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LIFE CYCLE ASSESSMENT AND SUSTAINABILITY ANALYSIS OF BLUE HYDROGEN PRODUCTION IN NIGERIA

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ABSTRACT

Transitioning to sustainable energy sources is critical for mitigating climate change, and hydrogen has emerged as a key alternative to fossil fuels. This study evaluates the feasibility of blue hydrogen production from carbon utilization in Nigeria, with a focus on environmental, economic, and policy dimensions. Using the ReCiPe Life Cycle Assessment (LCA) methodology, the study analyzes global warming potential (GWP), resource depletion, acidification, and human toxicity of blue hydrogen, compared to grey and green alternatives. The results show blue hydrogen reduces CO_2 emissions by up to 90% relative to grey hydrogen, with a GWP range of 1.5–2.5 kg CO_2-eq/kg H_2. However, methane leakage and water consumption remain significant concerns. Economically, blue hydrogen production costs $1.50–$2.50/kg, more than grey hydrogen but less than green hydrogen. Policy and infrastructure gaps continue to hinder large-scale adoption in Nigeria. The study recommends introducing carbon pricing, regulatory incentives, and investment in carbon capture and storage (CCS) to improve blue hydrogen competitiveness. Overall, blue hydrogen presents a viable transitional pathway toward Nigeria's low-carbon energy future.

KEYWORDS: Blue hydrogen**,** Life Cycle Assessment (LCA)**,** Carbon capture and storage (CCS)**,** Sustainable energy transition**,** Nigeria**,** Global warming potential (GWP).

1.0 INTRODUCTION

The global energy landscape is undergoing a paradigm shift driven by the urgency to mitigate climate change. Fossil fuel combustion accounts for over 70% of global greenhouse gas (GHG) emissions, contributing to extreme weather events, rising sea levels, and health crises

(IEA, 2023; UNFCCC, 2022). To address these challenges, a transition to sustainable energy systems has become imperative.

Hydrogen has gained prominence as a versatile clean energy vector capable of decarbonizing hard-to-abate sectors such as industry, transport, and power generation (European Commission, 2018; IRENA, 2023). Depending on the production method, hydrogen is classified as grey, blue, or green. Grey hydrogen, derived from steam methane reforming (SMR) of natural gas, emits significant amounts of CO_2. Blue hydrogen mitigates these emissions through the integration of carbon capture and storage (CCS), while green hydrogen, the cleanest form, is produced via water electrolysis using renewable energy (Friedmann et al., 2020; Voldsund et al., 2016).

Blue hydrogen represents a transitional solution by leveraging existing natural gas infrastructure while reducing emissions. It is particularly relevant for resource-rich, fossil-fuel-dependent economies like Nigeria (Tanko Fwadwabea et al., 2024). Nigeria, Africa's largest oil producer and most populous country, contributes significantly to regional carbon emissions, with the oil and gas sector alone responsible for 60% of national GHG emissions (Nigeria's NDC, 2021). Despite substantial solar and wind energy potential, the country's energy mix remains dominated by fossil fuels, exacerbating environmental degradation and energy insecurity.

This study explores the viability of blue hydrogen production in Nigeria through a Life Cycle Assessment (LCA) and techno-economic analysis. It applies the ReCiPe 2016 methodology to evaluate global warming potential (GWP), resource depletion, acidification, and toxicity impacts. The findings suggest that blue hydrogen can reduce CO_2 emissions by up to 90% compared to grey hydrogen while remaining more cost-effective than green alternatives (IEA, 2023; Fasihi et al., 2021). However, challenges such as methane leakage, high water consumption, and the lack of hydrogen-specific policy frameworks must be addressed to ensure large-scale implementation (Global CCS Institute, 2022).

The strategic importance of hydrogen is reflected in international climate commitments. Nigeria's Nationally Determined Contributions under the Paris Agreement include emission reduction targets that align with the deployment of low-carbon technologies like CCS (UNFCCC, 2022). Developing a domestic hydrogen economy could enhance energy security, support economic diversification, and position Nigeria as a regional hydrogen hub in West Africa (IRENA, 2023).

2.0 METHODOLOGY

This study adopts a mixed-methods approach integrating process simulation, Life Cycle Assessment (LCA), and economic evaluation to assess the technical feasibility and sustainability of blue hydrogen production in Nigeria. The quantitative analysis is supported by Aspen HYSYS and OpenLCA simulations, while the qualitative component draws insights from stakeholder interviews and policy reviews.

