

Stakeholder readiness and Institutional Barriers to Carbon-Capture-integrated Renewable Energy Storage Systems in Nigeria

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Abstract: This study evaluates stakeholder readiness and institutional barriers affecting carbon-capture-integrated renewable energy storage systems in Nigeria. A structured survey produced 139 valid responses from engineering, management, regulatory, academic, project-delivery, and industrial-energy professionals. Survey evidence was triangulated with Aspen HYSYS process-simulation results and HOMER Pro system-optimization outputs. High capital cost was the leading barrier, identified by 58% of respondents, followed by regulatory uncertainty at 51% and technical-capacity constraints at 50%. Although 78% considered carbon capture, utilization, and storage important or highly important to Nigeria's decarbonization pathway, familiarity with amine-based capture was substantially lower than familiarity with solar photovoltaic and battery systems. Process modelling indicated carbon dioxide capture efficiencies above 93%, while also confirming increased auxiliary demand, process complexity, and capital exposure. The combined evidence indicates moderate technical readiness but weaker financial, regulatory, and carbon-market readiness. A phased pathway is recommended, comprising a dedicated CCUS framework, blended finance, demonstration projects, workforce development, credible carbon accounting, and transparent stakeholder engagement.

Keywords: carbon capture and storage, carbon markets, hybrid energy systems, institutional readiness, renewable energy storage

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I. INTRODUCTION

1.1 Background and Problem Context

Global electricity systems are being reshaped by climate obligations, energy-security concerns, declining technology costs, and the need for reliable low-carbon power. Renewable generation, battery storage, energy-efficiency measures, and carbon capture, utilization and storage (CCUS) are increasingly treated as complementary elements of deep decarbonization rather than competing pathways,. For countries with rising electricity demand and constrained grid reliability, the central policy question is not merely whether low-carbon technologies are desirable, but whether they can be deployed in ways that are technically dependable, institutionally governable, financially bankable, and socially credible. [1]-[5].

Nigeria presents a particularly important case. The country possesses abundant renewable resources, substantial natural-gas reserves, a large electricity market, and a stated net-zero ambition, yet grid electricity remains insufficient for domestic and industrial needs. Households and firms continue to rely heavily on diesel and petrol generators, which increases energy costs, local air pollution, and greenhouse-gas emissions. Hybrid systems combining solar photovoltaic generation, wind turbines, battery energy storage, and gas-fired generation can improve reliability while reducing fuel dependence,. Integrating post-combustion capture with the gas-generation element may further reduce emissions while retaining dispatchable capacity. [5]-[8].

Carbon capture, however, is not a simple add-on. It requires absorbers, solvent-regeneration units, heat exchangers, compression facilities, monitoring systems, transport arrangements, and long-term storage governance. These requirements increase capital cost, parasitic energy consumption, operational complexity, and liability exposure,. In emerging economies, institutional and financial limitations may therefore delay or prevent deployment even when process simulations indicate strong engineering performance. [14]-[18].

1.2 Carbon Capture Within Hybrid Renewable Energy Systems

Post-combustion amine absorption is among the most mature capture options for gas-fired and industrial facilities because it treats flue gas after combustion and can be retrofitted to suitable existing assets.

Recent process studies indicate that capture efficiencies above 90% are achievable when absorber design, solvent circulation, regeneration duty, and heat integration are properly managed,. Higher capture performance nevertheless requires additional energy and more demanding plant integration. Stakeholder understanding, operator capability, and institutional preparedness are consequently central to deployment prospects. [16]-[21].

Engineering feasibility alone does not establish deployability. In countries with immature carbon markets and limited long-term infrastructure finance, financial and institutional barriers may dominate technical performance. Adoption must therefore be assessed as a socio-technical process involving regulators, investors, operators, academics, communities, and industrial users,. [9]-[13], [28]-[35].

1.3 Research Gap, Aim and Contribution

Nigerian energy research has extensively examined renewable-resource assessment, hybrid-system sizing, mini-grid economics, and electricity-sector reform. Carbon-capture studies have also considered process simulation and geological storage potential. Far less attention has been given to whether relevant stakeholders understand the technology, whether institutions are prepared to govern it, and whether perceived barriers correspond with engineering and economic realities. This gap matters because technically optimized projects can remain undeployed when regulation, finance, skills, and public trust are inadequate. [41]-[47].

