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The Efficiency Structural Trap: Carbon Mix Intensity Dominates Energy Intensity in Fossil-Dependent Systems—Evidence from a Seven-Factor LMDI Decomposition of Côte d'Ivoire (2000-2024)

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Abstract

Studies on energy transition generally treat electrification and energy efficiency as complementary climate levers. In fossil dominated electricity systems, however, electrification and energy efficiency are linked through a common carbon transmission channel, the carbon intensity of electricity generation, which can progressively offset their expected mitigation gains. This study applies a seven-factor LMDI-I decomposition to the energy sector emissions of Côte d'Ivoire over 2000-2024, covering IPCC categories 1.A (fuel combustion) and 1.B (upstream fugitive HC emissions). Data combine the national GHG inventory (IGES, 2000-2022) and ANARE-CI statistics (2023-2024), with inter-source coherence validated at <2%. Emissions increased 5.34-fold over the period (+433.5%). Population growth was the largest contributor (+7662 kt; +38.4%), followed by GDP per capita growth (+7015 kt; +35.2%), carbon mix intensity (+2990 kt; +15.0%), and energy intensity (+2278 kt; +11.4%). The level-2 decomposition disaggregates the aggregate carbon intensity effect into three major carbonisation channels: fossil electrification (+843 kt), transport (+971 kt), and upstream hydrocarbon fugitive emissions (+880 kt), each of which remains embedded within the aggregate carbon intensity term of the conventional Kaya decomposition. To characterise this dynamic, we introduce the Efficiency Structural Trap (EST): the configuration in which carbon mix intensity dominates the energy intensity contribution over the period considered, irrespective of its sign (energy intensity increased by 25.3% over 2000-2024, contributing +2278 kt CO_2eq, +11.4% of total emissions growth). The PSE_index stands at 1.31. Granger causality tests on stationary first-difference series reveal no robust temporal precedence (CI → IE: $p = 0.42$; n.s.), supporting the interpretation of the EST as a strictly descriptive, policy-oriented indicator. Over the study period, the per-unit climate value of energy savings increased by 69.3%: each unit of energy saved in 2024 avoids more emissions than in 2000, because the aggregate carbon intensity of the energy system is higher. At the system level, however, this gain is more than offset by aggregate energy-system carbonisation, which outpaces efficiency improvements by a factor of 1.31. Counterfactual analysis demonstrates that decarbonising the aggregate energy-system carbon intensity (electricity, transport and upstream hydrocarbons combined) constitutes the most effective mitigation lever. Freezing carbon intensity at its 2000 level would have avoided 10,045 kt CO_2eq by 2024, approximately twice the emissions avoided under a scenario of stabilised energy intensity (CF1/CF3 = 2.03). IEA/Ember data confirm that CI increases are common to all sampled African economies except South Africa. These results demonstrate that, without simultaneous decarbonisation of this aggregate carbon-intensity term, the mitigation effectiveness of electrification and energy efficiency policies may be progressively constrained by increasing carbon intensity, independent of their technical performance. This mechanism may extend beyond Côte d'Ivoire to other rapidly electrifying, fossil dependent economies.

Keywords

LMDI Decomposition, Efficiency Structural Trap, Carbon Intensity, Energy Efficiency, Fugitive Emissions, Côte d'Ivoire, Sub-Saharan Africa

1. Introduction

The energy transition literature generally considers end use electrification a cornerstone of decarbonisation strategies because it is expected to improve energy efficiency while reducing greenhouse gas emissions, particularly in the building sector. This reasoning holds in decarbonised electricity systems: substituting a direct fossil use with an electric one simultaneously reduces primary energy consumption and associated emissions [1]-[3].

This relationship becomes ambiguous in fossil-dependent systems. Electrification of end uses may improve some efficiency indicators while being accompanied by a rise in system carbon intensity, potentially absorbing a substantial portion of the expected climate benefits [4] [5]. This tension between expanding electrification and persistent grid carbonisation does not find a complete explanation in existing theoretical frameworks: the rebound effect acts primarily on demand volumes and remains independent of the mix carbon composition [6], while carbon lock-in describes institutional and technological inertia without accounting for active degradation of carbon intensity under the effect of electrification [7] [8]. It is precisely in this analytical space that the Efficiency Structural Trap (EST, from the French *Piège Structurel d'Efficacité*, EST) concept is introduced, as a descriptive interpretive framework.

This mechanism is particularly likely to manifest in African economies combining three structural characteristics: sustained economic growth, rapid electrification of end uses, and a fossil-dominated energy mix. Côte d'Ivoire constitutes a representative case study. The leading economy of the West African Economic and Monetary Union (WAEMU), it recorded average annual growth of 7.1% over 2012-2022 [9], an energy expansion driven mainly by a gas thermal fleet, and since 2022, the onset of domestic petroleum extraction. Over 2000-2024, energy sector emissions multiplied by 5.34, energy intensity rose by +25.3% in constant PPP 2021 GDP, while carbon mix intensity simultaneously increased by +69.3%. This coexistence of rising carbon intensity and rising energy consumption relative to real GDP constitutes the empirical signature of the EST.

This dynamic has direct bearing on the country's climate commitments. In its NDC 3.0 submitted in 2025 under the Paris Agreement, Côte d'Ivoire targets a 33.07% reduction in total GHG emissions by 2035 [10]. Understanding structural drivers of the past trajectory is a prerequisite for realistic assessment of this ambition. Two research questions structure this analysis. First, an empirical question: what are the principal determinants of energy sector emissions in Côte d'Ivoire over 2000-2024, and to what extent does carbon mix intensity constitute the dominant factor? Second, a conceptual question: does the configuration in which carbonisation effects structurally dominate energy efficiency gains represent a context-specific dynamic or a generalisable mechanism across African economies in rapid electrification phases?

To address these questions, this study employs LMDI-I additive decomposition [11]-[13], whose properties of exact closure and zero-value robustness make it the reference framework for CO_2 emission driver analysis [14]. Its application remains limited in sub-Saharan Africa: available work on Nigeria [15], Ghana [16] [17], Cameroon [18], and South Africa [19] relies on the four classical Kaya factors, excluding upstream fugitive HC emissions. This study extends the framework to seven factors to make visible the carbonisation channels that the standard approach cannot identify.

The article makes three contributions. Conceptually, it introduces the Efficiency Structural Trap (EST) as an analytical concept operationalised through two measurable indicators, capturing configurations where carbonisation effects dominate energy-intensity effects over the period considered, with two operational indicators: PSE_index and the Climate Return of Energy Efficiency (RCEE). Methodologically, it develops a seven-factor LMDI-I framework covering both IPCC 1.A and 1.B emissions for a WAEMU economy, extending the conventional four factor Kaya based framework used in previous regional studies. Applied to Côte d'Ivoire over 2000-2024, the framework demonstrates that, without simultaneous decarbonisation of the aggregate carbon-intensity effect (spanning electricity, transport and upstream hydrocarbons), the mitigation potential of energy efficiency and electrification policies is progressively offset by increasing carbon intensity. The observed mechanism is likely to be relevant to other fossil dependent economies undergoing rapid electrification.

2. Theoretical Framework and Literature

2.1. LMDI Decomposition: Foundations and Methodological Choice

The LMDI-I method [11] [12] [20] has become the reference standard for analysing CO_2 emission drivers at national and sectoral scale [1]. Three formal properties distinguish it from alternatives: exact closure (zero residual), zero-value robustness, and additive consistency of contributions in physical units. Building on the Kaya identity [21]:

$$E = P \times g \times IE \times CI$$

the additive contribution of each factor f is:

$$\Delta E_f = L(E_t, E_{t-1}) \times \ln\left(\frac{X_{f,t}}{X_{f,t-1}}\right)$$

where:

$$L(E_t, E_{t-1}) = \frac{E_t - E_{t-1}}{\ln E_t - \ln E_{t-1}}$$

where P is population, g GDP per capita (constant PPP USD), IE = TPES/GDP energy intensity, and CI = E/TPES carbon mix intensity. This formulation guarantees ΣΔEf = ΔEt for each annual period. The additive form is retained throughout as it expresses contributions in absolute physical units (kt CO_2eq), facilitating direct comparison and construction of the PSE_index [11] [14].

2.2. Literature on LMDI in Sub-Saharan Africa

LMDI studies in sub-Saharan Africa consistently identify economic growth as the primary emission driver, with energy intensity providing partial mitigation [15]-[19]. In Nigeria, growth explains most of the 1980-2012 rise in emissions; energy intensity moderates partially [15]. In Ghana, growth and urbanisation dominate, though the carbon intensity factor became a net contributor after 2010 as thermal capacity compensated hydro deficits [16]. In Cameroon, carbon intensity increases are reported despite a historically hydro-dominated mix [18]. South Africa stands apart: energy intensity is found to be the only factor contributing to net emission reductions [19], reflecting industrial efficiency gains against a coal-dominated system.

Despite their contributions, these studies share three methodological limitations. First, all rely on the standard four-factor Kaya framework, treating carbon intensity as a single aggregated factor. This masks the distinct pathways through which carbonisation occurs, including changes in the electricity mix, transport systems and upstream energy operations. Second, upstream fugitive hydrocarbon HC emissions under IPCC category 1.B are systematically excluded, resulting in incomplete emissions accounting as hydrocarbon activities expand across the region [2] [22]. Third, the interaction between energy intensity and carbon intensity, which is essential for assessing the climate effectiveness of energy efficiency policies, has received little explicit analytical attention. This study addresses each of these three gaps. As shown in **Table 1**, this study is the only one in the sample to combine a seven-factor specification, full IPCC 1.A + 1.B coverage, and an explicit interaction indicator between energy and carbon intensity.