2.1 Process Simulation Using Aspen HYSYS

The blue hydrogen production process was simulated using Aspen HYSYS v2.11, modeling a Steam Methane Reforming (SMR) system with integrated Carbon Capture and Storage (CCS). Key process units include pre-treatment, SMR, water-gas shift (WGS), CO_2 absorption, and hydrogen purification via pressure swing adsorption (PSA).

Table 2.1.1: Input Stream for Simulation (Aspen HYSYS).

Component	Flow Rate (kg/hr)	Source
Natural Gas (CH_4)	1,000	Feedstock
Steam (H_2O)	2,500	Boiler
Air	800	Combustion

Source: Aspen HYSYS

Table 2.1.2: SMR Unit Mass Balance

Component	Input (kg/hr)	Output (kg/hr)	Conversion Efficiency (%)
CH_4	1,000	850 reacted	85%
H_2O	2,500	2,000 reacted	80%
CO	0	900	-
H_2	0	600	-

Source: Aspen HYSYS

Table 2.1.3: WGS Unit Mass Balance

Component	Input (kg/hr)	Output (kg/hr)	Conversion Efficiency (%)
CO	900	855 reacted	95%
H_2O	900	855 reacted	95%
CO_2	0	1,800	-
H_2	0	200	-

Source: Aspen HYSYS

Table 2.1.4: CCS Unit Performance

CO_2 Input (kg/hr)	Captured CO_2 (kg/hr)	Emitted CO_2 (kg/hr)	Capture Efficiency (%)
1,800	1,530	270	85%

Table 2.1.5: PSA Unit Output

Component	Output (kg/hr)	Purity (%)
Purified H_2	800	90%
Impurities	900	-

2.2 Life Cycle Assessment (LCA)

The environmental performance of blue hydrogen production was evaluated using OpenLCA and the ReCiPe 2016 Midpoint method, following the ISO 14040/44 standards.

1. **Functional Unit**: 1 kg of hydrogen
2. **System Boundary**: Cradle-to-gate (natural gas extraction → hydrogen production → CO_2 capture)
3. **Databases**: Ecoinvent, EcoChain, IEA reports

Table 2.2.1: Life Cycle Inventory (LCI) Summary.

Input/Output	Value (per kg H_2)	Source
CH_4 Feedstock	1.25 Nm^3	Simulation
Electricity	4.5 kWh	SMR+CCS system
Water Use	19.5L	LCA tool
CO_2 Emissions	1.35 kg CO_2-eq	Calculated

Source: Ecoinvent, EcoChain, IEA reports

Impact Categories Analyzed:

1. Global Warming Potential (GWP)

2. Fossil Fuel Depletion
3. Water Use
4. Human Toxicity
5. Acidification

Table 2.2.2: LCIA Results (ReCiPe Midpoint)

Impact Category	Unit	Blue Hydrogen	Grey Hydrogen	Green Hydrogen
GWP	kg CO_2-eq/kg H_2	1.35	10 -12	0.1 – 0.5
Fossil Fuel Depletion	MJ/kg H_2	8.2	12 – 15	0.5 – 2.0
Water Consumption	L/kg H_2	19.5	25 – 30	10 - 15

Source: OpenLCA

2.3 Economic Evaluation

The economic analysis uses the Levelized Cost of Hydrogen (LCOH) to evaluate production viability, integrating CAPEX, OPEX, feedstock, and CCS-related costs.

Table 2.3.1: Blue Hydrogen Production Cost Breakdown

Cost Component	Cost ($/kg H_2)	% of Total
Natural Gas	0.7 – 1.00	40 – 50%
CCS Implementation	0.30 – 0.50	20 – 25%
Energy Consumption	0.25 – 0.40	15 – 20%
Operations & Maintenance	0.20–0.30	10–15%
Total LCOH	**1.50–2.50**	**100%**

Source: IEA reports

Table 2.3.2: LCOH Comparison Across Hydrogen Types

Hydrogen Type	LCOH ($/kg H_2)	GWP (kg CO_2-eq/kg H_2)
Grey Hydrogen	1.00–1.50	10–12
Blue Hydrogen	1.50–2.50	1.35
Green Hydrogen	3.00–7.00	0.1–0.5

2.4 Qualitative Analysis

To complement the quantitative assessments of blue hydrogen production, this study incorporated a qualitative component aimed at capturing the broader socio-political and institutional factors influencing hydrogen adoption in Nigeria. This component involved semi-structured interviews with stakeholders and a policy document review.