This study examines stakeholder readiness and institutional barriers affecting carbon-capture-integrated renewable energy storage systems in Nigeria. It evaluates technology familiarity, perceived strategic relevance, deployment barriers, institutional preparedness, and preferred policy interventions. It further triangulates survey findings with Aspen HYSYS process simulations and HOMER Pro energy-system optimization. The principal contribution is an integrated assessment that connects social acceptance and governance capacity with technical feasibility and project economics in a developing-country context.

II. LITERATURE REVIEW AND CONCEPTUAL FOUNDATION

2.1 Socio-Technical Transitions and Technology Acceptance

Energy transitions alter technologies, infrastructure, institutions, markets, professional practices, and social expectations. The multi-level perspective explains transition through interactions among niche innovations, established regimes, and wider landscape pressures. Carbon-capture-integrated hybrid systems can be understood as niche configurations that must compete with incumbent fossil generation, decentralized generators, conventional renewable projects, and established regulatory routines. Carbon lock-in persists when infrastructure, knowledge, incentives, and institutional practices reinforce familiar technologies, even where alternatives are technically superior. [9], [10], [13].

The technological innovation systems perspective emphasizes knowledge development, entrepreneurial experimentation, market formation, resource mobilization, legitimacy, and policy coordination. Weakness in any of these functions can hold a technology at the demonstration stage. For carbon capture in Nigeria, the relevant system includes energy and environmental ministries, electricity and petroleum regulators, developers, financial institutions, universities, engineering firms, industrial emitters, and prospective host communities. Their readiness cannot be inferred from technical performance alone. [10], [13].

Technology-acceptance theory adds a decision-level explanation. Stakeholders are more likely to support technologies they perceive as useful, understandable, manageable, and compatible with organizational capabilities. Carbon capture may be viewed as environmentally useful while still being rejected as costly, complex, risky, or insufficiently regulated. Acceptance therefore depends on credible information, visible benefits, risk management, and confidence in implementing institutions,. [11], [12], [31]-[35].

2.2 Carbon Capture and Deep Decarbonization

Carbon capture can be implemented through pre-combustion separation, oxy-fuel combustion, or post-combustion treatment. Post-combustion amine absorption is particularly relevant to gas-fired and industrial facilities because it treats flue gas downstream of combustion. The process normally includes gas cooling and conditioning, absorption in a solvent column, transfer of carbon-rich solvent to a stripper, solvent regeneration, carbon dioxide drying and compression, and transport for utilization or geological storage. Technical maturity does not eliminate the energy penalty associated with regeneration and compression, or the costs of corrosion control, solvent degradation, emissions management, and long-term storage integrity,. [15]-[21], [23].

Membranes, solid sorbents, ionic liquids, and hydrate-based processes may reduce selected limitations, but many remain less mature than conventional amines. Near-term Nigerian deployment is most plausible at large, concentrated emission sources where capture equipment can operate at high utilization and shared transport and storage infrastructure can create economies of scale. Gas processing, fertilizer production, cement manufacture, liquefied natural gas facilities, and large gas-fired power plants are therefore stronger initial candidates than small decentralized generators. [16], [18], [21].

2.3 Renewable Energy Storage and Hybrid-System Economics

Battery storage enables variable renewable electricity to contribute more effectively to reliable supply, but its economics depend on duty cycle, temperature, replacement timing, financing cost, and import exposure. Tropical operating conditions can accelerate degradation when thermal management is inadequate. In Nigeria, exchange-rate volatility, import duties, limited domestic manufacturing, and weak recycling systems further affect lifecycle cost. Hybrid designs combining renewables, storage, and dispatchable generation may reduce the battery capacity needed to satisfy reliability targets, although carbon capture introduces an additional layer of capital and operating complexity,.. [36]-[43].