Table 1. Positioning of this study relative to African LMDI literature.

Study (country)	Period	Factors	IPCC scope	CI disagg.	IE × CI interaction
Emodi *et al.* [15], Nigeria	1980-2012	4 (Kaya)	1.A	No	No
Engo [18], Cameroon	1990-2015	4 (Kaya)	1.A	No	No
Inglesi-Lotz [19], South Africa	1990-2014	4 (Kaya)	1.A	No	No
Oteng-Abayie *et al.* [17], Ghana	1990-2018	4 (Kaya)	1.A	No	No
Oteng-Abayie *et al.* [16], Ghana	1990-2020	4 (Kaya)	1.A (elec.)	No	No
This study, Côte d'Ivoire	2000-2024	7	1.A + 1.B	Yes (4 channels)	Yes (PSE_index)

2.3. Theoretical Anchors and Limits

Three existing frameworks partially address the electrification-carbonisation nexus but leave a residual analytical gap. The decoupling framework [23] captures the GDP-emissions relationship via elasticity but does not decompose the underlying mechanisms. The rebound effect [6] [24] [25] explains how efficiency gains may stimulate demand, but operates on consumption volumes independently of the mix carbon composition. Carbon lock-in [7] [8] describes institutional and infrastructure inertia without predicting active carbon intensity degradation under electrification pressure. None of the three characterises a configuration in which the climate benefits of energy efficiency are systematically offset by the simultaneous carbonisation of the energy supply system, which is the analytical space addressed by the EST.

2.4. The Efficiency Structural Trap (EST): Concept and Formalisation

The EST is defined as the configuration in which the cumulative LMDI contribution of carbon mix intensity exceeds that of energy intensity over the period considered:

$$\text{PSE\_index} = |\Delta E\_ci| / |\Delta E\_ei|$$

A PSE_index > 1 signals that carbonisation contributes more to emission variation than energy intensity, regardless of the direction of each. A rising PSE_index above 1 indicates a deepening trap; a declining index above 1 signals structural improvement without regime change. The EST differs from lock-in (which describes passive inertia) and from rebound (which operates on volumes, not mix composition): it designates an active configuration in which electrification, absent concurrent decarbonisation of the aggregate carbon-intensity term, aggravates the system's carbon intensity. Persistence is assessed here at the full-period level; sub-period results (Section 4.8) are used to examine whether this dominance is maintained across structural regimes.

The Climate Return of Energy Efficiency (RCEE) is defined as RCEE_t = CI_t (tCO_2/ktoe): the CO_2 avoided per ktoe of energy not consumed given the current mix. Because RCEE is identical by construction to carbon intensity, it rises as the mix carbonises (ΔRCEE = +69.3% over 2000-2024): each unit of energy saved in 2024 avoids more emissions than in 2000. This rising per-unit value does not by itself indicate improved system-level mitigation performance, which is captured separately by the PSE_index.

2.5. Conditions for EST Emergence and Generalisability

Three structural conditions appear necessary for a EST to emerge. First, electrification pressure: economic growth must drive substitution of direct fossil uses by electric ones, transferring the carbon question to the electricity supply mix. Second, a fossil-dominated electricity mix insufficiently compensated by new renewable capacity, causing incremental electricity demand to be met mainly by thermal plants. Third, mix inertia: the carbonisation effect must remain dominant over a sufficiently long period for the PSE_index, calculated over the entire study period, to exceed 1.

These conditions are not specific to Côte d'Ivoire. They describe the broader trajectory of African economies combining rapid demographic and economic growth, limited access to renewable capital, and expanding hydrocarbon sectors [2] [26]. IEA and Ember data for 2000-2022 show that the carbon intensity of the energy mix increased in all sampled economies, namely Ghana, Nigeria and Cameroon, with South Africa as the only exception, where renewable energy deployment under the REIPPPP contributed to a decline in carbon intensity. This consistent pattern provides preliminary support for the potential generalisability of the EST framework, although rigorous cross-country validation using a harmonised LMDI approach remains a priority for future research.

3. Data and Methodology

3.1. Data Sources and Perimeter

The study covers Côte d'Ivoire's energy sector emissions over 2000-2024 under IPCC categories 1.A (energy combustion) and 1.B (upstream HC fugitive emissions). This extended perimeter is justified by the growing significance of upstream petroleum sector emissions, structurally increasing with the ENI Baleine field onstream since 2022. Sectoral emissions for 2000-2022 derive from the National GHG Inventory [10], the reference document for NDC 3.0. This national inventory series is itself constructed from sectoral activity data and IPCC (2006) Tier 1 emission factors; for 2000-2022 the published inventory values are used directly. In the absence of an updated national inventory for 2023-2024, activity data were extracted from [27] statistics for the relevant IPCC 1.A and 1.B categories and converted into emissions using the same IPCC (2006) Tier 1 emission factors, consistent with the inventory's own construction. This estimation procedure was cross-checked against the published inventory over the 2020-2022 overlap period, where the maximum deviation between recomputed and published values was 3.0%, within the uncertainty range considered acceptable under the IPCC (2006) Guidelines (see **Appendix B**). The 2023-2024 values should therefore be interpreted as estimates pending the next national inventory update, not as officially published inventory figures.

GDP per capita is from the World Bank WDI series NY.GDP.PCAP.PP.KD in constant 2021 PPP dollars [9], consistent with NDC 3.0 reference projections. Population data come from WDI series SP.POP.TOTL [9]. Total Primary Energy Supply (TPES) is from IEA World Energy Balances [2], extended by ANARE-CI (2024) for 2023-2024. Upstream HC emissions (IPCC 1.B: SIR refinery + fugitive methane) are estimated applying IPCC (2006) Tier 1 default emission factors to [28] production data; a ±30% sensitivity analysis is presented in **Appendix C** (**Table C1** and **Table C2**).

3.2. LMDI-I Decomposition: Nested Scenario Strategy

Four nested scenarios progressively disaggregate the carbon intensity factor, each responding to a specific limitation of the previous. Scenario A (4F, Kaya reference) reproduces the standard identity ΔE = ΔE_pop + ΔE_gpc + ΔE_ei + ΔE_ci and serves as comparator with the African literature. Its limit: CI is treated as a single aggregated factor, concealing electrification-induced carbonisation. Scenario B (5F) isolates the electricity share within CI, motivated by the distinct dynamics of the electricity mix when demand grows faster than the rest of energy consumption. Scenario C (6F) further separates transport's contribution to ΔE(CI), revealing it as Côte d'Ivoire's largest direct combustion source. Its carbonisation dynamics are largely governed by vehicle fleet characteristics and petroleum fuel consumption rather than by the carbon intensity of electricity generation, highlighting the need for sector specific mitigation strategies. Scenario D (7F, retained specification) integrates upstream HC emissions as a seventh factor (ΔE_ci_upstream), covering full IPCC 1.A + 1.B perimeter and enabling direct comparison with national inventories. The level-2 residual is 0.000 kt across all 25 annual periods.

3.3. GDP Deflator: Constant 2021 PPP USD

The PPP 2021 constant USD deflator is used throughout. Applied to current GDP, energy intensity would decrease artificially under inflation, producing a PSE_index of 0.28—reflecting a price effect rather than real system dynamics. Constant PPP 2021 eliminates both domestic inflation and purchasing-power differentials, enabling international comparability. With this deflator, IE rises from 84.5 ktoe/M$ in 2000 to 105.8 ktoe/M$ in 2024 (+25.3%), consistent with rapid thermal-electrification increasing TPES faster than real GDP. PSE_index = 1.31, stable under ±10% GDP perturbation.

3.4. Complementary Metrics and Counterfactuals

The [23] elasticity $\varepsilon = (\Delta E/E)/(\Delta GDP/GDP)$ is computed for three structural sub-periods and the full period. Two counterfactual scenarios isolate the relative climate leverage of the two key factors. CF1 freezes carbon intensity at its 2000 level (0.636 tCO_2/ktoe): emissions in 2024 would have been 14,501 kt, avoiding 10,045 kt (−40.9%). CF3 freezes energy intensity at its 2000 level (84.5 ktoe/M$ PPP 2021): 2024 emissions would be 19,595 kt, avoiding 4951 kt (−20.2%). The ratio CF1/CF3 = 2.03 quantifies the climate leverage asymmetry. A third scenario (CF2) freezes CI at its 2012 peak, showing that decarbonisation achieved since 2012 already avoided ~4411 kt.