2.4.1 Stakeholder Engagement

A total of 12 semi-structured interviews were conducted with experts and stakeholders across government, industry, academia, and civil society. The participants were selected based on their roles in energy policy development, environmental regulation, infrastructure planning, or hydrogen technology research. Interviewees included representatives from the Ministry of Environment, Ministry of Petroleum Resources, Nigerian National Petroleum Company (NNPC), energy consulting firms, and university researchers.

The interviews were guided by four thematic areas

1. Regulatory readiness and gaps
2. Technical and infrastructural challenges
3. Economic feasibility and investment potential
4. Public and institutional perception of hydrogen

Table 2.4.1: Stakeholder Interview Categories and Key Roles.

Stakeholder Group	No. of Participants	Key Roles
Government agencies	4	Policy development, environmental regulation
Oil & gas industry	3	Infrastructure planning, CCS operations
Academia and research	3	LCA modeling, hydrogen innovation
NGOs and civil society	2	Environmental advocacy, public engagement
Total	**12**	

Source: Field Study, 2025

2.4.2 Thematic Analysis and Key Insights

A thematic coding approach was applied to interview transcripts using NVivo. The results were classified under four dominant themes:

1. **Policy Gaps and Institutional Uncertainty**: Stakeholders consistently emphasized the absence of a hydrogen-specific regulatory framework. While Nigeria has articulated

decarbonization goals under its Nationally Determined Contributions (NDCs), no dedicated hydrogen strategy or CCS regulation exists to support project deployment.

2. **Infrastructure and Technical Capacity Limitations**: Respondents highlighted infrastructural gaps, including inadequate CCS storage capacity, unreliable electricity supply, and aging gas transport networks. Concerns were also raised about Nigeria's limited technical workforce for managing high-purity hydrogen and CCS systems.
3. **Financial Barriers**: Capital expenditure for blue hydrogen projects was cited as a major constraint. Stakeholders noted that without carbon pricing, tax incentives, or international climate finance, private sector participation remains low.
4. **Perception and Awareness**: There was a widespread view that hydrogen is poorly understood outside expert circles. Most civil society actors and even policymakers perceive it as a "foreign" or "future-only" technology, not an immediate solution.

Table 2.4.2: Thematic Summary of Stakeholder Perceptions.

Theme	Observations from Stakeholders
Policy and Regulation	No hydrogen law; weak CCS governance; unclear carbon market Framework.
Technical/Infrastructure	Inadequate CCS facilities, aging pipelines, poor data for LCA Modeling
Economic and Financial	High initial costs; need for carbon credits and clean energy investment mechanisms
Social Perception and Trust	Low public awareness; skepticism over the governments commitment to implementation.

Source: Field Study, 2025

2.4.3 Policy Document Review

In parallel, this study reviewed key policy documents, including:

1. Nigeria's National Energy Master Plan (2014)
2. Petroleum Industry Act (2021)
3. Nigeria's NDCs (2021)
4. Energy Transition Plan (2022)

The review revealed that while Nigeria aims to reach net-zero by 2060, there is no formal hydrogen roadmap or funding instrument to support hydrogen-specific pilot projects or infrastructure. Comparisons with the EU Hydrogen Strategy and the U.S. Inflation Reduction Act showed that Nigeria lags in offering production subsidies, tax credits, or CCS risk guarantees.

3.0 RESULTS AND DISCUSSION

This section presents the environmental and economic performance of blue hydrogen production in Nigeria based on Life Cycle Assessment (LCA), economic modeling, and qualitative stakeholder insights. Results are benchmarked against grey and green hydrogen to assess relative sustainability and feasibility.

3.1 Life Cycle Assessment (LCA) Results

3.1.1 Environmental Impact Metrics

The LCA was conducted using the ReCiPe 2016 Midpoint method within OpenLCA software, using simulation data from Aspen HYSYS and inventory inputs from the Ecoinvent database. The results confirm that blue hydrogen reduces environmental impact substantially compared to grey hydrogen.

Table 3.1: Life Cycle Impact Assessment (LCIA) Results for 1 kg of Hydrogen.