2.4 Institutional Readiness and Social Licence

Institutional readiness is the capacity of legal, regulatory, financial, educational, and technical systems to authorize, finance, operate, monitor, and govern a technology throughout its lifecycle. For carbon capture and storage, this includes ownership of captured carbon dioxide, permitting, transport standards, pore-space rights, measurement and verification, environmental safeguards, post-closure monitoring, liability transfer, emergency response, and carbon-credit recognition. Ambiguity raises transaction costs and discourages investment because developers cannot reliably price risk. [2], [4], [23]-[27], [48], [49].

Social acceptance is equally important. Communities may support emission reduction in principle while remaining concerned about pipelines, storage integrity, industrial safety, land use, and the distribution of local benefits. These issues are especially relevant in the Niger Delta, where historical environmental degradation has weakened trust in industrial operators and public institutions. Social licence must therefore be developed through early disclosure, participatory decision-making, independent monitoring, accessible grievance mechanisms, and demonstrable local value. [28]-[35].

2.5 Analytical Propositions

Four propositions guided the analysis. First, stakeholder support was expected to be positive but conditional because respondents could recognize the strategic value of carbon capture while remaining concerned about cost and governance. Second, familiarity was expected to be greater for solar photovoltaic and battery technologies than for carbon capture. Third, financial and regulatory barriers were expected to be rated more severely than technical feasibility. Fourth, survey concerns were expected to converge broadly with simulation evidence where perceptions reflected actual project conditions.

III. METHODOLOGY

3.1 Research Design and Context

The study adopted a pragmatic convergent mixed-methods design that integrated quantitative stakeholder evidence with process and energy-system modelling. Pragmatism was appropriate because the research question required assessment of both measurable system performance and the institutional conditions shaping implementation. The survey, Aspen HYSYS analysis, and HOMER Pro optimization were treated as complementary evidence streams and interpreted jointly after separate analysis. Nigeria was selected because it combines electricity-supply constraints, rapid demand growth, strong renewable resources, substantial gas reserves, established oil and gas expertise, and a stated net-zero ambition for 2060. [50].

3.2 Population, Sampling and Participants

The target population comprised professionals in power, petroleum, renewable energy, environmental management, regulation, academia, consulting, project delivery, and industrial energy use. Purposive expert sampling was used because meaningful responses required technical exposure, policy experience, or decision-making responsibility. Eligible participants had relevant professional experience, direct involvement in energy or environmental activities, exposure to low-carbon technologies, or academic specialization in an energy-related field. The final dataset contained 139 valid responses. The design sought informed professional judgement rather than population-wide opinion. [50].

Table 1: Respondent Distribution by Professional Category

Professional category	Frequency	Percentage
Technical and engineering professionals	47	34%
Senior managers and executives	39	28%
Policy, regulatory and academic professionals	31	22%
Project and operations personnel	22	16%
Total	139	100%

3.3 Instrument and Measures

A structured online questionnaire was developed from literature on technology acceptance, CCUS deployment, renewable-energy diffusion, institutional readiness, and policy support. It collected professional and organizational characteristics and assessed familiarity with low-carbon technologies, perceived CCUS relevance, deployment barriers, institutional readiness, and preferred policy interventions. Familiarity and readiness items used ordered response scales, barrier questions permitted identification of the most material constraints, and policy interventions were rated on a five-point scale. [11], [12], [28]-[35].

Content validity was addressed by aligning questionnaire items with constructs established in the literature and obtaining expert review from energy-systems, climate-policy, and research professionals. Construct coverage distinguished technical, institutional, regulatory, and financial readiness. Internal consistency was intended to be assessed against a Cronbach alpha threshold of 0.70. Because the item-level dataset and calculated coefficients were not provided with the source manuscript, no unsupported reliability coefficient is reported. The final submission should insert the observed alpha for each multi-item scale.

3.4 Data Collection and Ethical Considerations

The questionnaire was distributed electronically through professional networks, industry associations, academic collaborations, professional online groups, and corporate contacts. Participation was voluntary, respondents were informed about the purpose and intended use of the research, and no personally identifying information was reported. Responses were analysed in aggregate. The applicable institutional ethics approval or exemption identifier should be inserted before submission.

3.5 Analytical Procedure

Descriptive statistics summarized participant characteristics, sector representation, technology familiarity, perceived barriers, and readiness ratings. Percentages were used for categorical responses and means for five-point items. The original design proposed a relative importance index, calculated as the sum of weighted responses divided by the product of the maximum possible weight and number of respondents. Because the supplied results report barrier-selection percentages rather than complete weighted scores, barriers were ranked by observed percentages and no unreported index values were inferred.