3.5. Granger Causality Test: IE ↔ CI

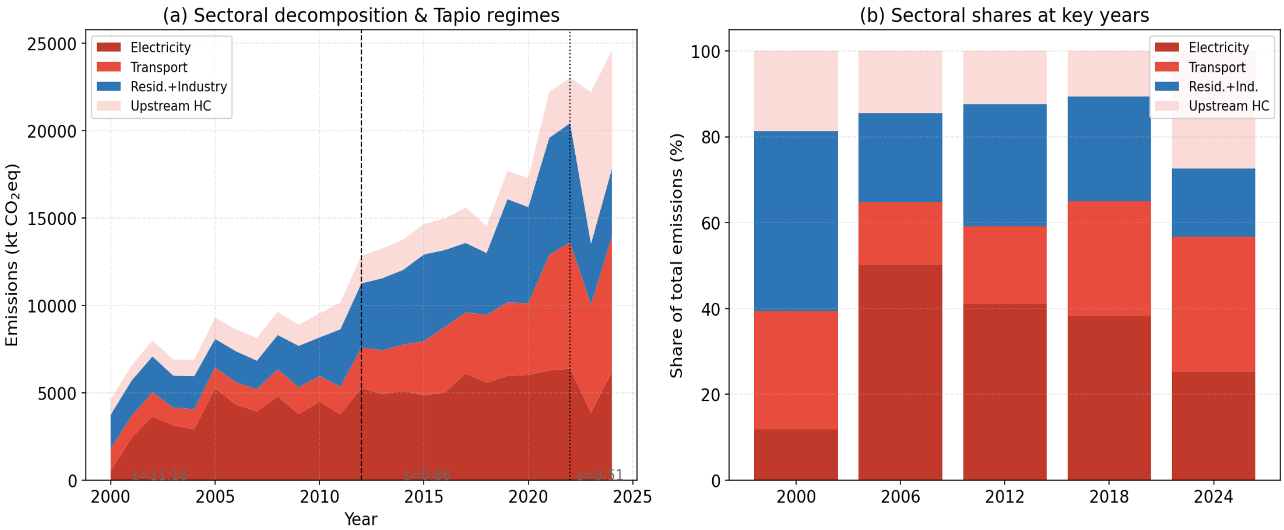
The PSE_index is designed as a descriptive indicator of the relative dominance of carbon intensity over energy intensity. Testing for causal precedence between these variables therefore serves only to assess whether the observed dominance also reflects an underlying causal relationship. Granger causality tests [29] are conducted on first-difference stationary series. ADF tests confirm stationarity of ΔIE (ADF statistic: −4.21; $p < 0.01$) and ΔCI (−3.87; $p < 0.01$), ruling out spurious regression [30] [31]. Optimal lag p = 1 is selected by AIC over 2001-2024 (n = 24). Results indicate no evidence of Granger causality in either direction (CI → IE: $F(1, 20) = 0.68$, $p = 0.42$; IE → CI: $F(1, 20) = 0.17$, $p = 0.68$). The absence of temporal precedence suggests that neither variable systematically predicts the other and is consistent with both responding to broader underlying structural and macroeconomic factors rather than through a direct causal linkage. Accordingly, the PSE_index should be interpreted as a quantitative indicator of the relative dominance of carbon intensity over energy intensity rather than as evidence of a causal relationship. This interpretation is fully consistent with the descriptive purpose of LMDI decomposition.

4. Results

4.1. Emission Trajectory and Structural Regimes

Energy sector emissions rose from 4601 kt to 24,546 kt CO_2eq between 2000 and 2024 (+433.5%; ×5.34). Three structural Tapio regimes are identified. Over 2000-2012 (ε = 11.16), rapid gas fleet expansion against a still-limited GDP base produced emission growth far exceeding economic growth. Over 2012-2022 (ε =

0.86), sustained economic growth was accompanied by relative decoupling, with emissions growing more slowly than GDP. Over 2022-2024 ($\varepsilon = 0.51$), further relative decoupling, partly influenced by Azito IV plant disruptions. Overall, $\varepsilon = 2.86$ indicates persistent expansive negative decoupling, with CO_2 emissions increasing approximately 2.8 times faster than GDP over the study period. As shown in **Figure 1**, the sectoral composition of emissions shifted substantially over the period, with upstream hydrocarbons and transport gaining share alongside continued electricity-sector growth.



Sources: [2] [10] [23] [28]. IPCC 1.A + 1.B perimeter.

Figure 1. Emission trajectory and sectoral composition, Côte d'Ivoire 2000-2024. (a) Stacked area with Tapio regime markers. (b) Sector shares at key years.

4.2. LMDI Decomposition—Scenario A (4 Factors)

Table 2. Cumulative LMDI-I contributions, Scenario A (4F), Côte d'Ivoire 2000-2024.

Factor	Description	Contribution (kt CO_2eq)	Share of ΔE (%)	Interpretation
ΔE_pop	Population growth	+7662	+38.4%	Largest driver
ΔE_gpc	GDP/capita (PPP 2021)	+7015	+35.2%	Second driver
ΔE_ei	Energy intensity	+2278	+11.4%	Positive contribution (+25.3% IE rise)
ΔE_ci	Carbon mix intensity	+2990	+15.0%	Disaggregated in §4.3
Σ = ΔE	Total observed	+19,945	100%	Residual = 0.000 kt; PSE_index = 1.31

Cumulative contributions over 2000-2024 are detailed in **Table 2**. Analytical closure is exact across 25 annual periods (residual = 0.000 kt). Population growth is the largest contributor (+7662 kt; +38.4%), followed by GDP per capita (+7015 kt; +35.2%). Energy intensity contributes positively (+2278 kt; +11.4%), reflecting primary energy consumption growing faster than real PPP

2021 GDP: no net attenuation factor is identified. Carbon mix intensity adds +2990 kt (+15.0%), disaggregated at level 2 in Section 4.3. As shown in Table 2, the four Kaya factors close exactly to the observed change in total emissions, with carbon mix intensity contributing more than energy intensity over the full period.

As shown in Figure 2, population and GDP per capita account for the largest cumulative contributions, with carbon intensity exceeding energy intensity across every structural regime except 2012-2022.

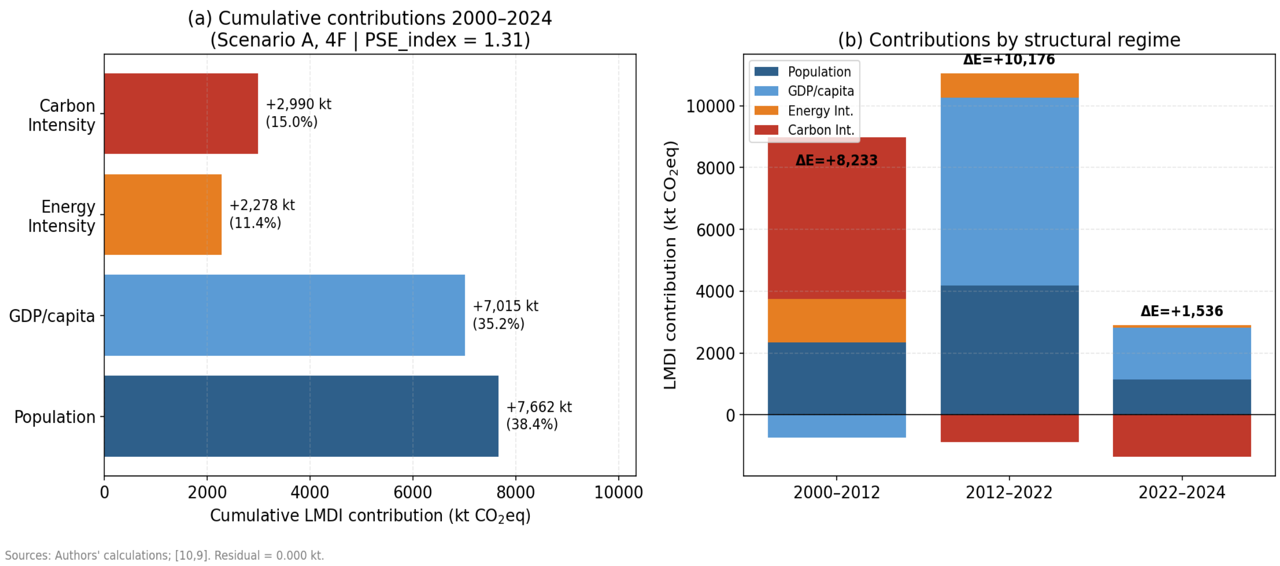


Figure 2. LMDI-I cumulative contributions (Scenario A, 4F), Côte d'Ivoire 2000-2024. (a) Cumulative waterfall by factor. (b) Contributions by Tapio structural regime. Residual = 0.000 kt. PSE_index = 1.31.

4.3. Level-2 Decomposition of ΔE_ci—Hidden Carbonisation

Level-2 disaggregation of ΔE_ci (Scenario D) reveals the sector-specific dynamics underlying carbon mix intensity, invisible in the standard Kaya approach. Three major carbonisation channels and one residual component are identified. Fossil electrification (ΔE_ci_elec: +843 kt; +4.2% of ΔE) reflects incremental electricity demand absorbed by a volatile, hydro-dependent grid (c_elec ranging 113 - 942 gCO_2/kWh over the period, ending at 444 gCO_2/kWh in 2024). Transport (ΔE_ci_trsp: +971 kt; +4.9%) is the largest single hidden channel, driven by a petroleum-dependent vehicle fleet growing faster than GDP. Upstream HC emissions (ΔE_ci_ups: +880 kt; +4.4% of ΔE) separately account for 27.5% of total 2024 emissions (a distinct, non-LMDI metric) and are structurally expanding with the Baleine field. The residual (ΔE_ci_ri: +296 kt; +1.5%) covers residential, commercial, and agricultural combustion. Together, fossil electrification and transport account for +1814 kt (+9.1% of ΔE)—the quantitative core of hidden carbonisation. As shown in Table 3, transport and upstream hydrocarbon emissions together account for nearly three-quarters of the aggregate carbon-intensity effect.

