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Capital Deepening, Energy Use, and Labour-Productivity Growth in African OIC Economies

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Abstract

Capital accumulation is central to Africa's development agenda, yet an important question remains: how strongly is capital deepening associated with labour-productivity growth, and is the response less than proportional? This study examines that question for 12 African member countries of the Organisation of Islamic Cooperation over 1991–2023. Real physical-capital stocks are reconstructed from gross fixed capital formation using the perpetual inventory method, while energy consumption per worker is incorporated into an augmented production framework. Because the panel exhibits cross-sectional dependence, non-stationary level variables, and heterogeneous country responses, the preferred specification is estimated in first-difference logarithms using the regularized Common Correlated Effects Mean Group estimator with cross-sectional bootstrap inference. A 1% increase in capital per worker is associated with an average 0.452% increase in real GDP per worker (bootstrap $p = 0.001$; 95% confidence interval: 0.188–0.715). A formal one-sided test rejects unit elasticity, so the preferred estimate satisfies the restriction $0 < \alpha < 1$ within the maintained production-function framework. The result remains stable under depreciation rates of 4%, 5%, and 6%, an alternative initial-capital-stock rule, exclusion of the COVID-19 years, and comparison with CCEMG and AMG estimators; estimated capital elasticities range from 0.401 to 0.632. By contrast, energy use per worker has no robust independent average short-run association with labour-productivity growth. Overall, the evidence points to a meaningful but less-than-proportional short-run association between capital deepening and labour-productivity growth, while also underscoring the importance of cautious interpretation given the observational design.

Keywords: capital deepening; labour productivity; diminishing returns; energy use; African OIC economies; regularized common correlated effects; cross-sectional dependence.

1. Introduction

Labour-productivity growth is central to sustained improvements in income, competitiveness and structural transformation. In Africa, however, productivity performance has remained modest despite periods of economic expansion and growth-enhancing labour reallocation. Earlier evidence showed that structural change became more favourable after 2000, whereas newer assessments indicate that manufacturing has played a limited role and that much of the continent's transformation has been led by services, including relatively low-productivity activities (McMillan et al., 2014; Mensah et al., 2023; Gollin et al., 2026). This pattern makes it necessary to examine the productive inputs that raise output within sectors, not only the movement of labour between them.

Capital deepening is one such mechanism. The neoclassical growth framework predicts that increasing physical capital relative to labour raises output per worker; however, diminishing marginal productivity implies a less-than-proportional response as capital intensity rises (Solow, 1956; Swan, 1956). Empirically, capital deepening has been identified as a distinct source of productivity growth and convergence, although factor accumulation alone does not explain the large international differences in output per worker (Hall & Jones, 1999; Kumar & Russell, 2002; Caselli, 2005). Likewise, recent cross-country evidence associates capital deepening with stronger GDP-per-worker growth, while showing that the productivity response is greater where technological capabilities are more advanced (Eder et al., 2023; Jalles, 2026).

The African evidence is supportive but not uniform. Capital accumulation has formed part of successful growth episodes, yet its benefits have depended on macroeconomic adjustment and structural change (Berthélemy & Söderling, 2001). More recent work finds that capital accumulation and financial development improve labour productivity in Sub-Saharan Africa (Zoaka & Güngör, 2023). However, foreign capital produces unequal outcomes according to its sectoral destination, technological content and domestic linkages (Bationo et al., 2023; Hoekman et al., 2026; Ndubuisi et al., 2026). Thus, the central issue is not only whether capital rises, but whether capital per worker expands and is deployed in activities capable of generating sustained efficiency gains.

Energy is also technologically connected to capital because machinery, transport systems and modern services require reliable energy inputs. Energy therefore merits explicit treatment within a production framework (Stern, 2011). African studies report positive effects of energy use or renewable-energy deployment on manufacturing productivity, per-capita growth and inclusive growth (Kebede & Heshmati, 2020; Konyeaso et al., 2022; Jinapor et al., 2025). Nevertheless, other evidence shows that the measured relationship depends on cross-sectional dependence, financing conditions, energy composition and whether the variable captures energy quantity, energy security or energy productivity (Boukhelkhal, 2022; Romero-Jordán et al., 2025; Damane & Ho, 2026).

A further difficulty is econometric. African economies are jointly exposed to commodity prices, global financial conditions, climate shocks, pandemics and regional policy developments. At the same time, their production technologies, sectoral structures and institutional conditions differ. Conventional panel estimators that impose cross-sectional independence and common slopes may therefore confound shared shocks with the underlying production relationship. The Common Correlated Effects framework addresses multifactor error structures, while regularization can improve the approximation of the common-factor space when cross-sectional averages are redundant (Pesaran, 2006; Juodis, 2022).