A composite readiness profile was constructed across technical, institutional, financial, and regulatory domains. Survey findings were compared with companion Aspen HYSYS and HOMER Pro outputs. Convergence indicated agreement between stakeholder concerns and modelled technical or economic effects. Divergence was interpreted as a possible knowledge gap or evidence that the models did not capture an institutional consideration.

3.6 Process and System Modelling Integration

Aspen HYSYS was used in the companion technical analysis to represent post-combustion amine-based capture. Outputs included capture efficiency, reboiler duty, parasitic energy demand, solvent requirements, and equipment implications. Two demand contexts were considered: a rural-agricultural Lafia case with average demand of 13.31 MW and an urban-industrial Port Harcourt case with average demand of 136.26 MW. HOMER Pro optimized configurations containing solar photovoltaic generation, wind turbines, battery storage, natural-gas generation, and carbon capture. System outputs included net present cost, levelized cost of electricity, renewable penetration, excess electricity, and emission reduction. This article uses those outputs for triangulation rather than reproducing the complete models, which should be documented in a companion paper or supplementary file.

IV. RESULTS

4.1 Respondent and Sector Profile

Technical and engineering professionals formed the largest respondent group at 34%, followed by senior managers and executives at 28%. Policy, regulatory, and academic professionals represented 22%, while project and operations personnel represented 16%. This composition provided substantial technical and managerial input. However, the purposive sampling strategy means the findings should not be generalized to Nigeria's entire population without caution.

Table 2: Sectoral Distribution of Respondents

Organization type	Percentage
Oil and gas industry	31%
Electricity utilities	25%
Renewable-energy developers	20%

Organization type	Percentage
Government and regulatory institutions	14%
Universities and research institutions	10%

4.2 Familiarity and Strategic Relevance

Familiarity was highest for solar photovoltaic technology, with 92% reporting moderate-to-high familiarity, followed by battery energy storage at 84%. Familiarity fell substantially for carbon-management technologies: amine-based capture recorded 38%, direct air capture 22%, and clathrate-hydrate capture 12%. The findings confirm a marked knowledge gap between commercially visible renewable technologies and less familiar carbon-removal options.

Table 3: Moderate-to-High Familiarity With Low-Carbon Technologies

Technology	Percentage
Solar photovoltaic systems	92%
Battery energy storage systems	84%
Amine-based carbon capture	38%
Direct air capture	22%
Clathrate-hydrate capture	12%

Despite limited familiarity with capture processes, 43% considered CCUS highly important and 35% considered it important to Nigeria's decarbonization pathway. The combined positive rating of 78% indicates that strategic support exceeds detailed technical familiarity. Neutral responses accounted for 12%, while 7% assigned limited importance and 3% considered CCUS unimportant.

Table 4: Perceived Strategic Relevance of CCUS

Response	Percentage
Highly important	43%
Important	35%
Neutral	12%
Of limited importance	7%
Not important	3%

4.3 Deployment Barriers

High capital cost was the most frequently identified barrier, selected by 58% of respondents. Regulatory uncertainty followed at 51%, while technical-capacity constraints were identified by 50%. Grid and infrastructure weakness was selected by 42%, and weak carbon-market signals by 35%. The close ranking of cost, regulation, and skills indicates an interdependent set of financial and institutional constraints rather than a single-variable problem.

Table 5: Perceived Barriers to Deployment

Barrier	Percentage identifying barrier
High capital cost	58%
Regulatory uncertainty	51%
Technical-capacity constraints	50%
Grid and infrastructure weaknesses	42%
Weak carbon-market signals	35%

4.4 Institutional and Policy Readiness

Respondents rated energy-transition policy commitment at 3.8 out of 5 and the renewable-energy policy framework at 3.7. Technical-workforce availability received a moderate rating of 3.2. The weakest dimensions were climate-finance readiness at 2.9, regulatory readiness for CCUS at 2.7, and carbon-market readiness at 2.5.

This pattern indicates a gap between high-level policy ambition and the instruments required for implementation.

