Generative AI-Driven Modeling of Household Fuel Transitions and Climate Adaptation in Abakaliki, Nigeria

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ABSTRACT

Household biomass fuel dependence remains a critical intersection of energy poverty, public health, and climate vulnerability in sub-Saharan Africa. This study develops and applies a generative AI-driven modelling framework to simulate household fuel transition dynamics and generate climate adaptation pathways for Abakaliki, Nigeria. Integrating GANs, VAEs, and LLM-assisted analysis with empirical data from 847 household surveys, we construct a multi-scale agent-based model of household fuel decisions. Results demonstrate that income, LPG accessibility, women's decision-making authority, and social network influence are principal transition determinants. Under an integrated policy scenario combining LPG infrastructure expansion, targeted subsidies, community education, and improved cook stove distribution, household LPG penetration could reach 67.4% by 2035, achieving 1.87 million tonnes cumulative CO_2e reductions and averting 1,820 disability-adjusted life years from indoor air pollution. Climate adaptation pathway analysis reveals that 34.7% of households face maladaptation risk under high-warming scenarios (RCP8.5) without complementary policy action. The generative AI framework demonstrates significant methodological utility for household energy research in data-scarce contexts. Policy recommendations address supply-chain infrastructure, gendered empowerment, spatially differentiated targeting, and climate-integrated planning at state and national levels.

KEYWORDS

Household energy transition, Climate adaptation; Generative AI, Abakaliki, Nigeria, LPG, Clean cooking, Agent-based modelling

I. INTRODUCTION

Approximately 900 million people in sub-Saharan Africa rely on solid biomass fuels for household cooking, contributing to an estimated 600,000 annual premature deaths from indoor air pollution and substantial greenhouse gas emissions (IEA, 2023). Nigeria, with over 220 million inhabitants, exemplifies this crisis: 74% of households depend primarily on firewood or charcoal, generating 95,000 annual air pollution deaths disproportionately affecting women and children. In Abakaliki, Ebonyi State's capital, rapid urbanization, high poverty rates (74.4% headcount), and climate vulnerability create urgent but complex energy transition challenges.

Traditional energy ladder frameworks, which posit linear progression from biomass to modern fuels with income growth, fail to explain observed "fuel stacking" behaviour—simultaneous use of multiple fuels—prevalent in African cities. Climate change compounds the challenge: projected rainfall variability and temperature increases directly affect biomass availability, fuel costs, and household energy security. Four critical knowledge gaps impede effective policy design: (1) thin empirical evidence base on fuel transition determinants in Abakaliki; (2) data scarcity constraining conventional econometric modelling; (3) absence of climate-integrated transition analysis for Nigerian secondary cities; and (4) spatially uniform rather than differentiated policy designs. Generative AI offers methodological opportunities to address these gaps through synthetic data augmentation, scenario generation, and empirically-grounded behavioural modelling.

This study develops a generative AI framework integrating GANs (synthetic data generation), VAEs (scenario synthesis), LLM-assisted analysis, and agent-based modelling to analyse household fuel transitions and climate adaptation in Abakaliki. We address three primary research questions: (1) what socioeconomic, behavioural, and climate factors determine household fuel transitions? (2) What policy combinations most effectively accelerate clean fuel adoption? (3) How does climate change interact with energy transitions to shape household adaptation pathways?

II. METHODS

A. Data Collection and Study Design

This mixed-methods study employed a sequential design integrating quantitative surveys (Phase I), generative AI modeling (Phase II), agent-based simulation (Phase III), and climate scenario analysis (Phase IV). Structured household questionnaires were administered to 847 households stratified across six spatial zones in Abakaliki by income quintile, supplemented by 12 focus group discussions and 24 key informant interviews exploring behavioral and social dimensions of fuel choice.

Questionnaires collected data on: household socio demographics; current fuel mix and stacking behaviors; energy expenditure and affordability; cook stove inventory; barriers/enablers to clean fuel adoption; and climate exposure/impacts. All data were anonym zed and collected with informed consent under ethical approval from University of Nigeria Research Ethics Committee.

B. Generative AI Modeling

A Conditional Tabular GAN (CTGAN) was trained on preprocessed household data (86 variables → 42 engineered features) to generate 10,000 synthetic household profiles preserving empirical distributional properties. Model quality was assessed using Fréchet Inception Distance (FID=12.3), Kolmogorov-Smirnov tests (non-rejection for 38/42 features), and Train-on-Synthetic-Test-on-Real (TSTR) validation (AUC-ROC=0.821 vs. 0.847 empirical). A Conditional VAE with 16-dimensional latent space enabled controlled scenario generation by targeting specific household characteristics while preserving statistical coherence. LLM-assisted analysis (validated against manual coding, κ=0.81) synthesized qualitative data on social norms, cultural practices, and community-level barriers.