Against this background, the study asks: Is capital deepening positively associated with labour-productivity growth at a less-than-proportional rate in selected African OIC economies after accounting for energy use, cross-

sectional dependence and heterogeneous country responses? The contribution is fourfold. First, the study shifts the empirical focus from investment flows to capital deepening by reconstructing real physical-capital stocks from a consistent SESRIC/OICStat GFCF series and expressing the resulting stock in per-worker terms. Second, it embeds capital deepening in an energy-augmented intensive-form production framework. Third, it addresses latent common shocks and cross-country heterogeneity through rCCE Mean Group estimation with cross-sectional bootstrap inference, while using CCEMG and AMG as alternative heterogeneous-panel benchmarks. Fourth, rather than testing only whether the average capital elasticity is positive, the analysis explicitly evaluates whether it is also statistically below unity and examines the sensitivity of that conclusion to depreciation rates, capital-stock initialization and the COVID-19 period. The empirical contribution is therefore a direct and robustness-oriented assessment of the joint restriction $0 < \alpha < 1$ in this specific African OIC setting, not a claim of a new theoretical proposition.

2. Literature review and hypothesis development

2.1 Capital deepening and productivity

The theoretical literature distinguishes movement along a production function from shifts in productive efficiency. Solow (1956) and Swan (1956) establish that a higher capital-labour ratio increases output per worker under diminishing marginal returns. Kumar and Russell (2002) likewise separate capital deepening from technological change and technological catch-up, finding that each contributes differently to international productivity dynamics. However, Hall and Jones (1999) and Caselli (2005) show that physical and human capital explain only part of cross-country income disparities, with institutions, technology and efficiency accounting for a substantial remaining component.

Recent evidence refines this interpretation. Koopman and Wacker (2023) find that capital accumulation accounts for only a limited average share of the initial increase during growth accelerations, although investment is important for their sustainability. Likewise, Eder et al. (2023) show that both traditional physical capital and robot capital contribute to labour-productivity growth and convergence. However, technological change and conventional capital remain more influential than robotization alone. Jalles (2026) further reports that slower population growth is associated with faster capital deepening and stronger GDP-per-worker growth, particularly in technologically advanced economies. Collectively, these studies support a positive capital-productivity relationship while implying that the magnitude of the return depends on technology and productive efficiency.

2.2 African capital accumulation and complementary capabilities

African research broadly supports the contribution of capital, but it also emphasizes complementarity. Berthélemy and Söderling (2001) argue that sustained African growth episodes require capital accumulation together with macroeconomic adjustment and structural change. Likewise, Zoaka and Güngör (2023) find that financial development and capital accumulation improve labour productivity in Sub-Saharan Africa. However, finance and investment do not guarantee equal productive returns. Bationo et al. (2023) show that the productivity effect of foreign private capital depends on the recipient sector, reframing the capital-allocation puzzle as a sectoral allocation problem.

Institutional, technological and human capabilities further condition productivity. Okunade et al. (2022) find that human capital and globalization affect African productivity through threshold-dependent relationships. Similarly, Adu-Darko and You (2025) show that the institutional contribution to total factor productivity changes across structural regimes, while technological progress becomes more important in later periods. Karacuka et al. (2025) identify weak aggregate productivity effects from digitalization and heterogeneous outcomes across agriculture, manufacturing and services. Likewise, Mazorodze et al. (2025) find that R&D has stronger labour-productivity effects in skill- and technology-intensive South African

industries. These findings imply that capital deepening is most productive when workers, firms and institutions possess the capacity to absorb and operate increasingly sophisticated assets.

2.3 Structural transformation, allocation and technology choice

Aggregate productivity reflects both within-sector efficiency and labour reallocation. McMillan et al. (2014) show that structural change reduced African productivity during the 1990s but became growth enhancing after 2000. Likewise, Mensah et al. (2023) find a positive contribution from structural transformation, although many workers have moved into relatively low-productivity services. Dieppe and Matsuoka (2024) similarly demonstrate that both sector-specific productivity growth and reallocation contribute to beta convergence, with agricultural productivity playing a particularly important role. However, Gollin et al. (2026) conclude that Africa's overall productivity growth remains modest because service-led transformation has not overcome foundational physical and social infrastructure constraints.

Capital allocation and technology choice help explain these outcomes. Sié (2023) finds that the productivity effect of industrial policy depends on whether technology choices are appropriate to domestic factor endowments. Likewise, Ndubuisi et al. (2026) show that imported capital and intermediate inputs from the Global South often promote structural change because they are better aligned with African production structures, whereas capital imports from the Global North require stronger absorptive capacity. Hoekman et al. (2026) find that greenfield FDI shifts workers toward modern industries and higher-skilled occupations, yet the effects differ across investor activities. In contrast, Bationo et al. (2023) show that capital directed toward sectors with weaker productivity potential can generate disappointing aggregate outcomes.

Infrastructure and policy coordination are similarly important. Herrera Dappe and Lebrand (2024) find that roads and electricity jointly promote labour reallocation from agriculture and that fast Internet strengthens the effect. Konte et al. (2022) report that structural reforms raise productivity mainly through within-sector channels, while Ndung'u et al. (2022) emphasize the infrastructure, technology and institutional constraints limiting African manufacturing. Lorato et al. (2025) show that Ethiopia's service-led transformation is shaped by sectoral productivity disparities, capital formation and credit, but may not correspond to the desired industrial trajectory. Likewise, Pinto et al. (2025) characterize African transformation as a multidimensional process involving technology, talent, public-sector capacity and urbanization. Therefore, capital quantity, allocation and complementary infrastructure must be considered jointly.