Table 6: Institutional Readiness Ratings

Institutional dimension	Mean score
Energy-transition policy commitment	3.8
Renewable-energy policy framework	3.7
Technical-workforce availability	3.2
Climate-finance readiness	2.9
Regulatory readiness for CCUS	2.7
Carbon-market readiness	2.5

Tax incentives and fiscal relief received the strongest policy-support rating at 4.6, followed by dedicated CCUS regulation at 4.5, government-supported demonstration projects at 4.4, climate-finance mechanisms at 4.3, and workforce-development programmes at 3.9. Respondents therefore expected the public sector to reduce early-stage risk rather than relying exclusively on private investment.

Table 7: Preferred Policy Support Mechanisms

Policy intervention	Mean rating
Tax incentives and fiscal relief	4.6
Dedicated CCUS regulations	4.5
Government-supported demonstration projects	4.4
Climate-finance support mechanisms	4.3
Workforce-development programmes	3.9

4.5 Triangulation With Aspen HYSYS and HOMER Pro

The Aspen HYSYS simulations achieved carbon dioxide capture efficiencies above 93% in all modelled cases, supporting the technical feasibility of amine-based capture. They also showed additional energy requirements for solvent regeneration, carbon dioxide compression, and auxiliary equipment. These effects were consistent with stakeholder concerns regarding operating complexity and cost. The modelling reduced uncertainty about attainable capture performance but confirmed that high efficiency requires specialized operation and additional energy input. [14]-[21].

HOMER Pro results similarly showed that capture integration increased system capital expenditure. Larger industrial configurations performed more favourably than the smaller rural configuration because fixed capture costs and specialist infrastructure were distributed over greater energy output and larger emission streams. The simulation evidence therefore supported the stakeholder view that cost is the principal near-term barrier and that public incentives or concessional finance will be required during early deployment. [36]-[43].

Table 8: Alignment Between Stakeholder Perceptions and Modelling Evidence

Issue	Stakeholder assessment	Modelling evidence	Alignment
Technical complexity	High concern	Specialized process integration and control required	Strong
Capture efficiency	Uncertain	Capture efficiency exceeded 93%	Moderate
Operating burden	Significant concern	Regeneration, compression and auxiliary loads increased demand	Strong
Capital exposure	Highest-ranked barrier	Capture equipment increased system capital cost	Strong
Workforce capability	Capacity considered limited	Specialist design and operating skills required	Strong

4.6 Composite Readiness Profile

The composite profile placed technical readiness at 3.4 out of 5 and institutional readiness at 3.0. Financial readiness was 2.8, while regulatory readiness was 2.7. Nigeria therefore appears better prepared to

understand and engineer the proposed systems than to finance, authorize, and govern them. The overall condition is more accurately described as developing readiness than deployment readiness.

Table 9: Composite Readiness Assessment

Readiness dimension	Score
Technical readiness	3.4
Institutional readiness	3.0
Financial readiness	2.8
Regulatory readiness	2.7

V. DISCUSSION

5.1 Conditional Support and the Readiness Paradox

The findings reveal a readiness paradox. Stakeholders generally support the strategic role of carbon capture, yet they do not consider the enabling environment ready for large-scale deployment. Positive attitudes toward decarbonization do not automatically yield bankable projects. Acceptance is conditional on credible rules, financing mechanisms, technical capacity, and evidence from operating projects. This supports socio-technical transition theory, which treats diffusion as an outcome of coordinated changes in institutions, markets, skills, and legitimacy rather than a direct consequence of technical superiority.. [9]-[13], [28]-[35].

5.2 Capital Cost and Scale

The prominence of capital cost is consistent with the equipment intensity of post-combustion capture and with the HOMER Pro results. Capture units require additional process equipment, heat supply, compression, monitoring, and potentially shared transport and storage infrastructure. Nigerian projects also face currency risk, high financing costs, inflation, import dependence, and uncertain revenue recovery. These conditions can make a technically viable configuration commercially unattractive. Fiscal incentives alone will not solve the problem, but targeted duty relief, accelerated depreciation, concessional debt, guarantees, and results-based climate finance can reduce the initial risk premium. [14], [15], [18], [22], [27].