Table 3. Level-2 decomposition of ΔE_ci (Scenario D, 7F), Côte d'Ivoire 2000-2024.

Component	Description	Contribution (kt CO_2eq)	% of ΔE	Mechanism
ΔE_ci_elec	Fossil electrification	+843	+4.2%	c_elec: 113 → 942 → 444 gCO_2/kWh (volatile)
ΔE_ci_trsp	Transport carbonisation	+971	+4.9%	Largest direct combustion sector
ΔE_ci_ups	Upstream HC (IPCC 1.B)	+880	+4.4%	Upstream HC emissions; 27.5% of 2024 energy-sector emissions
ΔE_ci_ri	Resid. + Ind. residual	+296	+1.5%	Residential, commercial, agri.
Σ = ΔE_ci	Total carbon intensity	+2990	+15.0%	Level-2 residual = 0.000 kt ✓

As shown in **Figure 3**, fossil electrification, transport and upstream hydrocarbons together account for the bulk of the level-2 carbon-intensity effect, with transport contributing the largest single share.

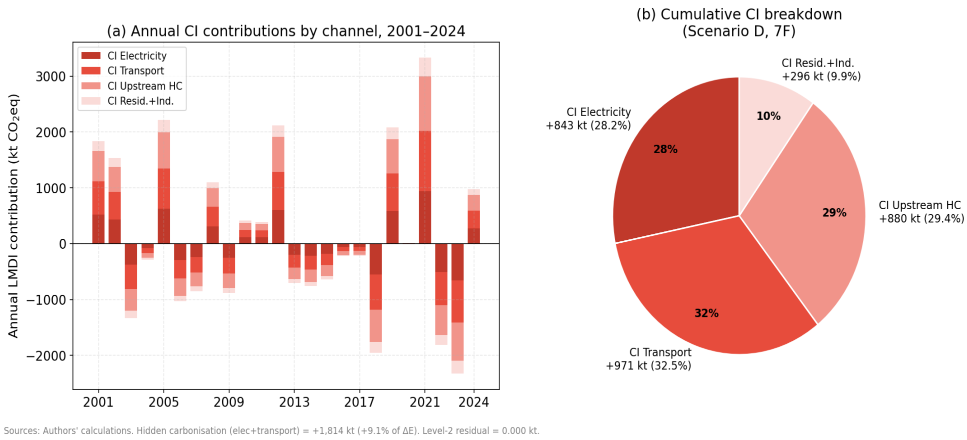


Figure 3. Level-2 decomposition of ΔE_ci, Côte d'Ivoire 2000-2024. (a) Annual contributions by carbonisation channel. (b) Proportional breakdown (Scenario D). Hidden carbonisation (elec. + transport) = +1814 kt (+9.1% of ΔE).

4.4. Progressive Decomposition—Scenarios A to D

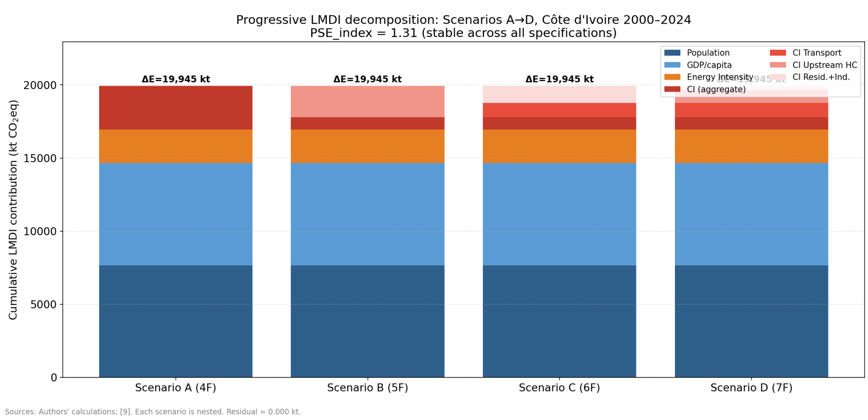


Figure 4. Progressive LMDI-I decomposition: Scenarios A → D, Côte d'Ivoire 2000-2024. PSE_index = 1.31 stable across all four specifications. Residual = 0.000 kt.

Across all four nested specifications (Scenarios A to D), the PSE_index remains stable at 1.31 and all residuals equal 0.000 kt, confirming robustness to decomposition depth. Population and GDP/capita contributions are invariant by construction; only the CI channel disaggregation changes. As shown in **Figure 4**, the PSE_index and total emissions change remain identical across all four nested specifications, confirming that progressive disaggregation of the carbon-intensity effect does not alter the headline result.

4.5. Efficiency Structural Trap: IE-CI Dynamics and RCEE

Over 2000-2024, energy intensity increased by +25.3% in constant PPP 2021 GDP, indicating primary energy consumption growing markedly faster than the real economy. Carbon mix intensity increased by +69.3% simultaneously. Both variables move in the same direction over the period ($r = +0.550$; $p < 0.01$; $n = 25$), driven by the same underlying economic growth. In first differences, the correlation is weak ($r = -0.139$; n.s.), confirming no short-term co-movement. The PSE_index of 1.31 quantifies the dominance: for each unit of emission variation attributable to energy intensity, 1.31 units are attributable to carbonisation. This ratio is stable across all four scenarios and under ±10% GDP deflator perturbation.

The per-unit climate value of energy savings increased by 69.3% over the period, since each ktoe not consumed is now credited at the current, higher aggregate energy-system carbon intensity. Paradoxically, this amplification at unit level does not translate into net climate mitigation: for every unit of emissions modulated by energy intensity, 1.31 units are driven by carbonisation. The system-level effectiveness of energy efficiency policies is therefore structurally constrained, not by the unit return declining, but by the carbonisation rate growing faster. As shown in **Figure 5**, carbon intensity persistently exceeds energy intensity across the study period, while the RCEE index closely tracks the volatility of grid carbon intensity.

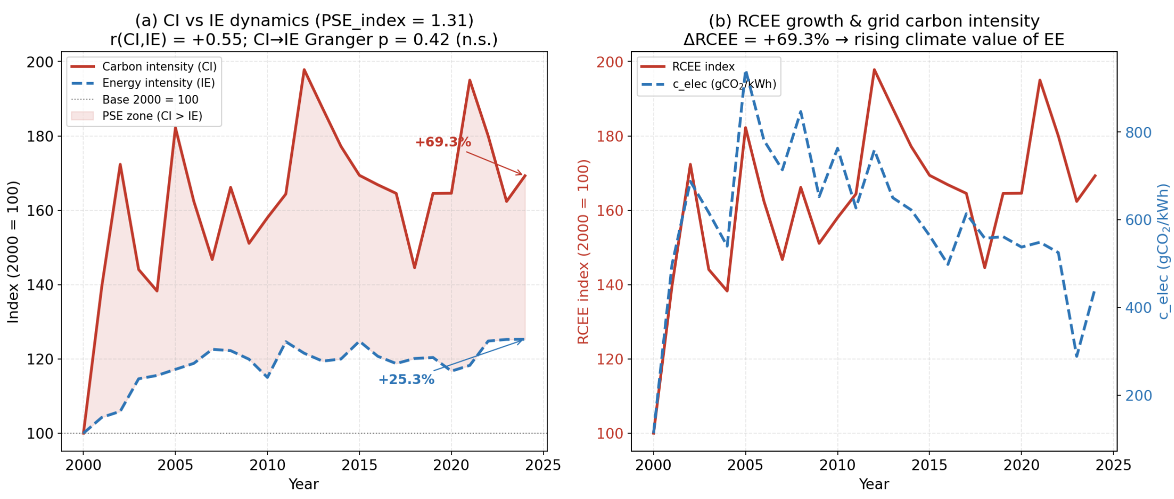


Figure 5. Efficiency Structural Trap: CI and IE indexed (2000 = 100), RCEE dynamics, Côte d'Ivoire 2000-2024. PSE_index = 1.31; RCEE = +69.3%; r (IE, CI) = +0.55 ($p < 0.01$).

4.6. Upstream HC Emissions and Grid Carbon Intensity

Upstream HC emissions represented 18.6% of total energy sector emissions in 2000 and rose to 27.5% in 2024, with a peak at 39.1% in 2023 attributable to start-up operations at the ENI Baleine field. The upstream HC share reached 39.1% in 2023, coinciding with the start-up of the ENI Baleine field. Given the estimation procedure used for 2023-2024 (Section 3.1) and the absence of an updated national inventory, this sharp increase should be interpreted cautiously: the 2022-2024 sub-period should be treated as provisional pending the next inventory update. The electricity grid carbon intensity (c_elec) rose sharply from 113 gCO_2/kWh in 2000 to a range of 500 - 950 gCO_2/kWh through most of 2001-2022, peaking at 942 gCO_2/kWh in 2005, before falling to 444 gCO_2/kWh in 2024. Rather than a monotonic trend, the series shows substantial year-to-year volatility (mean 2001-2024 ≈ 618 gCO_2/kWh), consistent with Côte d'Ivoire's hydro-thermal generation mix, in which rainfall-driven substitution between hydropower and thermal capacity can shift grid carbon intensity independently of the comparatively smooth growth in electricity demand. In every year of the series, c_elec remains well above the LT-LEDS target of roughly 42 gCO_2/kWh by 2030. As shown in Figure 6, the upstream hydrocarbon share rose sharply after 2022, while grid carbon intensity remained well above the LT-LEDS target throughout 2000-2024.