2.4 Energy use, energy productivity and economic performance

The energy literature distinguishes between energy as an input and the efficiency with which it is converted into output. Stern (2011) provides the theoretical basis for treating energy as a genuine production input, especially where scarcity constrains capital utilization. At the sector level, Kebede and Heshmati (2020) find that energy use raises labour productivity in Ethiopian manufacturing. Likewise, Konyeaso et al. (2022) report a positive renewable-energy-growth relationship across African country groups. However, sector-specific manufacturing evidence and aggregate per-capita growth evidence do not necessarily imply a uniform economy-wide energy elasticity.

Recent studies also emphasize financing and dynamics. Jinapor et al. (2025) find that energy consumption supports inclusive growth and that FDI strengthens the effects of both renewable and non-renewable energy. Similarly, Damane and Ho (2026) show that renewable-energy shocks are followed by medium-run improvements in energy productivity and intensity, although short-run dynamics are volatile and FDI effects are conditional on institutions and income. Boukhelkhal (2022) further demonstrates that conclusions regarding energy, growth and emissions change when cross-sectional dependence and heterogeneous responses are explicitly treated.

Energy quantity is also distinct from energy efficiency. Romero-Jordán et al. (2025) find that energy productivity improves total factor productivity in both the short and long run. This result does not require aggregate energy consumption per worker to have a positive independent coefficient because higher energy use may reflect either expanded productive services or inefficient, energy-intensive technologies. The literature therefore motivates including energy in the production model while remaining open to a weak or conditional average coefficient.

2.5 Methodological gap and study contribution

The closest African evidence establishes that capital accumulation matters for labour productivity, but several empirical issues remain insufficiently resolved. In particular, there is limited evidence that evaluates the Solow-Swan diminishing-returns restriction using capital stock per worker in African OIC economies while simultaneously accounting for energy use, latent common shocks and heterogeneous country responses. This distinction matters because investment flows are not equivalent to accumulated productive capital, while constructed capital stocks can be sensitive to depreciation and initial-stock assumptions (Nehru & Dhareshwar, 1993; Berlemann & Wesselhöft, 2014; Feenstra et al., 2015; Bu, 2006). The focus on a defined African OIC sample provides a coherent empirical setting, but the results are interpreted as applying to the sampled economies rather than to Africa or the OIC as a whole.

The econometric design responds to this gap. Cross-sectional dependence is assessed using Pesaran (2015), integration properties are evaluated using the cross-sectionally augmented test of Pesaran (2007), and slope homogeneity is tested using Pesaran and Yamagata (2008) with the HAC-robust extension of Blomquist and Westerlund (2013). The preferred rCCE estimator combines the multifactor approach of Pesaran (2006) with the regularization strategy of Juodis (2022), while the AMG estimator of Eberhardt and Teal (2010) provides an alternative heterogeneous common-dynamics benchmark. This design permits a direct test of whether the average capital elasticity is both positive and significantly below unity.

3. Methodology

3.1 Data, sample, and variable construction

The empirical analysis uses annual observations for 12 African member countries of the Organisation of Islamic Cooperation: Benin, Burkina Faso, Cameroon, Chad, Côte d'Ivoire, Gabon, Mozambique, Niger, Nigeria, Senegal, Togo, and Uganda. The balanced sample covers 1991–2023 ($N = 12$, $T = 33$), yielding 396 country-year observations in levels. First differencing reduces the estimation sample to 384 observations.

Table 1. Data definitions, measurement, construction, and sources

Variable symbol	/ SESRIC indicator or construction	Measurement / unit	Role in analysis
Real GDP (Y)	GDP, Constant 2020 Prices	USD, constant 2020 prices	Output measure
Employment (L)	Employment, Total (in Thousands)	Thousands of employed persons	Labor input
Gross fixed capital formation (I)	Gross Fixed Capital Formation, Constant 2020 Prices	USD, constant 2020 prices	Investment flow used to construct capital stock
Energy consumption (E)	Energy Consumption (in Millions)	Million tonnes of oil equivalent (Mtoe)	Energy input
Capital stock (K)	Author construction from real GFCF using the perpetual inventory method	USD, constant 2020 prices; baseline depreciation rate $\delta = 5\%$	Physical capital input

Variable symbol	/	SESRIC indicator or construction	Measurement / unit	Role in analysis
ln(GDP worker)	per	$\ln(Y) - \ln(L)$	Natural-log ratio	Labor-productivity measure; dependent variable in growth form
ln(Capital worker)	per	$\ln(K) - \ln(L)$	Natural-log ratio	Capital-deepening measure
ln(Energy worker)	per	$\ln(E) - \ln(L)$	Natural-log ratio	Energy-use intensity measure
Δ variables		First difference of the corresponding natural-log variable	Approximate annual proportional change	Stationary variables used in the preferred model

Source: Raw series from SESRIC/OICStat; derived variables and capital stock are author calculations.

Table 1 operationalizes the theoretical production framework using intensive-form variables. Real GDP per worker is used as the measure of labour productivity, capital per worker captures capital deepening, and energy per worker represents the additional productive input included in the augmented specification. This variable construction is important because the study is concerned with changes in productive resources available to each worker rather than with differences in the absolute size of national economies. Since a directly observed physical-capital stock is unavailable, capital is reconstructed from real gross fixed capital formation using the perpetual inventory method. The subsequent sensitivity analysis therefore treats both the depreciation rate and the initial-capital-stock rule as measurement assumptions to be tested rather than as fixed features of the data.