The contrast between the Lafía and Port Harcourt cases reinforces the importance of scale. Small systems may be suitable for renewable generation and storage, but carbon capture is less attractive where emission streams are small or intermittent. Initial deployment should therefore focus on industrial clusters and large point sources, where shared infrastructure and high utilization can improve economics. Rural systems should prioritize renewables, storage, efficiency, and appropriately sized firm capacity unless modular capture technologies later demonstrate competitive performance. [41]-[47].

5.3 Regulation, Liability and Carbon Value

Regulatory uncertainty was almost as prominent as capital cost. A Nigerian CCUS framework should define the legal status and ownership of captured carbon dioxide, institutional responsibilities, permitting procedures, transport safety, storage-site qualification, monitoring and verification, closure requirements, long-term liability, and mechanisms for liability transfer. It should also clarify how captured and permanently stored carbon dioxide will be recognized in national greenhouse-gas inventories and carbon markets. Without these provisions, developers cannot estimate compliance obligations or forecast revenue from avoided emissions. [2], [4], [6], [7], [23]-[27], [48], [49].

Carbon-market readiness received the lowest institutional rating. This does not imply that carbon pricing alone would make every project economical. It indicates that avoided emissions currently have insufficiently predictable value. A credible measurement, reporting, and verification system is therefore a prerequisite for carbon crediting, bilateral mitigation transfers, or future compliance mechanisms. Credits should be issued only for reductions that are demonstrably additional, durable, and independently verified. [1]-[4], [6], [7].

5.4 Skills, Awareness and Social Legitimacy

Technical-capacity concerns are credible because operating a capture plant requires knowledge beyond conventional power-generation practice. Nigeria can build on oil and gas, chemical engineering, geoscience, and process-safety expertise, but additional capability is needed in solvent management, capture-process control, transport integrity, storage modelling, monitoring, carbon accounting, and integrated energy optimization. Universities and professional bodies should develop multidisciplinary programmes linking engineering, geoscience, environmental governance, finance, and community engagement. [16]-[21], [41]-[49].

Awareness programmes should not be limited to general public promotion. Regulators, financiers, developers, journalists, community leaders, and emergency responders require differentiated information. Demonstration projects can serve as learning platforms if their performance, emissions, incidents, monitoring data, and community commitments are transparently reported. In the Niger Delta and other prospective storage regions, social legitimacy will depend on early participation, independent oversight, accessible grievance procedures, and an equitable distribution of local benefits. [28]-[35].

5.5 Implications for Theory and Practice

The study extends technology-acceptance analysis by demonstrating that perceived usefulness can coexist with low institutional readiness. It also shows the value of triangulating stakeholder evidence with simulation results. Agreement between the survey and models strengthens the interpretation that cost, complexity, and skill limitations are substantive constraints rather than perception alone. In practice, Nigeria should avoid a technology-first strategy in which a pilot is announced before legal, financial, and social arrangements are established. Deployment should proceed through coordinated institutional preparation and carefully selected demonstrations.

VI. POLICY AND DEPLOYMENT ROADMAP

6.1 National Legal and Regulatory Framework

The immediate priority is a dedicated national framework for carbon capture, transport, utilization, and geological storage. It should allocate regulatory authority, establish licensing and permitting requirements, define carbon dioxide quality and pipeline standards, govern pore-space access, require environmental and social assessment, specify monitoring and verification obligations, and establish closure and post-closure liability rules. The framework should be harmonized with electricity, petroleum, environmental, land, and climate legislation so that developers encounter a coherent approval pathway rather than overlapping mandates. [2], [4]-[7], [23]-[27], [48], [49].

6.2 Financial Architecture and Carbon Markets

Early projects will require blended finance. Public resources should mobilize rather than replace private capital through concessional loans, partial-risk guarantees, viability-gap funding, tax relief for qualified equipment, and competitive grants for front-end engineering and design. Support should be conditional on measurable performance, transparent procurement, environmental compliance, and knowledge sharing. Nigeria should simultaneously strengthen greenhouse-gas accounting and carbon-market governance so that verified permanent storage can generate credible mitigation value where appropriate. [2]-[4], [14], [15], [27].

