The study asks: (i) how capture efficiency differs across the two scales; (ii) how the absolute and proportional parasitic loads compare; (iii) how specific electrical intensity changes with scale; and (iv) what these results imply for design and deployment. The principal contribution is a scale-sensitive interpretation of capture performance that links process outcomes from Aspen HYSYS with system-level operation in HOMER Pro.

II. LITERATURE REVIEW

2.1 Post-Combustion Carbon Capture and Energy Penalty

Post-combustion capture separates carbon dioxide from flue gas after combustion. Chemical absorption with aqueous alkanolamines, particularly monoethanolamine, remains a benchmark technology because of its high reactivity, commercial experience and suitability for retrofit [11], [20]-[23]. The conventional process includes flue-gas cooling, absorption, rich-solvent transfer, heat exchange, stripping, lean-solvent return, drying and compression. Major energy demands arise from reboiler heat, solvent pumping, induced-draft fans and multistage compression.

The literature consistently shows that solvent regeneration dominates the thermal energy requirement of amine capture. Process improvements therefore focus on solvent formulation, absorber and stripper design, intercooling, heat integration, advanced configurations and improved compression trains [12], [14], [20]-[25]. Piperazine-promoted and concentrated piperazine solvents have been investigated as alternatives to conventional monoethanolamine because they can offer faster kinetics and improved thermal stability under selected conditions [26]-[30]. Nevertheless, solvent degradation, corrosion, emissions and reclaiming remain operational concerns.

Gas-fired power plants present a distinct capture challenge because their flue gas generally has lower carbon dioxide concentration than coal-fired systems. Lower concentration increases gas volume per unit of carbon dioxide and raises separation work. Studies of natural-gas combined-cycle plants show that exhaust-gas recirculation, supplementary firing, oxygen enrichment and advanced solvent systems can improve capture integration, but each measure changes plant performance and cost [31]-[34]. Accordingly, capture efficiency should not be treated as an invariant technology parameter. It is the outcome of feed composition, solvent condition, equipment design, recovery target and operating regime.

Published cost and performance assessments also show that capture percentage and energy penalty must be reported together. A nominally high capture rate may carry an excessive thermal or electrical burden, while a slightly lower recovery can provide a more favourable net-abatement outcome when energy use and additional fuel are considered [13], [15], [16], [35]. This study therefore distinguishes capture efficiency from specific electrical intensity and parasitic share of load.

2.2 Hybrid Renewable-Gas-Battery Systems

Hybrid systems combine complementary resources to meet electricity demand with lower fuel use and improved resilience. Solar and wind reduce variable operating cost and emissions, batteries provide short-duration balancing, and dispatchable generators manage prolonged renewable deficits and peak demand. HOMER-based studies have demonstrated the value of such configurations for remote electrification and microgrids, although results are sensitive to load, resource quality, component cost, battery replacement and fuel price [6]-[10], [36]-[39].

Battery storage is particularly important when an additional capture load is introduced. The battery may supply short-duration capture auxiliaries, prevent rapid gas-turbine ramping and absorb excess renewable production. Yet batteries also introduce round-trip losses, degradation and replacement costs. If capture is modelled as a constant auxiliary demand when it is operationally flexible, the system may be oversized. Conversely, omitting the capture load understates generation, storage and reserve requirements. An integrated dispatch model is therefore needed.

The existing hybrid-energy literature rarely incorporates process-derived carbon-capture loads. Most studies optimise renewable fraction, levelised cost, fuel savings or unmet load, while treating fossil backup emissions as an unavoidable residual. Carbon-capture studies, by contrast, usually model a thermal plant or industrial source without representing renewable generation and battery dispatch. Bridging these modelling traditions is necessary to understand how capture auxiliaries compete with load and how renewable-rich systems can schedule capture operation.

2.3 Nigerian Energy Context and Research Gap

Nigeria has strong solar resources, regional wind potential and substantial natural-gas reserves, but electricity supply remains constrained by generation, transmission, distribution and financial weaknesses. The continued use of decentralised petrol and diesel generation raises cost and local pollution. Nigeria's Energy Transition Plan positions gas as a transition fuel while expanding renewable electricity and pursuing a net-zero pathway [5]. This creates a policy rationale for examining low-carbon gas-backed hybrid systems rather than assuming an immediate gas exit.