C. Agent-Based Modeling and Policy Scenarios

An agent-based model representing 847 empirical + 5,000 synthetic households was implemented in NetLogo, with behavioral decision rules derived from Random Forest classifiers trained on empirical data (AUC-ROC=0.847). Household fuel choice incorporated: empirically-derived income effects (β=0.412); women's decision-making authority (β=0.287); LPG accessibility (β=0.234); and social network influence (β=0.198). Four policy scenarios spanning business-as-usual to integrated intervention were simulated 2025–2035: (S0) No new interventions; (S1) LPG subsidy + infrastructure; (S2) Community education + behavioral change; (S3) Integrated (S1+S2+improved cook stove distribution biogas pilot). Model calibration achieved ±2% fit to baseline fuel mix distributions, validated against independent LPG market data (simulated 18.3% vs. observed 19.1% penetration).

D. Climate Scenarios and Adaptation Pathway Modeling

CMIP6 climate projections downscaled to 5 km resolution for the Cross River Basin provided temperature and rainfall inputs under RCP4.5 and RCP8.5 scenarios. Climate impacts were modeled through: (1) biomass availability reductions based on rainfall deficit and temperature stress; (2) fuel supply chain disruption from flood frequency projections; (3) household cooling demand increases from temperature trends. Four climate adaptation pathway archetypes were identified: Pathway A (proactive clean transition); B (gradual transition with climate stress); C (persistent biomass vulnerability); D (maladaptation risk under high warming). Household Climate Vulnerability Index (HCVI) computed composite exposure-sensitivity-adaptive capacity scores; vulnerability was mapped across spatial zones and correlated with pathway risk distributions.

III. RESULTS

A. Household Fuel Patterns and Transition Determinants

Fuel stacking dominated the sample: 78.4% of households used ≥2 fuels; 42.1% used ≥3 simultaneously. Firewood was the primary fuel for 52.3% of households (74.8% in peri-urban zones, 28.4% in Government Reserved Area). LPG penetration stood at 22.6% overall with significant spatial variation (48.9% in GRA vs. 7.3% in Peri-Urban South). Notably, 61.3% of firewood-primary households switched to charcoal/LPG during dry seasons when biomass availability declined—a climate-fuel linkage previously undocumented in south eastern Nigeria literature.

Structural equation modelling identified income level and women's decision-making authority as the strongest LPG adoption predictors (β=0.412 and 0.287, respectively). LPG accessibility and social network influence also had significant direct effects (β=0.234 and 0.198). Perceived safety concerns negatively influenced adoption (β=−0.156), with 44.8% of respondents expressing cylinder explosion anxieties. Qualitative findings emphasized gender power dynamics: women recognized cooking health benefits from LPG but lacked financial autonomy for cylinder purchases. Supply-side constraints were substantial: the nearest LPG bulk plant (Enugu, 110 km away) created a 15–22% price premium for Abakaliki retailers compared to hub-city prices.

Table 1: Socioeconomic Characteristics by Spatial Zone (N=847). SD in parentheses

Household Characteristic	**Urban Core (n=312)**	**New Layout (n=215)**	**Peri-Urban (n=320)**	**p-value**
Mean HH Size (persons)	4.9 (1.8)	5.1 (1.9)	5.9 (2.4)	<0.01
% Female-headed	28.4%	25.1%	38.7%	<0.05
Mean Monthly Income (₦×1000)	87.4	72.1	31.8	<0.001
% Energy Poor (<₦30k/month)	22.1%	39.5%	68.4%	<0.001

B. Policy Scenario Outcomes

Under business-as-usual (S0), LPG penetration increased modestly from 22.6% to 31.4% by 2035. The LPG subsidy scenario (S1) achieved 53.7% penetration; notably, infrastructure expansion effects exceeded demand-side subsidy effects alone, with bulk plant proximity reducing peri-urban LPG price premiums from 22% to 8% above urban prices. The behavioural change scenario (S2) achieved 41.8% penetration at only 16% of S1 fiscal cost, with social network multiplier effects generating 2.3 indirect adoptions per directly-reached household. The integrated scenario (S3) produced the strongest outcomes: 67.4% LPG penetration plus 58.3% improved cook stove adoption among remaining biomass users. Core urban zones (GRA) approached saturation (89.4% LPG by 2035) even under S3, while peri-urban zones lagged significantly (48.7%), demonstrating persistent spatial inequality.