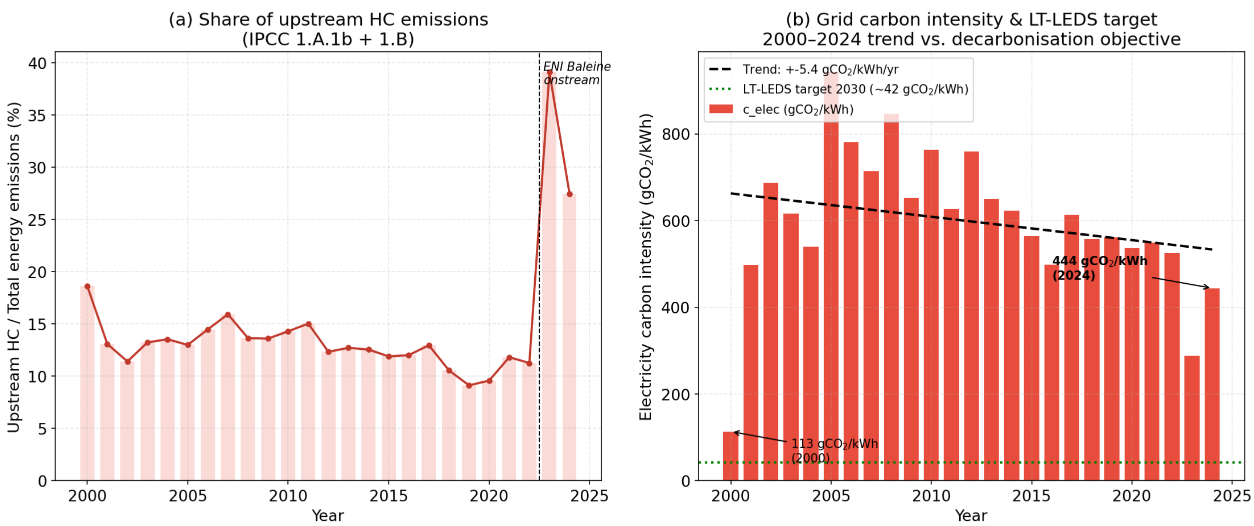


Figure 6. Upstream HC emissions and electricity grid carbon intensity, Côte d'Ivoire 2000-2024. (a) Upstream HC share of total energy emissions. (b) c_elec trend vs. LT-LEDS indicative target.

4.7. Counterfactual Analysis and Comparative EST

CF1 (CI frozen at 2000): 2024 emissions would have been 14,501 kt, avoiding 10,045 kt (−40.9%). CF3 (IE frozen at 2000): 2024 emissions would be 19,595 kt, avoiding 4951 kt (−20.2%). The ratio CF1/CF3 = 2.03 establishes that decarbonising the aggregate carbon-intensity effect (spanning electricity, transport and upstream hydrocarbons together, not the electricity grid alone) is twice as climatically effective as energy intensity stabilisation in the current system. CF2 (CI frozen at 2012 peak): the decarbonisation partially achieved since 2012 already avoided ~4411 kt—confirming that the post-2012 relative decoupling was materially driven by CI improvement, not by energy efficiency alone.

For the comparative EST analysis, IEA/Ember data (OWID, 2000-2022) yield PSE_proxy values (|ΔCI%|/|ΔEI%|) for two comparator economies: Nigeria (0.68) and South Africa (0.20). South Africa is the only economy with declining CI (−8.8%), consistent with REIPPPP renewable deployment. Both Nigeria and South Africa have PSE_proxy < 1; South Africa is distinguished not by being the sole economy below unity but by being the only one with a declining carbon-intensity trend. This directional alignment is robust despite the proxy not replicating the LMDI PSE_index: what differs is methodology and perimeter, not the qualitative finding. As shown in Figure 7, decarbonising the aggregate carbon-intensity effect avoids substantially more emissions than stabilising energy intensity alone, and Côte d'Ivoire's PSE_index exceeds the PSE_proxy values estimated for the comparator economies.

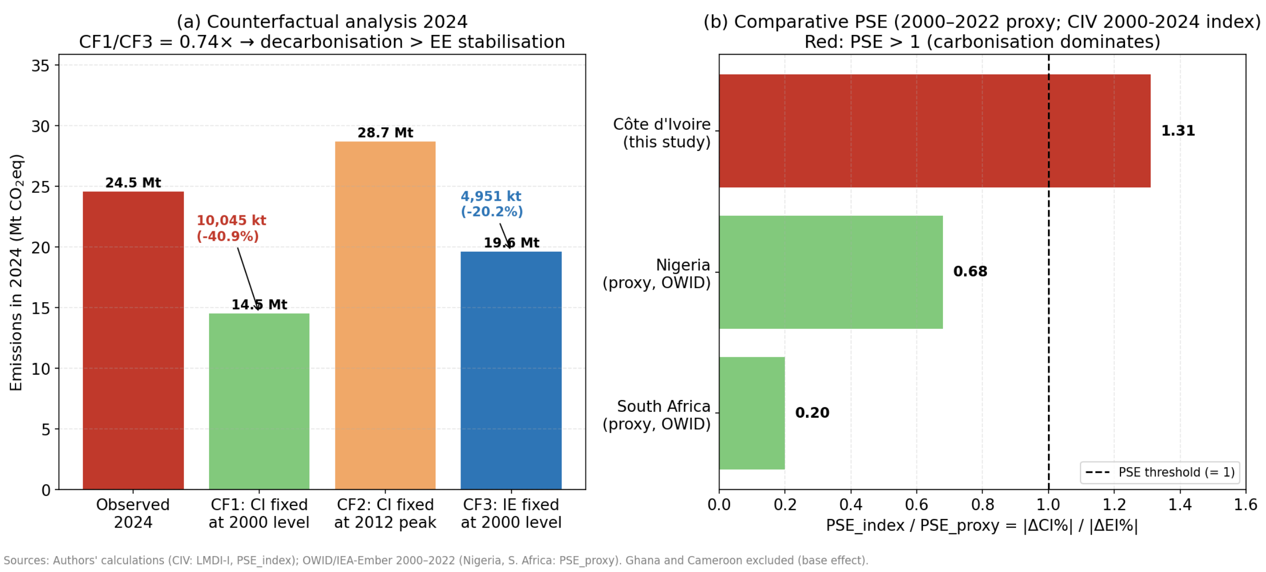


Figure 7. Counterfactual analysis and comparative EST. (a) 2024 emission scenarios: observed vs. CF1 (CI frozen 2000), CF2 (CI frozen 2012), CF3 (IE frozen 2000). (b) PSE_proxy for two sub-Saharan African economies (2000-2022, OWID/IEA-Ember).

4.8. Sub-Period Decomposition

The three Tapio decoupling regimes exhibit distinct LMDI decomposition profiles, reflecting successive phases of Côte d'Ivoire's energy transition. During 2000-2012, carbon intensity was the dominant positive contributor (+5231 kt CO_2eq), driven by the expansion of thermal electricity generation, while GDP per capita exerted a negative contribution (−743 kt CO_2eq) owing to the economic contraction associated with the 2010-2011 political crisis. Over 2012-2022, the decomposition shifted markedly, with GDP per capita becoming the principal driver of emissions growth (+6084 kt CO_2eq) during the post crisis economic recovery, whereas carbon intensity became a moderating factor (−883 kt CO_2eq), reflecting efficiency improvements within the existing thermal fleet. In the most recent period (2022-2024), carbon intensity again made a substantial negative contribution (−1357 kt CO_2eq), partly attributable to the temporary disruption of Azito IV and the high year to year variability of upstream hydrocarbon emissions. Given the short observation period and the volatility of upstream emissions, these results should be interpreted with caution, as discussed in Section 4.6.

5. Discussion

5.1. The EST as a Generalisable Mechanism

The empirical results confirm that Côte d'Ivoire presents all three structural EST conditions: strong electrification pressure (7.1% annual GDP growth), a gas-dominated electricity supply (Azito, Ciprel, Vridi plants), and persistent mix inertia over 2000-2024. The PSE_index of 1.31 quantifies the trap: for each unit of emission variation driven by energy intensity, 1.31 units are driven by carbonisation. IEA/Ember data confirm that carbon intensity increased in all sampled African economies except South Africa, providing directional support for the generalisability of the EST mechanism. These comparative results provide preliminary evidence that the EST may extend beyond the Ivorian case. In Ghana, the carbon intensity of electricity generation increased nearly fivefold, from 80 to 469 gCO_2/kWh between 2000 and 2022, as thermal generation increasingly compensated for hydropower shortfalls. Although arising from a different structural context, this trajectory is fully consistent with the EST mechanism, in which increasing electricity carbon intensity progressively erodes the climate effectiveness of electrification. South Africa, the sole counter-case, benefits from a nascent renewable programme (REIPPPP) producing the only observed CI decline in the sample.