Nigerian research has considered hybrid mini-grids, rural electrification and renewable-gas or renewable-diesel systems, with many studies concluding that technical feasibility can coexist with affordability barriers. The viability study by Mas'ud et al. specifically evaluates hybrid renewable energy systems in Nigeria [40]. Wider African and developing-country literature similarly identifies financing, imported-component exposure, operation and maintenance capacity, and local load uncertainty as decisive factors [37]-[39], [41].

Carbon capture research relevant to Nigeria has focused more heavily on policy potential, industrial applications, geological storage or stand-alone process simulation than on integration with renewable-rich power systems. Recent technical reviews emphasise the need for improved process configurations, stronger energy efficiency and system-level techno-economic evaluation [42]-[45], [50]. Public acceptance and infrastructure lock-in also shape deployment choices, particularly where long-lived fossil assets and community trust affect project legitimacy [48], [49]. The unresolved issue is scale: whether a rural system with lower throughput can absorb the same capture architecture as an urban-industrial system without suffering a disproportionate burden. This study addresses that gap through a controlled two-case comparison.

III. MATERIALS AND METHOD

3.1 Research Design and Case Selection

A comparative simulation design was adopted. Process-level carbon capture modelling was undertaken in Aspen HYSYS, and system-level energy optimisation was undertaken in HOMER Pro. The two models were linked through the electrical parasitic load required by capture and compression. Port Harcourt was selected as an urban-industrial case, while Lafia was selected as a rural-agricultural case. The comparison is scale-sensitive rather than statistically representative: its purpose is to identify how different demand magnitudes change the operational significance of the capture load.

3.2 Hybrid System Configuration

Each case contained solar photovoltaic arrays, wind turbines, a natural-gas turbine, lithium-ion battery storage, converters and a post-combustion carbon capture unit. Solar and wind provided the dominant annual electricity contribution. Batteries managed intraday variability and supported continuity, while the gas turbine supplied dispatchable power during renewable deficits and periods of high demand. The capture plant treated the gas-turbine exhaust when the thermal unit operated.

The modelling boundary extended from flue-gas entry to compressed carbon dioxide at the capture-plant outlet. It included flue-gas conditioning, absorption, solvent circulation, regeneration, cooling, drying and compression. Carbon dioxide transport, utilisation, injection, geological storage, monitoring and post-closure liability were excluded. This boundary isolates the energy burden directly attributable to capture and compression.

3.3 Aspen HYSYS Capture Model

The HYSYS model represented an amine-based absorber-regenerator process. Aqueous monoethanolamine was used as the benchmark solvent because of its established application in post-combustion capture studies [11], [20]-[23]. The process model generated treated-gas composition, capture efficiency, solvent circulation, regeneration duty and compression-related electrical demand. Capture efficiency was computed as the fraction of inlet carbon dioxide removed from the treated stream, expressed as a percentage.

Specific electrical intensity was defined as the electrical energy used for capture auxiliaries and compression divided by the mass of carbon dioxide captured. The metric is expressed in kWh kg⁻¹ CO₂. The parasitic electrical load was then calculated as the product of specific electrical intensity and hourly captured carbon

dioxide mass. Expressed mathematically: $P_{\text{parasitic}} \text{ (kW)} = S \text{ (kWh kg}^{-1}\text{)} \times m_{\text{CO}_2, \text{captured}} \text{ (kg h}^{-1}\text{)}$. The percentage burden equals $P_{\text{parasitic}}$ divided by the relevant system power base multiplied by 100.

3.4 HOMER Pro System Model

HOMER Pro was used to optimise component dispatch and system adequacy under location-specific load and renewable-resource conditions. Port Harcourt recorded mean electricity demand of 136.26 MW, ranging from 97.6 to 185.9 MW. Lafia recorded mean demand of 13.31 MW, ranging from 7.4 to 20.0 MW. Seasonal patterns were retained because renewable availability and load variation influence the capacity to serve both consumer demand and capture auxiliaries.