Impact Category	Unit	Blue Hydrogen	Grey Hydrogen	Green Hydrogen
Global Warming Potential	kg CO_2-eq	1.35	10 – 12	0.1 – 0.5
Fossil Resource Depletion	MJ/kg H_2	8.2	12 – 15	0.5 – 2.0
Water Consumption	L/kg H_2	19.5	25 – 30	10 – 15
Acidification Potential	kg SO_2-eq	0.12	0.30	0.05
Human Toxicity	kg 1,4-DCB-eq	0.15	0.60	0.02

Source: OpenLCA, Ecoinvent, Ecochain

3.1.2 Interpretation

Blue hydrogen shows an 85% reduction in GWP compared to grey hydrogen, mainly due to 85% carbon capture efficiency during the SMR process. However, emissions remain higher than green hydrogen, indicating blue hydrogen's transitional role. Water consumption and fossil depletion are moderate, emphasizing the need for renewable integration and water reuse strategies.

3.2 Sensitivity Analysis

Two sensitivity analyses were conducted:

1. Carbon Pricing Impact on Cost Competitiveness
2. CCS Efficiency Impact on GWP

Table 3.2.1: Impact of Carbon Pricing on Hydrogen Competitiveness.

Carbon Price (\$/ton CO_2)	Grey H_2 Cost (\$/kg)	Blue H_2 Cost (\$/kg)	Green H_2 Cost (\$/kg)
\$0 (No Carbon Tax)	1.00 – 1.50	1.50 – 2.50	3.00 – 7.00
\$30	1.50 – 2.00	1.40 – 2.10	2.80 – 6.50
\$50	2.00 – 2.50	1.30 – 1.90	2.00 – 6.00

Source: IEA, Carbon Pricing Leadership Coalition

This analysis shows that carbon pricing can make blue hydrogen more cost-competitive than grey hydrogen, particularly at \$50/ton CO_2.

Table 3.2.2: Sensitivity of CCS Efficiency on Global Warming Potential.

CCS Efficiency (%)	GWP (kg CO_2-eq/kg H_2)
70%	4.5 – 6.0
85% (Baseline)	1.35 – 3.0
95%	<1.0

Source: OpenLCA, Ecoinvent

Greater CCS efficiency significantly improves the environmental viability of blue hydrogen, highlighting the need for investment in capture technology.

3.3 Economic Viability

3.3.1 Production Cost Breakdown

The Levelized Cost of Hydrogen (LCOH) was calculated using CAPEX, OPEX, and fuel data.

Table 3.3.1: Cost Structure of Blue Hydrogen Production.

Cost Component	Estimated Cost ($/kg H_2)	Share of Total Cost (%)
Natural Gas Feedstock	0.75 – 1.00	40 – 50%
CCS Implementation	0.30 – 0.50	20 – 25%
Energy Consumption	0.25 – 0.40	15 – 20%
Operations & Maintenance	0.20 – 0.30	10 – 15%
Total LCOH	**1.50 – 2.50**	**100%**

Source: IEA (2023), Hydrogen Council (2023)

3.3.2 Comparison with Other Hydrogen Types

Table 3.3.2: LCOH and GWP Comparison.

Hydrogen Type	LCOH ($/kg H_2)	GWP (kg CO_2-eq/kg H_2)
Grey Hydrogen	1.00 – 1.50	10 – 12
Blue Hydrogen	1.50 – 2.50	1.35
Green Hydrogen	3.00 – 7.00	0.1 – 0.5

The findings confirm that blue hydrogen is more affordable than green hydrogen but costlier than grey hydrogen, unless carbon pricing is applied. Economically, blue hydrogen is viable only with policy support, such as tax incentives, subsidies, or clean energy investment funds.

3.4 Discussion

The results demonstrate that blue hydrogen is a promising transitional energy source for Nigeria. Its GWP is drastically reduced relative to grey hydrogen, and it leverages Nigeria's abundant natural gas resources. However, challenges remain:

1. **Methane Leakage Risk**: Natural gas extraction can result in methane emissions that offset environmental gains. Leak detection and prevention are vital.
2. **Water Use**: Although better than grey hydrogen, water demand for blue hydrogen production remains significant, requiring recycling strategies.
3. **Infrastructure Gaps**: Lack of hydrogen pipelines, CCS storage infrastructure, and skilled labor continue to hinder scalability.
4. **Policy Dependency**: Without strong regulatory frameworks, blue hydrogen remains vulnerable to market volatility and investment risk.

4. CONCLUSION AND RECOMMENDATIONS

4.1 Conclusion

This study evaluated the feasibility of blue hydrogen production in Nigeria using Steam Methane Reforming (SMR) combined with Carbon Capture and Storage (CCS). Through detailed process modeling, Life Cycle Assessment (LCA), and economic analysis, the study confirmed that blue hydrogen is a **technically viable and environmentally superior** alternative to grey hydrogen, with the potential to reduce carbon emissions by up to **85%** when CCS efficiency reaches 85% or higher.