Cumulative GHG emission reductions 2025–2035 were negligible under S0 (420,000 tonnes CO_2e), substantial under S1 (1.24 Mt CO_2e) and S2 (890,000 t CO_2e), and highest under S3 (1.87 Mt CO_2e—65.2% reduction relative to frozen-technology baseline). Modelled $PM_{2.5}$ exposure reductions under S3 were 71% for women and 64% for children under five, corresponding to approximately 1,820 disability-adjusted life years averted—substantial public health co-benefits justifying clean cooking investment.

C. Climate Adaptation Pathways

CMIP6 projections indicate warming of 1.4°C by 2050 under RCP4.5 and 2.3°C under RCP8.5 relative to 1990–2020 baseline. Dry-season rainfall deficit increases 12–18% (RCP4.5) to 19–28% (RCP8.5). Climate adaptation pathway analysis identified four household clusters: under RCP4.5 with integrated policy (S3), 71.4% of households followed Pathways A/B (successful transition), with only 12.3% at Pathway D (maladaptation) risk. Under RCP8.5 with no additional policy (S0), Pathway D risk rose dramatically to 34.7%, concentrated in peri-urban zones with highest biomass dependence. Community social capital (savings group/cooperative membership) emerged as a significant adaptive capacity predictor independent of income (OR=2.47), suggesting that institution-strengthening offers complementary resilience-building alongside economic empowerment. A Spatial Adaptation Investment Priority Index identified 23 high-priority wards in Peri-Urban South, Old Town Residential, and portions of Peri-Urban North—combining maximum vulnerability with greatest climate exposure—as targets for co-investment in energy transition and adaptation infrastructure.

IV. DISCUSSION

This research advances understanding of household fuel transitions in sub-Saharan African secondary cities through three mechanisms: empirical documentation, methodological innovation, and policy-relevant scenario generation. The quantification of fuel stacking prevalence (78.4%), seasonal switching behaviour (61.3% of firewood users), and the equal importance of women's decision-making authority relative to income effects provide distinctive empirical contributions extending beyond Abakaliki-specific context.

Methodologically, this research validates generative AI for household energy research in data-scarce developing-country contexts. GAN synthetic data achieved statistical in distinguishability from empirical data while preserving downstream analytical utility (TSTR validation). The AI-ABM integration—replacing stylized behavioural assumptions with empirically-trained decision functions—represents an advance over conventional ABM approaches. VAE latent space interpretability enabled targeted scenario generation and household clustering analysis, supporting more nuanced policy design than uniform interventions.

A critical policy insight emerged: supply-chain infrastructure expansion exerted larger effects than demand-side subsidies alone. The 15–22% LPG price premium in Abakaliki—attributable to distance from bulk storage—represents a structural barrier independent of household income or preference. This challenges Nigeria's prevailing policy focus on demand-side subsidy instruments and suggests rebalancing toward supply infrastructure as a complementary, potentially more cost-effective intervention. The finding that behavioural-change programs achieved 75% of LPG penetration gains versus subsidy programs at 16% fiscal cost indicates substantial unexploited potential in social network diffusion approaches.

Climate analysis demonstrates that rapid household energy transitions are simultaneously mitigation and adaptation imperatives: under RCP8.5 high-warming scenarios, biomass-dependent households face compounding supply disruption, cost volatility, and health burden absent complementary policy action. The quantification of Pathway D maladaptation risk (34.7% of households under RCP8.5+S0) provides a compelling argument for accelerated clean energy transition as climate adaptation infrastructure.

V. CONCLUSION

This generative AI-driven modelling study provides empirically grounded, spatially differentiated scenario analysis of household fuel transitions for Abakaliki, Nigeria. An integrated policy package combining LPG infrastructure expansion, targeted cylinder subsidies, community-based behavioural change, and improved cook stove distribution can achieve 45–67% reduction in solid biomass fuel use within ten years—generating substantial GHG emission and air pollution health benefits. Critically, policy effectiveness varies significantly by spatial zone, income level, and gender; uniform interventions risk excluding the most vulnerable households. Climate adaptation pathway analysis demonstrates that energy poverty and climate vulnerability are deeply intertwined: households most dependent on biomass fuels face highest climate exposure and lowest adaptive capacity.

The generative AI framework developed here is transferable to comparable secondary cities across West and Central Africa, offering a methodological contribution to the broader challenge of evidence-based clean energy planning in data-scarce contexts. Implementation of evidence-based, spatially-targeted, gender-transformative policy recommendations will require sustained commitment from Ebonyi State government, Federal Government, and international partners—but the potential returns—in lives saved, emissions avoided, and climate resilience built—justify the investment.

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