The capture load was incorporated as an internal auxiliary demand rather than subtracted after optimisation. This treatment ensures that solar, wind, battery and gas-turbine capacities respond to the real electricity requirement of the integrated system. Key outputs were renewable penetration, unmet load, gas-turbine dispatch, battery behaviour and the capture-related parasitic burden. Reliability was considered acceptable when the optimised configuration met the modelled demand without material unmet load.

3.5 Performance Indicators

Five indicators guided the comparison: carbon dioxide capture efficiency; specific electrical intensity; absolute parasitic load; parasitic load as a share of mean system demand; and renewable penetration. Capture efficiency measures separation performance, while specific electrical intensity measures the electricity required per kilogram captured. Absolute parasitic load indicates the auxiliary capacity that must be supplied. Percentage parasitic load reveals the burden relative to system scale. Renewable penetration tests whether the added capture load is compatible with a renewable-dominant architecture.

IV. RESULTS AND ANALYSIS

4.1 Comparative Performance

Both optimised systems achieved renewable penetration above 90% while maintaining operational reliability. This confirms that a renewable-dominant hybrid architecture can accommodate dispatchable gas generation, battery storage and post-combustion capture. However, the capture burden differed markedly between the two locations. Table 1 presents the principal comparative indicators.

Table 1: Comparative Carbon Capture and Parasitic Energy Indicators

Indicator	Lafia	Port Harcourt
Mean electricity demand	13.31 MW	136.26 MW
Demand range	7.4-20.0 MW	97.6-185.9 MW
CO ₂ capture efficiency	97.88%	93.78%
Specific electrical intensity	0.057 kWh kg ⁻¹ CO ₂	0.0185 kWh kg ⁻¹ CO ₂
Average parasitic load	0.512 MW	1.109 MW
Parasitic load as share of demand	2.56%	0.79%
Renewable penetration	Above 90%	Above 90%

Lafia achieved the higher capture efficiency, removing 97.88% of carbon dioxide from the treated stream. Its specific electrical intensity was 0.057 kWh kg⁻¹ CO₂, and the resulting capture auxiliary demand was 0.512 MW. Relative to the selected power base, this represented a parasitic burden of 2.56%. The result indicates strong separation performance but a comparatively high electricity requirement per unit of carbon dioxide captured.

Port Harcourt achieved 93.78% capture efficiency. Although this percentage was lower than Lafia's, the specific electrical intensity fell to 0.0185 kWh kg⁻¹ CO₂. The absolute auxiliary load was 1.109 MW, more than twice Lafia's value, yet it represented only 0.79% of the larger system power base. The urban-industrial system therefore carried a greater absolute load but a much smaller proportional burden.

4.2 Scale Effects

The comparison reveals a clear scale effect. Port Harcourt's mean demand was approximately ten times Lafia's, while its parasitic percentage was less than one-third of Lafia's. Its specific electrical intensity was also roughly one-third of the Lafia value. These differences are consistent with improved utilisation of fixed equipment at higher throughput, more favourable compression operation and wider scope for process integration. The result should not be interpreted as a universal scaling law, because flue-gas composition and component design also influence performance, but it demonstrates that scale materially affects how the same functional capture boundary interacts with a hybrid power system.

The apparently superior capture percentage in Lafia does not overturn this conclusion. Capture percentage indicates the fraction removed, not the electricity expended to remove it. A system can achieve higher removal by circulating more solvent, providing greater regeneration duty or operating equipment away

from its most efficient point. For integrated power-system planning, net emissions reduction, specific energy use and the ability to maintain reliable supply are more informative than capture percentage alone [13], [15], [35].

4.3 Reliability and Renewable Penetration

Renewable penetration above 90% was retained in both cases. The capture auxiliary load therefore did not force either system into fossil-dominant operation. This outcome reflects the complementary role of batteries and dispatchable gas generation. Renewable electricity served the majority of annual demand; batteries managed short-duration mismatch; and the gas turbine supported periods of low renewable supply. The capture unit operated as an additional internal load within this coordinated dispatch structure.