The underlying series are obtained from SESRIC/OICStat. Real GDP and gross fixed capital formation (GFCF) are measured at constant 2020 US dollars; employment is measured in thousands of persons; and energy consumption is measured in millions of tonnes of oil equivalent (Mtoe). The physical capital stock is not directly observed and is constructed from real GFCF using the perpetual inventory method. The capital-stock construction follows established international applications of the perpetual inventory method (Nehru & Dhareshwar, 1993; Berlemann & Wesselhöft, 2014; Feenstra et al., 2015).

The model variables are

$$\begin{aligned}
 \ln y_{it} &= \ln \left(\frac{Y_{it}}{L_{it}} \right) \\
 \ln k_{it} &= \ln \left(\frac{K_{it}}{L_{it}} \right) \\
 \ln e_{it} &= \ln \left(\frac{E_{it}}{L_{it}} \right)
 \end{aligned}
 \tag{1}$$

Because employment is recorded in thousands, rescaling it to persons would add the same constant, $\ln(1000)$, to the relevant level logarithms. This rescaling does not affect first differences or the estimated growth elasticities.

3.2 Theoretical framework

This study is anchored in the neoclassical growth framework of Solow (1956) and Swan (1956). The central mechanism is capital deepening: an increase in the quantity of productive capital available to each worker raises output per worker, but under diminishing marginal returns the additional productivity gain from successive increases in capital intensity becomes progressively smaller. Because modern production also requires energy services, the baseline Cobb-Douglas technology is extended to include energy as an

additional productive input. The explicit treatment of energy follows the view that energy services are genuine production inputs rather than merely intermediate expenditures (Stern, 2011).

For country $i = 1, \dots, N$ and year $t = 1, \dots, T$, aggregate output is represented by the energy-augmented production function

$$Y_{it} = A_{it} K_{it}^{\alpha_i} L_{it}^{1-\alpha_i-\gamma_i} E_{it}^{\gamma_i}. \quad (2)$$

Here, Y_{it} denotes real output, A_{it} total factor productivity and other unobserved efficiency influences, K_{it} the physical capital stock, L_{it} employment, and E_{it} energy consumption. The parameters α_i and γ_i are country-specific output elasticities of capital and energy. The exponent on labour is written as $1 - \alpha_i - \gamma_i$ so that the technology is homogeneous of degree one:

$$\alpha_i + (1 - \alpha_i - \gamma_i) + \gamma_i = 1. \quad (3)$$

Constant returns to scale allow the aggregate technology to be expressed exactly in per-worker terms. Dividing the production function by employment gives

$$\frac{Y_{it}}{L_{it}} = A_{it} \left(\frac{K_{it}}{L_{it}} \right)^{\alpha_i} \left(\frac{E_{it}}{L_{it}} \right)^{\gamma_i}. \quad (4)$$

Define output per worker, capital per worker, and energy per worker as

$$y_{it} = \frac{Y_{it}}{L_{it}}, \quad k_{it} = \frac{K_{it}}{L_{it}}, \quad e_{it} = \frac{E_{it}}{L_{it}}. \quad (5)$$

The intensive-form production function is therefore

$$y_{it} = A_{it} k_{it}^{\alpha_i} e_{it}^{\gamma_i}. \quad (6)$$

Taking natural logarithms yields the log-linear representation

$$\ln y_{it} = \ln A_{it} + \alpha_i \ln k_{it} + \gamma_i \ln e_{it}. \quad (7)$$

The capital coefficient has the elasticity interpretation

$$\alpha_i = \frac{\partial \ln y_{it}}{\partial \ln k_{it}}, \quad (8)$$

so that, conditional on the other components of the model, α_i measures the percentage change in real output per worker associated with a 1% change in capital per worker.

3.2.1 Diminishing returns to capital deepening

The main theoretical proposition concerns the shape of the intensive production function with respect to capital per worker. From the production function,

$$\frac{\partial y_{it}}{\partial k_{it}} = \alpha_i A_{it} k_{it}^{\alpha_i - 1} e_{it}^{\gamma_i}. \quad (9)$$

A positive capital elasticity, $\alpha_i > 0$, implies that greater capital intensity raises labour productivity. The second derivative is

$$\frac{\partial^2 y_{it}}{\partial k_{it}^2} = \alpha_i(\alpha_i - 1) A_{it} k_{it}^{\alpha_i - 2} e_{it}^{\gamma_i}. \quad (10)$$

If

$$0 < \alpha_i < 1, \quad (11)$$

then

$$\frac{\partial^2 y_{it}}{\partial k_{it}^2} < 0. \quad (12)$$

Thus, capital deepening continues to raise output per worker, but the marginal productivity gain declines as capital per worker increases. This is the precise theoretical restriction examined in the empirical analysis.