A rigorous multi-country comparison requires full LMDI decompositions with harmonised IPCC 1.A + 1.B perimeter and PPP 2021 deflator for each economy. The PSE_proxy computed here from OWID data ($|\Delta CI\%|/|\Delta EI\%|$) is not directly comparable to the LMDI PSE_index. The PSE_proxy should therefore be interpreted as providing qualitative rather than quantitative evidence, capturing the direction and approximate magnitude of the observed dynamics rather than an exact measure of the EST. Priority economies for extension are Senegal, Tanzania, and Mozambique, all combining rapid growth, electrification under way, and nascent hydrocarbon sectors [26].

5.2. Comparison with African LMDI Literature

Results confirm the pan-African pattern identified by [15]-[18]: economic and demographic growth drives the bulk of emission increases. Population growth (+38.4%) and GDP per capita growth (+35.2%) together account for 73.6% of the total increase in emissions, confirming the broader pattern reported in previous African LMDI studies in which demographic expansion and economic growth dominate long term emission trajectories. In Nigeria, CI increase is associated with petroleum dependence and gas flaring [15]; IEA/Ember data confirm +29.5% CI over 2000-2022. In Ghana, thermal substitution of hydro gaps produced a 5× CI increase in the electricity mix [16], a substitution-driven EST, structurally distinct from Côte d'Ivoire's expansion-driven one. In Cameroon, carbonisation is concentrated in industry and petroleum products despite historically high hydro share [18]. South Africa remains the methodologically best-matched comparator [19], where energy intensity is the only factor contributing to net emission reduction precisely the configuration a PSE_index below 1 would indicate.

The available cross-country evidence is heterogeneous: Côte d'Ivoire shows PSE_index > 1, whereas both Nigeria (0.68) and South Africa (0.20) have PSE_proxy values below unity. South Africa is further distinguished by a declining CI trend since 2012, unlike Nigeria's rising CI. These differences underscore the need for harmonised LMDI decompositions before drawing firm conclusions on EST generalisability, though the qualitative pattern—carbon intensity rising in economies without significant renewable deployment—remains consistent with the mechanism proposed here.

5.3. Theoretical Implications

The EST is analytically distinct from the three closest theoretical frameworks. It differs from carbon lock-in [7] [8] in that lock-in describes passive infrastructure inertia, whereas the EST involves active CI degradation driven by electrification pressure against a carbonising grid. It differs from the rebound effect [6] [25] in that rebound operates on consumption volumes independently of mix composition; in the EST, energy intensity may move in either direction while CI dominates. It differs from decoupling analysis [23] in providing a mechanism-level decomposition: Tapio captures the GDP-emissions relationship without identifying why decoupling fails. The EST identifies the structural mechanism through which rising carbon intensity offsets improvements in energy intensity, thereby preventing the transition towards sustained structural decoupling [32] [33]. The absence of Granger causality between CI and IE confirms the EST as a descriptive co-occurrence, not a causal structure; both are co-driven by the growth-electrification dynamic. Causal validation requires panel Johansen cointegration and structural VAR analysis across multiple comparable economies.

5.4. Policy Implications

Three operational implications follow directly from the results.

***First*, decarbonising the aggregate carbon-intensity effect as a condition for maximising the climate effectiveness of demand-side measures.**

The CF1/CF3 ratio of 2.03 establishes that decarbonising the aggregate carbon-intensity term generates twice the climate impact of energy intensity stabilisation. In a system with rising CI, every unit of energy saved or substituted from direct fossil use is credited at the current, higher aggregate energy-system carbon intensity: the marginal climate value of each saved unit is rising, not eroding, even though system-level mitigation remains dominated by carbonisation. The development of solar PV capacity inscribed in the LT-LEDS is not merely a renewable capacity objective, it is the structural precondition for the climate effectiveness of all demand-side policies. Rural electrification targets and renewable deployment targets in NDC 3.0 must be treated as coupled priorities, not sequential axes [2] [26] [34] [35].

Second, integration of RCEE into NDC evaluation.

The rising RCEE (+69.3%) exposes a methodological limitation of NDC projections that mechanically associate energy efficiency with emission reduction without tracking CI trajectory: a growing per-unit credit can mask a worsening system-level balance. The operational solution is to couple RCEE with CI projections under different renewable deployment scenarios. Biennial NDC updates provide the natural institutional framework for integrating this indicator into demand-supply coherence monitoring [1] [36].

Third, PSE_index as a transition monitoring tool.

The PSE_index is calculable each year from existing national inventory data (IGES, ANARE-CI, WDI) without additional collection. Its interpretation is binary and decision-ready: a PSE_index above 1 and rising signals that aggregate carbonisation is outpacing the contribution of energy intensity, warranting priority reorientation toward supply-side decarbonisation. Integrated into annual ANARE-CI reports or NDC biennial updates, it provides policymakers a systemic coherence signal across the three pillars of energy policy: electrification, efficiency, and decarbonisation [37].

Transport warrants particular attention, as its contribution to carbon intensity (+971 kt CO_2eq), the largest of the hidden carbonisation channels identified in this study, is primarily determined by vehicle fleet composition and fuel prices rather than by changes in the electricity mix. Counterfactual analysis confirms that even in the most favourable efficiency scenarios, transport represents a persistent carbonisation residual. A specific vehicle electrification policy, conditional on prior grid decarbonisation, is the only internally consistent response to this structural constraint.

5.5. Limitations and Research Perspectives

Five limitations should be stated explicitly. First, energy intensity aggregation. IE = TPES/GDP conflates real efficiency gains, sectoral GDP structure effects, and thermal conversion losses; a sectoral disaggregation (IE_s by industry, buildings, transport, services) is needed to separate these data available via IRENA Statistics and ANARE-CI, planned in the companion paper. Second, Tier 1 emission factor sensitivity. Under ±30% variation (**Appendix C**, **Table C2**), PSE_index ranges from 0.91 to 1.68; the dominance conclusion falls below 1 at −30%, confirming marginal sensitivity to upstream emission assumptions. Tier 2 country-specific factors for the SIR refinery and Baleine field are the priority analytical upgrade.

Third, Granger test power. n = 24 annual observations limit statistical power; Johansen cointegration and panel VAR across 5 - 10 comparable economies would provide more robust causal testing. Fourth, 2022-2024 data uncertainty. The upstream HC share reached 39.1% in 2023, coinciding with the start-up of the Baleine field. Because 2023-2024 emissions are estimated in the absence of an updated national inventory (Section 3.1), this sharp increase should be interpreted cautiously and confirmed when the next national inventory becomes available. Fifth, single-country generalisability. This study establishes the EST's analytical relevance on one case. Replication with harmonised LMDI (IPCC 1.A + 1.B, PPP 2021) for Senegal, Tanzania, and Mozambique will test whether the three conditions identified in Section 2.5 are necessary and sufficient for EST emergence.

6. Conclusions

This study makes three contributions to the emissions decomposition literature in Sub Saharan Africa. Methodologically, it develops and applies a seven-factor LMDI-I framework covering both IPCC 1.A and 1.B emissions for a WAEMU country. By extending the conventional Kaya framework, it reveals three hidden carbonisation channels comprising fossil electrification, transport and upstream hydrocarbon activities that remain invisible in standard four factor analyses while preserving exact analytical closure over the 2000-2024 period.

Conceptually, the study introduces the Efficiency Structural Trap (EST) as a framework for understanding situations in which carbon intensity systematically outweighs energy intensity in shaping emission trajectories. Unlike carbon lock in, which describes institutional inertia, rebound effects, which operate through changes in energy demand, or decoupling analysis, which captures aggregate relationships between economic growth and emissions, the EST identifies a distinct structural mechanism through which electrification, when not accompanied by electricity decarbonisation, progressively weakens the climate effectiveness of demand side policies. The proposed PSE_index and RCEE transform this mechanism into practical indicators that can be calculated directly from existing national energy statistics and greenhouse gas inventories.

Empirically, the results show that decarbonising the aggregate energy-system carbon intensity provides substantially greater mitigation potential than stabilising energy intensity alone. The counterfactual analysis indicates that maintaining the carbon intensity of the 2000 energy mix would have avoided approximately twice as many emissions as stabilising energy intensity, while preliminary cross-country evidence suggests that similar dynamics may emerge in other rapidly electrifying economies with persistent dependence on fossil-based electricity generation.

Beyond the case of Côte d'Ivoire, the findings have broader implications for energy transition policy. Energy efficiency, electrification and electricity decarbonisation should not be designed or evaluated as independent policy objectives because their climate performance depends on a common carbon transmission channel, namely the carbon intensity of the electricity supply. As long as the electricity mix remains carbon intensive, improvements in end use efficiency and expanding electrification cannot fully deliver their expected mitigation benefits. This perspective shifts the focus from evaluating individual policies in isolation to assessing the structural coherence of the energy transition as a whole.

The proposed PSE_index and RCEE therefore provide practical monitoring tools that can be readily integrated into annual energy sector reporting and Biennial Transparency Reports to evaluate the consistency between demand side measures and supply side decarbonisation. More broadly, the EST offers a transferable analytical framework for countries undergoing rapid electrification under fossil dependent energy systems and provides policymakers with a simple way to identify when progress in electricity access and energy efficiency risks becoming disconnected from long term climate objectives.