1. The Global Warming Potential (GWP) of blue hydrogen was found to be 1.35 kg CO_2-eq/kg H_2, a significant improvement over grey hydrogen (10–12 kg CO_2-eq/kg H_2).
2. Economically, the Levelized Cost of Hydrogen (LCOH) for blue hydrogen ranges from $1.50–$2.50/kg, which is lower than green hydrogen but slightly above grey hydrogen.
3. Sensitivity analysis showed that with a carbon price of $50/ton CO_2, blue hydrogen becomes cost-competitive with grey hydrogen.
4. Nigeria's vast natural gas reserves (206 TCF) position it strategically for developing a regional hydrogen hub.

While blue hydrogen offers clear environmental benefits, its widespread adoption depends on addressing infrastructure gaps, methane leakage risks, and the absence of a comprehensive hydrogen policy.

4.2 Recommendations

Based on the findings, the following strategic recommendations are made:

1. Implement Carbon Pricing and Financial Incentives

1. Introduce a carbon tax ($30–$50 per ton CO_2) and establish a carbon credit trading system to internalize the cost of emissions and reward CCS adoption.
2. Provide production tax credits (e.g., up to $3/kg H_2) for low-carbon hydrogen, modeled after the U.S. Inflation Reduction Act.
3. Offer import duty exemptions on hydrogen equipment to reduce initial capital investment.

2. Develop a National Hydrogen Strategy and Legal Framework

1. Establish a National Hydrogen Strategy that defines production targets, safety regulations, CCS protocols, and market structures.
2. Align with global hydrogen policies such as the EU Hydrogen Roadmap and Japan's Basic Hydrogen Strategy to attract international partnerships.

3. Build Hydrogen Infrastructure and CCS Hubs

1. Invest in retrofitting gas pipelines to transport hydrogen blends and develop dedicated hydrogen refueling stations.
2. Establish CCS hubs in industrial zones like the Niger Delta, leveraging depleted oil reservoirs for CO_2 sequestration.
3. Support hydrogen storage and integration into Nigeria's electricity grid for renewable energy balancing.

4. Facilitate Public-Private Partnerships (PPPs) and Foreign Investment

1. Create a Hydrogen Investment Fund (e.g., $500 million) to finance pilot projects and scale-up infrastructure.
2. Encourage bilateral trade agreements with hydrogen-importing nations (e.g., Germany, Japan).
3. Partner with institutions like the World Bank and Green Climate Fund to access concessional loans and technical expertise.

5. Advance Research and Capacity Building

1. Establish hydrogen R&D centers in Nigerian universities to support local innovation.
2. Offer training programs for engineers and operators in hydrogen safety, CCS technology, and LCA methods.
3. Promote collaboration with international research institutions for knowledge transfer and technology localization.

With strategic action, Nigeria can unlock the economic and environmental benefits of blue hydrogen, positioning itself as a regional leader in low-carbon energy and aligning with global decarbonization goals.

REFERENCES

1. Andrew, R. M. (2019). Global CO_2 emissions from cement production. *Earth System Science Data*, *11*(4), 1675–1710.
2. Bryson, J. M. (2011). *Strategic planning for public and nonprofit organizations*. John Wiley & Sons.Cherubini, F., Strømman, A. H., & Hertwich, E. (2011). Life cycle assessment of bioenergy systems: State of the art and future challenges. *Bioresource Technology, 102*(2), 437–451.