3.2.2 Growth-rate representation and common shocks

The level variables are potentially non-stationary. Taking first differences of the log-linear production relation produces a growth-rate representation:

$$\Delta \ln y_{it} = \alpha_i \Delta \ln k_{it} + \gamma_i \Delta \ln e_{it} + \Delta \ln A_{it}. \quad (13)$$

The productivity component is allowed to contain common shocks that affect several countries simultaneously but with country-specific exposure:

$$\Delta \ln A_{it} = \lambda_i' \mathbf{f}_t + \varepsilon_{it}, \quad (14)$$

where $\mathbf{f}_t$ is a vector of unobserved common factors, λ_i is the corresponding vector of heterogeneous country-specific factor loadings, and ε_{it} is an idiosyncratic disturbance. Substitution gives the empirical production-growth equation

$$\Delta \ln y_{it} = \alpha_i \Delta \ln k_{it} + \gamma_i \Delta \ln e_{it} + \lambda_i' \mathbf{f}_t + \varepsilon_{it}. \quad (15)$$

This formulation is consistent with an environment in which African economies are exposed to shared global and regional disturbances, while the strength of those disturbances and the responses to productive inputs differ across countries.

3.3 Research hypotheses

The theoretical framework generates two linked hypotheses for capital deepening. First, capital per worker should have a positive productivity elasticity:

$$H_{0a}: \alpha = 0 \quad \text{against} \quad H_{1a}: \alpha > 0. \quad (16)$$

Second, the elasticity should be less than unity if diminishing returns characterize capital deepening:

$$H_{0b}: \alpha = 1 \quad \text{against} \quad H_{1b}: \alpha < 1. \quad (17)$$

The joint theoretical condition of interest is therefore

$$0 < \alpha < 1. \quad (18)$$

For energy, the study evaluates whether changes in energy use per worker have an independent average association with productivity growth after capital deepening and common factors are controlled for:

$$H_{0c}: \gamma = 0 \quad \text{against} \quad H_{1c}: \gamma \neq 0. \quad (19)$$

3.4 Construction of the physical capital stock

3.4.1 Baseline perpetual inventory method

The stock of physical capital is constructed using the perpetual inventory identity:

$$K_{it} = (1 - \delta)K_{i,t-1} + I_{it}, \quad (20)$$

This formulation is standard in cross-country capital measurement (Nehru & Dhareshwar, 1993; Berlemann & Wesselhöft, 2014).

where I_{it} denotes real GFCF and δ is the depreciation rate. The baseline depreciation rate is 5% per year:

$$\delta = 0.05. \quad (21)$$

The recursion requires an initial capital stock. In the baseline construction, the initial 1991 stock is approximated using:

$$K_{i,1991} = \frac{I_{i,1991}}{g_i + \delta}, \quad (22)$$

The steady-growth initialization is consistent with modified Harberger-type procedures used in international capital-stock construction (Nehru & Dhareshwar, 1993).

where g_i is the country-specific average real GDP growth rate used as a proxy for the long-run growth rate of the capital stock. Thereafter,

$$K_{it} = 0.95K_{i,t-1} + I_{it}, \quad t > 1991. \quad (23)$$

This produces a continuous annual capital-stock series for every country in the balanced panel.

3.4.2 Depreciation-rate sensitivity

Because the capital stock is constructed rather than directly observed, the assumed depreciation rate is treated as a source of measurement uncertainty. The complete PIM is therefore repeated under depreciation rates of 4%,

5%, and 6%. Sensitivity is especially important in developing-country applications, where maintenance, utilization and economic depreciation may differ from standard assumptions (Bu, 2006).

$$\delta \in \{0.04, 0.05, 0.06\}. \quad (24)$$

For each value of δ , the initial stock and the entire recursive capital series are recomputed before re-estimating the productivity equation. This ensures that the sensitivity exercise changes the underlying capital stock itself rather than only changing a parameter label in the regression.

3.4.3 Alternative initial capital stock

A second sensitivity exercise addresses dependence on the baseline initialization rule. Country-specific early investment growth is computed from 1991 to 2000 as

$$g_i^I = \left(\frac{I_{i,2000}}{I_{i,1991}} \right)^{1/9} - 1. \quad (25)$$

The alternative initial stock is

$$K_{i,1991}^{ALT} = \frac{I_{i,1991}}{g_i^I + 0.05}, \quad (26)$$

followed by the same 5% PIM recursion:

$$K_{it}^{ALT} = 0.95K_{i,t-1}^{ALT} + I_{it}. \quad (27)$$

The alternative capital-per-worker series is then defined by

$$\ln k_{it}^{ALT} = \ln K_{it}^{ALT} - \ln L_{it}. \quad (28)$$

This exercise is particularly important because it evaluates whether the estimated capital-deepening elasticity is sensitive to the starting-value assumption used in the PIM.

3.5 Cross-sectional dependence

Countries in the sample may share commodity-price shocks, global financial conditions, regional business cycles, technological change, energy-market developments, health emergencies, or other common disturbances. Cross-sectional dependence is therefore assessed before estimation. The testing strategy follows the weak cross-sectional-dependence framework of Pesaran (2015).