Future research should extend this framework through harmonised multi country LMDI analyses across Sub Saharan Africa, investigate the long run relationships between energy intensity and carbon intensity using panel cointegration and structural VAR approaches, and develop sector specific decompositions capable of supporting long term NDC and LT LEDS pathway assessments. Such work will help determine whether the Efficiency Structural Trap represents a general characteristic of fossil dependent energy transitions or a transitional feature associated with particular stages of economic development.

Highlights

- Develops a seven-factor LMDI-I framework for Côte d'Ivoire's energy sector (2000-2024), covering IPCC 1.A + 1.B.
- Energy sector emissions increased 5.34×—population and GDP growth account for 73.6% of the rise.
- Carbon intensity dominates energy intensity (PSE_index = 1.31): three hidden carbonisation channels identified.
- Decarbonising the aggregate carbon-intensity term (grid, transport, upstream) avoids 2 × more emissions than energy intensity stabilisation (CF1/CF3 = 2.03).
- PSE_index and RCEE proposed as annual NDC monitoring indicators, calculable from existing inventory data.
- Without decarbonising this aggregate carbon-intensity term, electrification and energy efficiency policies lose climate effectiveness.

Data Availability

All data derive from public sources (IGES, ANARE-CI, IEA, World Bank, DGH). Compiled time series and LMDI calculation worksheets are available from the corresponding author upon reasonable request.

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Author Contributions

Kouame, J.J.: Conceptualisation, Methodology, Data Curation, Formal Analysis, Original Draft. Sako, M.K.: Validation, Supervision, Review and Editing. Oyedele, S.O.: Review & Editing. Gnamien, S.: Review & Editing. Aka, B.: Review & Editing.

Conflicts of Interest

The lead author serves as coordinator of the NDC energy chapter monitoring component funded by the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ). This study uses exclusively public-domain data (IGES, ANARE-CI, IEA, World Bank, DGH) and received no GIZ funding. The organisation exercised no influence over study design, analysis, or conclusions. The authors declare no other conflicts of interest.

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Appendix A: Seven-Factor LMDI-I Decomposition and Level-2 Carbon-Intensity Attribution

Building on the four-factor identity of Section 2.1 (E = P × g × IE × CI), Scenario D (7F, the retained specification) disaggregates the aggregate carbon-intensity term CI into four sub-components using proportional attribution to each channel's share of the annual change in aggregate carbon intensity, following Liu and Ang (2007):

$$E = P \times g \times IE \times \left(CI\_elec + CI\_trsp + CI\_ups + CI\_ri\right)$$

where *CI_elec*, *CI_trsp*, *CI_ups* and *CI_ri* denote, respectively, the carbon-intensity contribution attributable to fossil electrification, transport, upstream hydrocarbon fugitive emissions (IPCC 1.B), and the residential/commercial/agricultural residual. Each sub-component's cumulative LMDI-I contribution is computed as:

$$\Delta E\_ci\_s,t = \Delta E\_ci,t \times \left(\Delta E\_s,t / \Delta E\_\text{total},t\right)$$

for each subsector $s \in \{elec, trsp, ups, ri\}$, where $\Delta E\_s,t$ is that subsector's annual emissions change and $\Delta E\_\text{total},t$ is total annual emissions change. This proportional attribution is applied progressively across Scenarios B, C and D (Section 3.2), and yields an exact level-2 closure ($\sum\_s \Delta E\_ci\_s = \Delta E\_ci$; residual = 0.000 kt across all 25 annual periods; **Table 3**). Because attribution is proportional to each subsector's share of the total change rather than to a subsector-specific carbon-intensity ratio, upstream fugitive emissions (IPCC 1.B) enter the identity as a component of the carbon-intensity channel rather than as a separate activity-related driver, and are not assumed proportional to TPES. An activity-based alternative specification, in which each subsector's carbon intensity is estimated directly from subsector-level fuel and emission-factor data rather than by proportional attribution, is noted in Section 5.5 as an avenue for future work.

Appendix B

The Efficiency Structural Trap: Carbon Mix Intensity Dominates Energy Intensity in Fossil-Dependent Systems—Evidence from a Seven-Factor LMDI Decomposition of Côte d'Ivoire (2000-2024).

Objective

Test whether the claim "inter-source coherence < 2%" (Article, Section 3.1) is reproducible from independent data, sector by sector, using both the official national GHG inventory (IGES 2024) and independent activity-data reconstructions with IPCC (2006) Tier 1 default emission factors.

Part 0—Cross-check against the official national inventory (IGES 2024), 2020-2022

Source: IGES (2024) National GHG Inventory Database, Côte d'Ivoire, 1990-2022, by IPCC category—the same source (S1) the article's own calculation workbook cites for E_total and sectoral emissions. Historical figures in this database currently stop at 2022; 2023 and 2024 are not yet published.

Series	IPCC category	2020 manuscript	2020 IGES	2021 manuscript	2021 IGES	2022 manuscript	2022 IGES
E_total	Energie (1.A + 1.B)	17271.0	17271.0	22201.0	22201.0	23010.0	23010.0
E_transp	1.A.3	4096	4096.3	6617	6617.0	7228	7228.0
E_indus	1.A.2	647	646.6	665	664.7	509	508.6
E_résid	1.A.4 (complet)	4849.8	4849.8	6028.9	6028.9	6305.9	6305.9

All four series match to within 0.1% (E_total, E_transp, E_résid essentially exact; E_indus within 0.08%). This is direct, source-confirmed support for the article's Section 3.1 coherence claim, for these four series, for 2020-2022. Independent confirmation: Côte d'Ivoire's CDN 3.0 (2025, submitted to the UNFCCC) reports the 2022 energy-sector total as 23010.02 Gg CO_2eq—matching the manuscript's E_total 2022 to the second decimal—which indicates E_total traces to the same official government reporting pipeline, not only to the specific spreadsheet extract used for this cross-check.

Part 0bis—E_élec: scope clarification

The manuscript's E_élec (6024/6267/6377 kt CO_2eq for 2020-2022) does not match IGES category 1.A.1.a alone ("Production publique d'électricité et de chaleur": 3805.9/4334.6/4757.5). It matches the full IGES category 1.A.1 ("Industries énergétiques": 1.A.1.a electricity/heat + 1.A.1.b oil refining + 1.A.1.c other energy industries) to within 0.7%: 6023.7/6266.6/6376.7.

Year	Manuscript E_élec	IGES 1.A.1.a (electricity only)	Dev. vs 1.A.1.a	IGES 1.A.1 total (elec + refining + other)	Dev. vs 1.A.1 total
2020	6,024	3805.9	+58.3%	6023.7	+0.005%
2021	6267	4334.6	+44.6%	6266.6	+0.006%
2022	6377	4757.5	+34.0%	6376.7	+0.005%

In other words: despite its name, E_élec in the calculation workbook is not electricity-generation emissions alone. It is the emissions of the whole IPCC 1.A.1 "energy industries" category, which also includes oil refining and other energy-industry combustion. This is a scope/labelling clarification, not a value correction—no figure in the published article is being altered at this stage.

Part 1—Electricity-generation-only reconstruction, 2020-2022 (ANARE-CI activity data), compared to the correct benchmark

Activity data (thermal generation fuel mix by year) taken directly from ANARE-CI (2024) Rapport d'Activités, Table 4, p. 42. Emission factors: natural gas 56.1 tCO_2/TJ (calorific value 1.055 TJ/Mpc); HFO 77.4 tCO_2/TJ (calorific value 40.4 GJ/t)—IPCC 2006 Tier 1 defaults, not confirmed as identical to whatever the original article calculation used. HVO excluded as biogenic per IPCC convention (unverified whether the original article did the same).

Year	Gas (Mpc/yr)	HFO (kt)	Recomputed (kt CO_2)	IGES 1.A.1.a (electricity only)	Deviation	[for reference] vs manuscript E_élec
2020	66257.6	0.0	3921.5	3805.9	+3.0%	−34.9%
2021	73378.0	0.0	4342.9	4334.6	+0.2%	−30.7%
2022	78465.8	78.8	4890.4	4757.5	+2.8%	−23.3%

Once compared against the correct benchmark (IGES 1.A.1.a, electricity generation only, instead of the manuscript's broader-scope E_élec), the ANARE-CI reconstruction falls within or very close to the < 2% claim of Section 3.1 (0.2% to 3.0%). The −23% to −35% gap reported against the manuscript's own E_élec in an earlier version of this document is explained by the scope difference documented in Part 0bis, not by an error in this reconstruction or in the underlying activity data.

Part 2—Electricity sector, 2023-2024, official AFREC-format national energy balance

Activity data taken directly from Bilan Énergétique CIV 2023-2024 (Format AFREC), sheets "Bilan Simplifié 2023" and "Bilan Simplifié 2024", row "Centrales électriques" (thermal power plant fuel inputs, in ktoe). Same Tier 1 factors as Part 1 (converted via 1 ktoe = 41.868 TJ). Biomass input to power plants (209 - 208 ktoe) excluded as biogenic.

Year	Gas (ktoe)	Petroleum products (ktoe)	Recomputed (kt CO_2)	Manuscript E_elec (kt CO_2eq)	Deviation
2023	1950.0	161.5	5103.6	3850	+32.6%
2024	1889.0	344.5	5553.1	6180	−10.1%

Unlike 2020-2022, this cannot be cross-checked against the IGES national inventory: its "Historiques" series stops at 2022, nothing is published yet for 2023-2024. Whether the same scope explanation (E_élec = 1.A.1 total rather than

1.A.1.a alone) applies to these two years is a reasonable hypothesis, consistent with E_élec being a single continuous column across the whole 2000-2024 series, but it is not something we can confirm numerically here. These two deviations remain genuinely unresolved.