3. Chiarello, M., et al. (2020). Algal biofuels and carbon capture: A sustainable strategy. *Bioresource Technology, 298*, 122445.
4. De Kleijne, K., et al. (2020). Economic viability of blue hydrogen and its role in the energy
5. transition. *Energy Policy, 140*, 111426.
6. Elkington, J. (1997). *Cannibals with forks: The triple bottom line of 21st century business*.
7. Capstone Publishing.
8. Fasihi, M., Bogdanov, D., & Breyer, C. (2021). Techno-economic assessment of CO_2 direct air capture plants. *Journal of Cleaner Production, 276*, 123007.
9. Finnveden, G., et al. (2009). Recent developments in life cycle assessment. *Journal of*
10. *Environmental Management, 91*(1), 1–21.
11. Friedmann, S. J., Ochu, E., & Brown, S. (2020). The role of carbon capture and storage in
12. achieving net-zero emissions. *Energy & Environmental Science, 13*(6), 1695–1707.
13. Giorgis, D., et al. (2021). Accelerated carbonation as a CO_2 mitigation tool: Challenges and
14. opportunities. *Journal of Cleaner Production, 283*, 124564.
15. Global CCS Institute. (2022). *The global status of CCS: 2022 report*.
16. Guinée, J. B., et al. (2011). Life cycle assessment: Past, present, and future. *Environmental Science & Technology, 45*(1), 90–96.
17. Hauschild, M. Z., Rosenbaum, R. K., & Olsen, S. I. (2018). *Life cycle assessment: Theory and practice*. Springer.
18. Heath, G. A., et al. (2014). Harmonization of methane emissions estimates from natural gas
19. production. *Environmental Science & Technology, 48*(14), 8419–8427.
20. Hertwich, E. G., et al. (2014). Integrated life-cycle assessment of electricity-supply scenarios
21. confirm global environmental benefit of low-carbon technologies. *Proceedings of the National Academy of Sciences, 112*(20), 6277–6282.
22. Howarth, R. W., & Jacobson, M. Z. (2021). How green is blue hydrogen? *Energy Science &*
23. *Engineering, 9*(10), 1676–1687.
24. International Energy Agency (IEA). (2021). *Net zero by 2050: A roadmap for the global energy sector*. Paris: IEA Publications.

25. International Energy Agency (IEA). (2021). *The future of hydrogen: Seizing today's opportunities*.
26. Paris: IEA Publications. International Energy Agency (IEA). (2021). *The role of carbon capture in clean energy transitions*.
27. Paris: IEA Publications. International Energy Agency (IEA). (2023). *Global hydrogen review 2023*. Paris: IEA Publications.
28. International Renewable Energy Agency (IRENA). (2023). *The role of hydrogen in the energy transition*. Abu Dhabi: IRENA Publications.
29. ISO. (2006). *ISO 14040: Environmental management—Life cycle assessment—Principles and framework*. Geneva: International Organization for Standardization.
30. Mac Dowell, N., Fennell, P. S., Shah, N., & Maitland, G. C. (2017). The role of CO_2 capture and utilization in mitigating climate change. *Nature Climate Change, 7*(4), 243–249.
31. Meadows, D. H. (2008). *Thinking in systems: A primer*. Chelsea Green Publishing.
32. Monkman, S., et al. (2016). Utilizing CO_2 for concrete production. *Cement and Concrete Composites, 67*, 48–52.
33. Nigeria National Petroleum Corporation (NNPC). (2023). *Developing Nigeria's hydrogen economy: Policy and infrastructure considerations*.
34. Nigeria's Nationally Determined Contribution (NDC). (2021). *Nigeria's updated nationally determined contributions to the Paris Agreement*. Federal Ministry of Environment, Nigeria.
35. OECD. (2020). *The future of hydrogen: Seizing today's opportunities*. Organization for Economic Co-operation and Development.
36. Osama Massarweh, Al-Khuzaei, M., Al-Shafi, M., Bicer, Y., & Abushaikha, A. S. (2023). Blue hydrogen production from natural gas reservoirs: A review of application and feasibility. *Journal of CO_2 Utilization, 70*, 102–438.
37. Pehl, M., et al. (2017). Understanding future emissions from low-carbon power systems by integration of life cycle assessment and integrated energy modelling. *Nature Energy, 2*, 939–945.
38. Singh, A., et al. (2021). CO_2 bio-conversion to bioethanol and organic acids. *Biotechnology*
39. *Advances, 48*, 107695.
40. Tanko Fwadwabea, et al. (2024). *Low-carbon design and technologies: Pathway to net zero emissions in Nigeria*. University of Abuja.

41. United Nations. (2022). *Pathways to sustainable carbon management*. United Nations Environment Programme (UNEP).
42. United Nations Framework Convention on Climate Change (UNFCCC). (2022). *Climate change 2022: Mitigation of climate change*. IPCC Working Group III Contribution to the Sixth Assessment Report.
43. Voldsund, M., Jordal, K., & Anantharaman, R. (2016). Hydrogen production with CO_2 capture. *International Journal of Hydrogen Energy, 41*(9), 4969–4992.
44. Zhou, Z., et al. (2020). Assessing CO_2-EOR projects for carbon sequestration potential. *Energy Procedia, 232*, 76–82.