The Pesaran CD statistic is based on pairwise residual or variable correlations and can be written as

$$CD = \sqrt{\frac{2T}{N(N-1)}} \sum_{i=1}^{N-1} \sum_{j=i+1}^N \hat{\rho}_{ij}, \quad (29)$$

where $\hat{\rho}_{ij}$ is the estimated pairwise correlation between cross-sectional units i and j . The null is weak/no cross-sectional dependence against the alternative of strong cross-sectional dependence.

The analysis also reports complementary residual-dependence diagnostics, including weighted and power-enhanced CD statistics and the factor-robust CD-star statistic. These additional tests are treated as diagnostic evidence rather than as competing estimators; their purpose is to evaluate whether the preferred common-factor specification materially reduces remaining cross-sectional dependence.

Table 3. Cross-sectional dependence tests

Variable		CD	CDw	CDw+	CD*
ln(GDP worker)	per	26.67 (<0.001)	-2.48 (0.013)	315.92 (<0.001)	1.40 (0.162)
ln(Capital worker)	per	29.26 (<0.001)	-2.52 (0.012)	256.39 (<0.001)	0.24 (0.813)
ln(Energy worker)	per	1.38 (0.169)	-0.97 (0.334)	156.59 (<0.001)	3.26 (0.001)

Table 3 provides clear evidence that cross-sectional independence is not a tenable assumption for the panel as a whole. For ln(GDP per worker) and ln(Capital per worker), the conventional CD statistics are large and statistically significant, indicating that movements in productivity and capital intensity are correlated across countries. The conventional statistics for ln(Energy per worker) are less uniform; however, the power-enhanced CDw+ statistic rejects weak dependence for all three variables, while the factor-robust CD* statistic also rejects for energy. The diagnostic pattern therefore points to economically relevant common components in the data, even though their strength differs across variables and test formulations. This result is consistent with the exposure of the sampled economies to shared regional and global shocks and provides the empirical basis for using second-generation panel procedures and common-correlated-effects estimators rather than models that assume cross-sectional independence.

3.6 Second-generation panel unit-root testing

When cross-sectional dependence is present, first-generation panel unit-root tests can be size-distorted. The analysis therefore uses the cross-sectionally augmented Dickey-Fuller (CADF) approach and the associated CIPS statistic of Pesaran (2007).

For a generic series x_{it} , a cross-sectionally augmented regression can be represented as

$$\Delta x_{it} = a_i + b_i x_{i,t-1} + c_i \bar{x}_{t-1} + \sum_{j=0}^{p_i} d_{ij} \Delta \bar{x}_{t-j} + \sum_{j=1}^{p_i} \phi_{ij} \Delta x_{i,t-j} + u_{it}, \quad (30)$$

where $\bar{x}_t$ is the cross-sectional mean. The CIPS statistic averages the individual CADF statistics:

$$\text{CIPS} = \frac{1}{N} \sum_{i=1}^N \text{CADF}_i. \quad (31)$$

The null hypothesis is that the series contains a unit root for all cross-sectional units, against the alternative that at least a non-zero fraction of the panel is stationary. The variables are tested in levels and first

differences, with intercept and trend specifications used as appropriate. Because the per-worker variables are treated as integrated of order one, the production model is estimated in stationary first differences.

Table 4. Pesaran CADF/CIPS panel unit-root tests

Variable		Level: constant t-bar (p)	Level: trend t-bar (p)	First difference t-bar (p)	Order
ln(GDP worker)	per	-1.514 (0.827)	-1.894 (0.960)	-3.467 (<0.001)	I(1)
ln(Capital worker)	per	-1.734 (0.553)	-1.543 (0.999)	-2.435 (0.007)	I(1)
ln(Energy worker)	per	-1.906 (0.308)	-2.264 (0.618)	-3.555 (<0.001)	I(1)

Table 4 reports the cross-sectionally augmented panel unit-root results. In levels, the unit-root null cannot be rejected for ln(GDP per worker), ln(Capital per worker), or ln(Energy per worker) under either the intercept-only or intercept-and-trend specification. Once the variables are first differenced, the null is rejected in every case, with p-values below 1% for output per worker, capital per worker, and energy per worker. The evidence therefore supports treating all three series as integrated of order one, I(1). This finding has a direct modeling implication: estimating the production relation in unrestricted levels could confound common stochastic trends with an economic relationship. The empirical model is consequently specified in first-difference logarithms, so the estimated coefficients are interpreted as average short-run growth elasticities rather than as long-run level coefficients.

3.7 Slope heterogeneity

A common production elasticity across all sample economies would be restrictive because countries differ in capital quality, technology, industrial structure, institutions, energy systems, and factor allocation. Slope homogeneity is therefore assessed using the Pesaran-Yamagata (2008) test.

The null and alternative are

$$\begin{aligned}
 H_0: \beta_i &= \beta \quad \forall i \\
 H_1: \beta_i &\neq \beta_j \quad \text{for at least some } i \neq j
 \end{aligned}
 \tag{32}$$

A generic standardized statistic is

$$\tilde{D} = \sqrt{N} \left(\frac{N^{-1} \tilde{S} - k}{\sqrt{2k}} \right),
 \tag{33}$$

where $\tilde{S}$ is a Swamy-type dispersion statistic and k is the number of slope coefficients. A bias-adjusted version, $\tilde{D}_{adj}$, is also reported. Rejection of slope homogeneity supports the use of Mean Group estimators that allow country-specific production responses.