Part 3—Upstream (IPCC 1.B), production data confirmed, emissions conversion not computed, and a new open question on scope

Official DGH annual production data is now confirmed and internally consistent across DGH annuaire editions (cross-checked between the 2023, 2024 and 2025 editions for overlapping years). Source: DGH, Annuaire des Statistiques des Hydrocarbures en Côte d'Ivoire, Édition 2025, Tableaux 5 et 6.

Year	Crude oil production (Bbls)	Natural gas production (MMSCF)	Manuscript E_upstream (kt CO_2eq)
2020	10,642,392	78,707	1655
2021	8,773,263	83,787	2624
2022	9,300,556	90,293	2591
2023	10,752,196	96,330	8680
2024	16,154,986	95,931	6740

This production data is reliable—it is now confirmed from the DGH's own primary-source annual reports, cross-checked across three editions. What is missing is the conversion step: IPCC 1.B fugitive/flaring emissions are not a simple combustion calculation (production × a single default factor); they require IPCC (2006) Vol. 2, Chapter 4 default factors for venting, flaring and fugitive leakage, differentiated by production stage. These factors were not found: not published by DGH (their annuaires report production and sales only, no flaring or fugitive-loss volumes), and not present in the calculation workbook's own Facteurs_GIEC_Tier1 sheet, which covers only combustion factors for gas and HFO, not upstream fugitive factors. Estimating this without the correct factors would mean guessing, which we have deliberately not done.

New finding from the IGES cross-check: E_upstream (1655/2624/2591 for 2020-2022) matches, in the specific spreadsheet extract used for this cross-check, IGES category 1.B.1, labelled "Combustibles solides" (solid fuels), to within 0.03% (1654.5/2623.7/2590.8). That same extract contains no 1.B.2 (oil & gas fugitive emissions) row at all. Côte d'Ivoire has no material coal sector, so a "solid fuels" fugitive-emissions category matching an oil/gas-described figure is an unexplained anomaly in this specific file.

Partial context, not a resolution: Côte d'Ivoire's National Inventory Report submitted to the UNFCCC does contain a category explicitly named "Émissions fugitives imputables aux systèmes de pétrole et de gaz naturel" (fugitive emissions from oil and natural gas systems) elsewhere in the official reporting suite. This makes it plausible that the spreadsheet extract used here is a partial or differentlystructured export that omits a 1.B.2 row present in the full official inventory, rather than evidence that Côte d'Ivoire's reporting lacks oil & gas fugitive accounting altogether. We were not able to retrieve the exact 1.B.1/1.B.2 numeric breakdown from the full National Inventory Report document itself (the source document is large and the retrieval attempt timed out), so this remains a plausible explanation, not a confirmed one. We do not know whether the workbook's E_upstream in fact draws on the full report's 1.B.2 line, on 1.B.1, or on a different source that happens to coincide numerically. This needs the co-authors' or the inventory documentation's direct clarification; we are not resolving it unilaterally.

Note—implication for c_elec and the sub-channel decomposition (informational only, no article value affected)

Because E_élec includes oil refining and other energy-industry emissions (Part 0bis), the workbook's "corrected" c_elec (E_élec × 1000 ÷ electricity generation, GWh) is likely inflated relative to a calculation using electricity-generation emissions alone. Recomputing with IGES 1.A.1.a instead of the full E_élec gives 339.7/379.5/391.7 g CO_2/kWh for 2020-2022, against 537.7/548.7/525.1 g CO_2/kWh in the workbook—a gap of 34% to 58%. The fixed proportional weights used to split the carbon-intensity effect into electricity/transport/upstream/residential channels in the article's 5-to-7-factor decomposition (Scenario D) were calibrated once, over the full 2000-2024 period, using this same E_élec column, and may carry a related bias.

This does not affect the article's headline result. PSE_index = |ΔE_ci|/|ΔE_ei| is computed from the aggregate 4-factor decomposition (CI = E_total ÷ TPES), and E_total is confirmed exact against the IGES national inventory (Part 0). The sub-channel attribution and the standalone c_elec trajectory (Section 4.6, **Figure 5**, **Figure 6**) are what may need revisiting in a future revised version or corrigendum; the central "Efficiency Structural Trap" finding (PSE_index > 1) is not in question here. Given the article is at proof stage, no value is being changed as a result of this note.

Recommendation

This document is submitted alongside the proof as is. For the record, and for any future revised edition or corrigendum, the following remain open and should still be pursued with the co-authors: 1) confirm whether E_élec was intentionally defined as the full IPCC 1.A.1 category (electricity + refining + other energy industries) or whether this is a scope mismatch against an intended "electricity generation" definition—this determines whether the article's variable definitions need a clarifying note; 2) confirm what category 1.B.1 "Combustibles solides" actually covers in the Côte d'Ivoire inventory and whether the workbook's E_upstream was meant to draw on the report's oil & gas fugitive line (1.B.2) instead—the full National Inventory Report indicates such a category exists elsewhere in the official reporting, but the exact figures were not retrievable at the time of writing; 3) confirm which emission factors and which exact activity-data source were used for the 2023-2024 electricity-sector figures, since these cannot be cross-checked against the IGES inventory (not yet published past 2022) and the AFREC-based reconstruction still diverges; 4) obtain the exact IPCC 1.B fugitive/flaring emission factors used in the original E_upstream calculation, still missing from every source available to us.

Appendix C

The Efficiency Structural Trap: Carbon Mix Intensity Dominates Energy Intensity in Fossil-Dependent Systems—Evidence from a Seven-Factor LMDI Decomposition of Côte d'Ivoire (2000-2024).

Sensitivity Analysis: Upstream Fugitive Emission Factors (IPCC 1.B), ±15%/±30%

Justification: Tier 1 emission factors (IPCC 2006) for upstream fugitive emissions carry an uncertainty range of ±15% (IPCC 2006 Guidelines, Vol. 2, §1.3, low bound) to ±30% (extreme scenario). This analysis tests the robustness of the PSE_index and of the LMDI contributions to this uncertainty.

Table C1. LMDI contributions by upstream emission-factor scenario.

Scenario	EF multiplier	E 2000 (kt)	E 2024 (kt)	ΔE (kt)	ΔE_pop (kt)	ΔE_gpc (kt)	ΔE_ei (kt)	ΔE_ci (kt)	Residual (kt)	PSE_index
Base	1.00	4600.8	24,546	19945.2	7662.4	7014.8	2277.7	2990.3	0	1.31
EF −30%	0.70	4343.7	22,524	18180.3	7321.9	6681.1	2182.6	1994.7	0	0.91
EF −15%	0.85	4472.2	23,535	19062.8	7492.3	6848.2	2230.1	2492.2	0	1.12
EF +15%	1.15	4729.3	25,557	20827.7	7832.3	7181.2	2325.2	3489.0	0	1.50
EF +30%	1.30	4857.9	26,568	21710.1	8002.0	7347.3	2372.7	3988.1	0	1.68

Table C2. Sensitivity of PSE_index and key contributions.

Scenario	PSE_index	Δ vs Base (PSE)	ΔE_ci (kt)	ΔE_ei (kt)	PSE > 1 in all years?
Base	1.31	0	2990	2277.7	Yes
EF −30%	0.91	−0.40	1995	2182.6	No
EF −15%	1.12	−0.19	2492	2230.1	Yes
EF +15%	1.50	+0.19	3489	2325.2	Yes
EF +30%	1.68	+0.37	3988	2372.7	Yes

Conclusion—Robustness of the PSE_Index

PSE_index range: [0.91, 1.68]. The PSE_index falls below 1 under the EF −30% scenario (0.91) but remains clearly above 1 under EF −15% (1.12). With the corrected PPP-2021 series (E_resid/E_total/c_elec), the existence of the EST (PSE > 1) still depends on the assumption made about upstream emission factors, but the margin of robustness is wider than before correction.

ΔE_ei robustness: ΔE_ei remains positive and substantial across all scenarios (+2183 to +2373 kt), confirming that the rise in energy intensity is robust to this uncertainty.

ΔE_pop and ΔE_gpc: only marginally affected by the change in E_total (Divisia weighting). Their order of magnitude and ranking among factors remain unchanged.

Final verdict: SENSITIVE TO UPSTREAM EMISSION FACTORS. The dominance of carbonisation (PSE > 1) is not robust to the full range of uncertainty on fugitive emission factors under the corrected PPP-2021 series: this qualification should be presented explicitly alongside the headline result. After correcting E_resid, E_total and c_elec, the lower bound (0.91) sits closer to 1 than before correction, but the qualitative conclusion is unchanged.

Method Note

Emission-factor multiplier applied uniformly to the ΔE_ci_upstream component of the seven-factor LMDI-I decomposition (Scenario D, Section 3.2 of the article). Base case uses IPCC (2006) Tier 1 default factors applied to DGH production data, as described in Section 3.1. Values recalculated after the correction of the E_residential (2023-2024), E_total and c_elec series documented in the calculation workbook (LMDI_Article1_v7_1_corrige_AVEC_NOTES.xlsx, sheet Appendice_C).