The reliability implication is nevertheless different across scales. In Lafia, a 0.512 MW auxiliary load is significant relative to mean demand and reserve capacity. Battery state of charge, renewable curtailment and turbine headroom must therefore be managed carefully. In Port Harcourt, 1.109 MW is larger in absolute terms but small relative to the load range. The larger system has greater operational flexibility to absorb capture demand without altering the dominant dispatch pattern.

V. DISCUSSION

5.1 Interpreting Capture Efficiency and Energy Intensity Together

The principal finding is that carbon dioxide capture efficiency and parasitic energy burden can move in opposite directions. Lafia achieved higher percentage removal but poorer electrical intensity. Port Harcourt achieved lower percentage removal but considerably better specific electrical performance. This supports the broader literature's warning that capture rate should not be reported without energy and net-output indicators [12]-[16]. For decision-makers, the relevant question is not simply how much carbon dioxide is separated, but how much additional generation, storage and fuel are required to deliver that separation.

A marginal increase in capture rate can become counterproductive if it requires disproportionate energy input. Additional electricity may be supplied by renewable overgeneration, battery discharge or gas-turbine output. If supplied by gas, the auxiliary load creates secondary emissions and reduces net abatement. If supplied by batteries, it consumes stored energy that might otherwise serve peak demand. If supplied through additional renewable capacity, it raises capital requirements. Therefore, the selected recovery target should be optimised at system level rather than imposed as an isolated process target.

5.2 Why Smaller Systems Face a Higher Proportional Burden

Smaller systems have less demand over which to spread fixed auxiliary loads. Pumps, blowers, control systems, cooling and compression equipment may retain minimum operating requirements even when carbon dioxide throughput is modest. Turndown can also reduce efficiency. The Lafia result illustrates this effect: the absolute parasitic load is modest, but its proportional significance is substantial. Similar concerns appear in distributed and modular capture literature, where equipment simplification and flexible operation are central design requirements [17]-[19].

This does not make rural capture inherently infeasible. It indicates that rural applications require a different design logic. Modular absorbers, shared compression, clustered emitters, seasonal capture operation, flexible recovery targets and deliberate use of otherwise-curtailed renewable electricity may reduce the burden. Carbon capture may also be more appropriate for rural agro-processing clusters than for isolated small generators because clustered operation increases utilisation and carbon dioxide throughput.

5.3 Urban-Industrial Deployment Advantage

Port Harcourt provides a stronger early-deployment case. High demand, concentrated industrial activity and larger gas throughput create conditions in which capture auxiliaries account for a small share of power. Industrial clusters may also share carbon dioxide conditioning, compression, transport and storage infrastructure, reducing unit cost. International CCS experience shows that coordinated infrastructure and policy support are important for demonstration and scale-up [2], [3], [46], [47].

The urban-industrial advantage is not solely economic. Large projects can support specialised operators, maintenance teams, solvent management, continuous emissions monitoring and stronger safety systems. They also generate more absolute abatement. For Nigeria, this suggests prioritising large gas-based embedded generation, industrial estates, refining and petrochemical clusters, fertiliser facilities and other concentrated sources before extending capture to small decentralised systems.

5.4 Dispatch Strategy for Capture-Enabled Hybrids

The capture plant should be treated as a dispatchable or semi-flexible subsystem where process constraints permit. During periods of high renewable output, capture and compression can operate at higher throughput or batteries can be charged while capture continues. During low-renewable periods, capture

throughput may be reduced within emissions-compliance limits, or the battery can support auxiliaries. Such coordination can lower curtailment and prevent capture from forcing unnecessary gas-turbine operation.

However, frequent cycling can affect solvent condition, thermal integration and equipment life. A practical control strategy must therefore balance electrical flexibility with chemical-process stability. Future models should represent minimum load, ramp rates, solvent inventory, start-up energy and temporary carbon dioxide buffering. The present study uses average parasitic indicators and therefore establishes a planning benchmark rather than a full dynamic control design.