Table 5. Slope homogeneity tests

Test	Statistic	p-value	Adjusted statistic	Adjusted p-value
Pesaran-Yamagata (2008)	3.373	0.001	3.606	<0.001
HAC robust (Blomquist-Westerlund, 2013)	7.102	<0.001	7.592	<0.001

Table 5 rejects the hypothesis of slope homogeneity using both the standard Pesaran-Yamagata statistic and the HAC-robust version. The conventional Delta statistic is significant at the 1% level, and the rejection becomes even stronger under the HAC correction. The result indicates that the response of labour-productivity growth to changes in capital and energy intensity is not adequately summarized by a single coefficient imposed on all 12 economies. Such heterogeneity is economically plausible given cross-country differences in technology, capital quality, sectoral composition, institutions, and energy systems. Methodologically, the rejection supports the use of Mean Group estimators, which allow the country-specific production elasticities to differ before computing the cross-country average effect.

3.8 Regularized Common Correlated Effects Mean Group

3.8.1 Common-correlated-effects representation

The preferred estimator is the regularized Common Correlated Effects Mean Group (rCCE-MG) estimator. The CCE principle of Pesaran (2006) approximates unobserved common factors by augmenting each country equation with cross-sectional averages of observed variables. In the present application, define the cross-sectional-average vector

$$\bar{\mathbf{z}}_t = \frac{1}{N} \sum_{i=1}^N \begin{bmatrix} \Delta \ln y_{it} \\ \Delta \ln k_{it} \\ \Delta \ln e_{it} \\ \Delta \ln L_{it} \end{bmatrix}. \quad (34)$$

The country-specific CCE production-growth equation is

$$\Delta \ln y_{it} = c_i + \alpha_i \Delta \ln k_{it} + \gamma_i \Delta \ln e_{it} + \boldsymbol{\delta}'_i \bar{\mathbf{z}}_t + u_{it}. \quad (35)$$

The cross-sectional averages proxy the unobserved factor space, while their coefficients are allowed to differ across countries.

3.8.2 Regularization of the common-factor proxy space

Standard CCE can become inefficient or unstable when the set of cross-sectional averages contains redundant proxies relative to the dimension of the underlying common-factor space. Following Juodis (2022), rCCE regularizes this proxy space rather than mechanically forcing every available cross-sectional average into the factor approximation.

Let $\mathcal{R}_r(\cdot)$ denote the regularization operator that retains the empirically relevant r -dimensional component of the cross-sectional-average space. The regularized proxy vector is written as

$$\tilde{\mathbf{z}}_t = \mathcal{R}_r(\bar{\mathbf{z}}_t). \quad (36)$$

The estimated country equation is therefore

$$\Delta \ln y_{it} = c_i + \alpha_i \Delta \ln k_{it} + \gamma_i \Delta \ln e_{it} + \boldsymbol{\delta}'_i \tilde{\mathbf{z}}_t + u_{it}. \quad (37)$$

This specification simultaneously accommodates unobserved common shocks and heterogeneous country-specific responses.

3.8.3 Mean Group aggregation

Country-specific coefficients are not pooled into a single common slope. Instead, the panel effects are obtained by averaging the individual-country estimates:

$$\begin{aligned}\hat{\alpha}_{MG} &= \frac{1}{N} \sum_{i=1}^N \hat{\alpha}_i \\ \hat{\gamma}_{MG} &= \frac{1}{N} \sum_{i=1}^N \hat{\gamma}_i\end{aligned}\tag{38}$$

Accordingly, the reported coefficient is the average capital-deepening elasticity across the sampled economies rather than a restriction that all countries share an identical elasticity.

3.9 Bootstrap inference and the formal diminishing-return test

Juodis (2022) notes that standard plug-in variance estimators may not account for all uncertainty introduced by regularization and recommends cross-sectional bootstrap inference. The preferred rCCE estimates are therefore accompanied by 500 cross-sectional bootstrap replications.

For the standard test of a positive capital elasticity,

$$z_{\alpha=0} = \frac{\hat{\alpha}_{MG}}{SE_{boot}(\hat{\alpha}_{MG})}.\tag{39}$$

The key one-sided theoretical test evaluates whether the elasticity is statistically below unity:

$$z_{\alpha=1} = \frac{\hat{\alpha}_{MG} - 1}{SE_{boot}(\hat{\alpha}_{MG})}.\tag{40}$$

The alternative is one-sided because the theoretical proposition is specifically

$$H_1: \alpha < 1.\tag{41}$$

Evidence of a statistically positive coefficient together with rejection of unit elasticity provides empirical support for

$$0 < \alpha < 1,\tag{42}$$

the condition implied by diminishing returns to capital deepening in the intensive-form production function.

3.10 Robustness estimators

3.10.1 Standard Common Correlated Effects Mean Group

The standard CCEMG estimator is used as a direct robustness benchmark. Its country-specific equation is

$$\Delta \ln y_{it} = c_i + \alpha_i \Delta \ln k_{it} + \gamma_i \Delta \ln e_{it} + \boldsymbol{\delta}'_i \bar{\mathbf{z}}_t + u_{it},\tag{43}$$

without regularizing the cross-sectional-average space. The panel estimator is

$$\hat{\boldsymbol{\beta}}_{CCEMG} = \frac{1}{N} \sum_{i=1}^N \hat{\boldsymbol{\beta}}_i.\tag{44}$$

Comparison with rCCE shows whether the substantive inference depends on regularization of the common-factor proxies.