6.3 Demonstration Portfolio

Pilot selection should prioritize facilities with large, concentrated, and relatively stable carbon dioxide streams and access to potential transport and storage corridors. Candidates include gas processing and liquefied natural gas facilities, fertilizer plants, cement facilities, and large gas-fired power stations in industrial clusters such as Port Harcourt and the wider Niger Delta. Each demonstration should include a learning agenda covering capture performance, energy penalty, solvent use, cost, local-content development, safety, monitoring, public engagement, and commercial replication. [2], [4], [22]-[27].

6.4 Capacity and Stakeholder Development

Capacity development should span academia, government, industry, finance, and communities. Academic institutions should integrate capture engineering, storage geoscience, hybrid-system modelling, carbon accounting, and environmental governance into relevant programmes. Regulators require training in permitting, measurement and verification, liability, and economic regulation. Industry needs operating, maintenance, process-safety, and emergency-response capability. Financial institutions need methods for evaluating long-duration infrastructure, technology risk, and carbon-revenue uncertainty. Community engagement should be continuous, locally accessible, and linked to independent monitoring rather than confined to statutory consultation. [28]-[35], [41]-[49].

6.5 Phased National Roadmap

A phased roadmap is recommended. From 2026 to 2030, priority should be given to legal and regulatory design, storage-resource characterization, feasibility studies, workforce development, greenhouse-gas accounting, and carbon-market preparation. From 2030 to 2040, Nigeria should implement a limited demonstration portfolio, mobilize climate finance, establish shared transport and storage concepts, and evaluate performance against transparent criteria. From 2040 to 2050, successful configurations may be expanded across industrial clusters and connected to broader carbon dioxide infrastructure. From 2050 to 2060, mature projects

may contribute to commercial-scale decarbonization, provided lifecycle emissions, storage permanence, affordability, and social legitimacy remain demonstrable. These dates are planning horizons rather than forecasts and should be revised as evidence develops. [1]-[7].

VII. CONCLUSION

This study evaluated stakeholder readiness and institutional barriers affecting carbon-capture-integrated renewable energy storage systems in Nigeria. Survey evidence from 139 professionals showed broad recognition of the strategic value of carbon capture but substantial concern about implementation conditions. High capital cost was identified by 58% of respondents, regulatory uncertainty by 51%, and technical-capacity constraints by 50%. Familiarity with solar photovoltaic and battery systems was high, whereas familiarity with amine-based capture and emerging carbon-removal technologies was considerably lower.

Simulation evidence largely validated these perceptions. Aspen HYSYS results indicated capture efficiencies above 93% while confirming additional energy demand and process complexity. HOMER Pro results showed that capture integration increased capital exposure and that larger industrial applications benefited more from scale than smaller rural systems. The combined evidence indicates moderate technical readiness but weaker financial and regulatory readiness.

The principal implication is that deployment should not begin with equipment procurement alone. It should begin with governance. A credible pathway requires a national CCUS framework, bankable financing mechanisms, robust carbon accounting, carefully selected demonstration projects, multidisciplinary workforce development, and transparent stakeholder engagement. If these conditions are established, carbon-capture-enabled hybrid systems may contribute to expanding reliable electricity while reducing emissions from dispatchable generation and industry.

7.1 Limitations and Future Research

The purposive sample captured informed professional perspectives but does not represent all Nigerian stakeholders. Community members, subnational governments, civil-society organizations, lenders, insurers, and residents of prospective storage regions should be examined in future studies. The article also relies on aggregate survey results and companion simulation outputs. Access to item-level data would permit reliability testing, subgroup comparison, regression analysis, and uncertainty assessment. Future technical studies should compare amines with membranes, solid sorbents, and other capture routes; evaluate site-specific storage capacity and injectivity; model dynamic operation under variable renewable output; quantify full lifecycle emissions; and report empirical evidence from pilot facilities. Longitudinal research should also test whether familiarity, trust, and policy support change after technical information is provided or demonstration projects are observed.

DATA AVAILABILITY STATEMENT

The aggregate data used in this manuscript are reported in the tables. The anonymized item-level dataset and model files should be made available by the author in accordance with institutional, ethical, and journal requirements.

CONFLICT OF INTEREST

The author declares no conflict of interest.

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