VI. POLICY AND PRACTICAL IMPLICATIONS

First, carbon-capture policy should be scale-sensitive. Uniform performance requirements or incentives may impose a heavier effective burden on small systems. Rural and agricultural projects may require concessional finance, modular-technology grants, shared infrastructure and support for engineering demonstration. Urban-industrial projects should be prioritised for early pilots because they offer lower proportional energy penalties and greater absolute abatement.

Second, capture auxiliaries must be included explicitly in hybrid-system sizing. Renewable, battery and gas capacities should not be selected solely against consumer load. Designers must include pumps, fans, solvent circulation, cooling, regeneration support and compression. Excluding these loads creates optimistic reliability and cost results. The modelling linkage used in this study provides a transparent method for incorporating process-derived capture demand.

Third, technology standards and project approval should require simultaneous reporting of capture efficiency, specific thermal duty, specific electrical intensity, parasitic percentage, net plant output and net emissions avoided. A single high capture percentage can conceal poor integrated performance. Standardised reporting would improve project comparison and reduce the risk that technically impressive but energetically inefficient designs receive support.

Fourth, Nigeria needs integrated capacity development. Engineers and operators require skills spanning renewable-system design, gas-turbine operation, battery management, amine-process control, compression, emissions measurement and safety. Training should connect universities, equipment suppliers, power developers, regulators and industrial operators. The knowledge base must also cover measurement, reporting and verification if captured carbon dioxide is to support climate finance or carbon-market claims.

Finally, research and demonstration should proceed in stages. Initial pilots should focus on large load centres and concentrated emitters. Data from these pilots should be used to refine solvent performance, parasitic-load models, flexible operation, maintenance schedules and local cost assumptions. Smaller systems should follow when modular designs and shared-service models have demonstrated acceptable energy intensity and reliability.

VII. LIMITATIONS AND FUTURE RESEARCH

The paper compares two case studies and should not be interpreted as a national statistical estimate. The process boundary stops at compression; transport and storage energy, cost and risk are excluded. The parasitic indicators are planning-level averages and do not represent second-by-second dynamics, capture start-up, solvent degradation or equipment ramping. The HOMER Pro model captures system dispatch but does not reproduce all chemical-process constraints. In addition, conclusions about scale may also reflect differences in flue-gas composition and equipment configuration.

Future research should couple dynamic process simulation with sub-hourly energy dispatch, evaluate heat integration between the gas turbine and solvent regenerator, test flexible capture operation, and compare monoethanolamine with advanced solvents, membranes and hybrid processes. Further studies should include transport and storage, lifecycle emissions, water consumption, degradation products, uncertainty analysis and Nigerian financing conditions. Multi-site analysis would help distinguish pure scale effects from location-specific resource and load effects.

VIII. CONCLUSION

This study evaluated the parasitic electrical burden and carbon dioxide capture performance of renewable-gas-battery hybrid power systems in Port Harcourt and Lafia. Post-combustion capture was technically integrated into renewable-dominant configurations with renewable penetration above 90%. Lafia achieved higher capture efficiency, 97.88%, but required 0.057 kWh kg⁻¹ CO₂ and incurred a parasitic burden of 2.56%, equivalent to 0.512 MW. Port Harcourt achieved 93.78% capture efficiency, but required only 0.0185 kWh kg⁻¹ CO₂ and incurred a parasitic burden of 0.79%, equivalent to 1.109 MW.

The results show that capture performance is scale-sensitive. Percentage removal alone does not determine technical quality. Specific electrical intensity and parasitic share of demand are necessary to understand how capture affects an integrated power system. Larger urban-industrial systems can absorb greater absolute auxiliary power while experiencing a smaller proportional penalty. Smaller rural systems remain

technically possible, but require more careful reserve planning, battery sizing, flexible capture operation and policy support.

For Nigeria, early deployment should therefore focus on large industrial and embedded-power systems where emissions are concentrated and economies of scale are available. Smaller systems should be approached through modular technology, clustered loads and shared infrastructure. A scale-sensitive deployment strategy can preserve reliability while advancing the decarbonisation of gas-backed hybrid electricity.

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