3.10.2 Augmented Mean Group estimator

The Augmented Mean Group (AMG) estimator of Eberhardt and Teal (2010) provides an additional heterogeneous-panel robustness check. The approach first extracts a common dynamic process from a pooled first-difference regression containing time indicators. Schematically,

$$\Delta \ln y_{it} = \boldsymbol{\theta}' \Delta \mathbf{x}_{it} + \sum_{s=2}^T \eta_s D_s + v_{it}, \quad (45)$$

where D_s denotes time dummies. The estimated time effects define a common dynamic process,

$$\hat{\mu}_t = \hat{\eta}_t. \quad (46)$$

Each country equation is then augmented with this common component:

$$\Delta \ln y_{it} = c_i + \alpha_i \Delta \ln k_{it} + \gamma_i \Delta \ln e_{it} + \phi_i \hat{\mu}_t + \varepsilon_{it}. \quad (47)$$

The AMG coefficient vector is the mean of the country-specific estimates:

$$\hat{\boldsymbol{\beta}}_{AMG} = \frac{1}{N} \sum_{i=1}^N \hat{\boldsymbol{\beta}}_i. \quad (48)$$

Agreement between rCCE, CCEMG, and AMG strengthens the interpretation that the estimated capital-deepening relationship is not an artifact of a single common-factor estimator.

3.11 Additional sensitivity analysis

The preferred model is subjected to four main sensitivity exercises.

First, the capital stock is reconstructed using 4%, 5%, and 6% depreciation rates. Second, the alternative country-specific early-investment-growth initialization is used. Third, 2020 and 2021 are excluded to assess sensitivity to the exceptional COVID-19 disruption:

$$t \notin \{2020, 2021\}. \quad (49)$$

Fourth, the rCCE estimate is compared with standard CCEMG and AMG estimates. The robustness design therefore evaluates stability across estimator choice, depreciation assumptions, capital-stock initialization, and sample-period composition.

These exercises are interpreted as sensitivity checks rather than as a search for the specification producing the most favorable coefficient.

3.12 Residual cross-sectional dependence

After each common-factor estimator, residual dependence is reassessed. Let $\hat{u}_{it}$ denote the fitted residuals. Pairwise residual correlations are

$$\hat{\rho}_{ij}^u = \text{corr}(\hat{u}_{it}, \hat{u}_{jt}). \quad (50)$$

The conventional residual CD statistic is

$$CD_u = \sqrt{\frac{2T}{N(N-1)}} \sum_{i=1}^{N-1} \sum_{j=i+1}^N \hat{\rho}_{ij}^u. \quad (51)$$

Because CCE-type estimators estimate many nuisance parameters and explicitly filter latent common factors, no single residual-dependence statistic is treated as decisive. Conventional CD, weighted CD, power-enhanced CD, and factor-robust CD-star diagnostics are considered jointly. The purpose is to determine whether common-factor correction substantially reduces dependence, while acknowledging that different diagnostics can have different power and finite-sample behavior.

4. Results and discussion

4.1 Descriptive statistics

Table 6. Descriptive statistics

Variable	Obs.	Mean	Std. deviation	Minimum	Maximum
Real GDP, constant 2020 USD	396	4.11e+10	1.04e+11	1.93e+09	6.49e+11
Employment (thousands)	396	10,991.61	18,670.12	233.40	106,691.00
GFCF, constant 2020 USD	396	1.01e+10	2.50e+10	1.32e+08	1.38e+11
Energy consumption (Mtoe)	396	7.055	10.587	0.800	60.140
Constructed capital stock	396	1.22e+11	3.35e+11	2.46e+09	1.73e+12
ln(GDP per worker)	396	14.797	0.956	12.802	17.517
ln(Capital per worker)	396	15.360	0.994	13.847	17.821
ln(Energy per worker)	396	-7.175	0.732	-8.567	-4.476

Table 6 reveals substantial dispersion in the scale and productive structure of the sampled economies. Real GDP ranges from approximately USD 1.93 billion to USD 649 billion, while the constructed physical-capital stock varies from roughly USD 2.46 billion to USD 1.73 trillion. Employment and energy consumption also display wide ranges, confirming that the sample combines economies with markedly different sizes and resource intensities. These differences reinforce the usefulness of the per-worker transformation, which shifts the empirical focus from aggregate scale to productive intensity. The logarithmic per-worker variables are also considerably more compact than their corresponding level series, facilitating elasticity-based interpretation. The negative average value of ln(Energy per worker) is purely a consequence of the measurement scale of the ratio and should not be interpreted as negative physical energy consumption.

4.2 Correlation structure

Table 7. Pairwise correlation matrix

Variable	(1)	(2)	(3)
(1) ln(GDP per worker)	1.000		
(2) ln(Capital per worker)	0.906***	1.000	
(3) ln(Energy per worker)	0.756***	0.674***	1.000

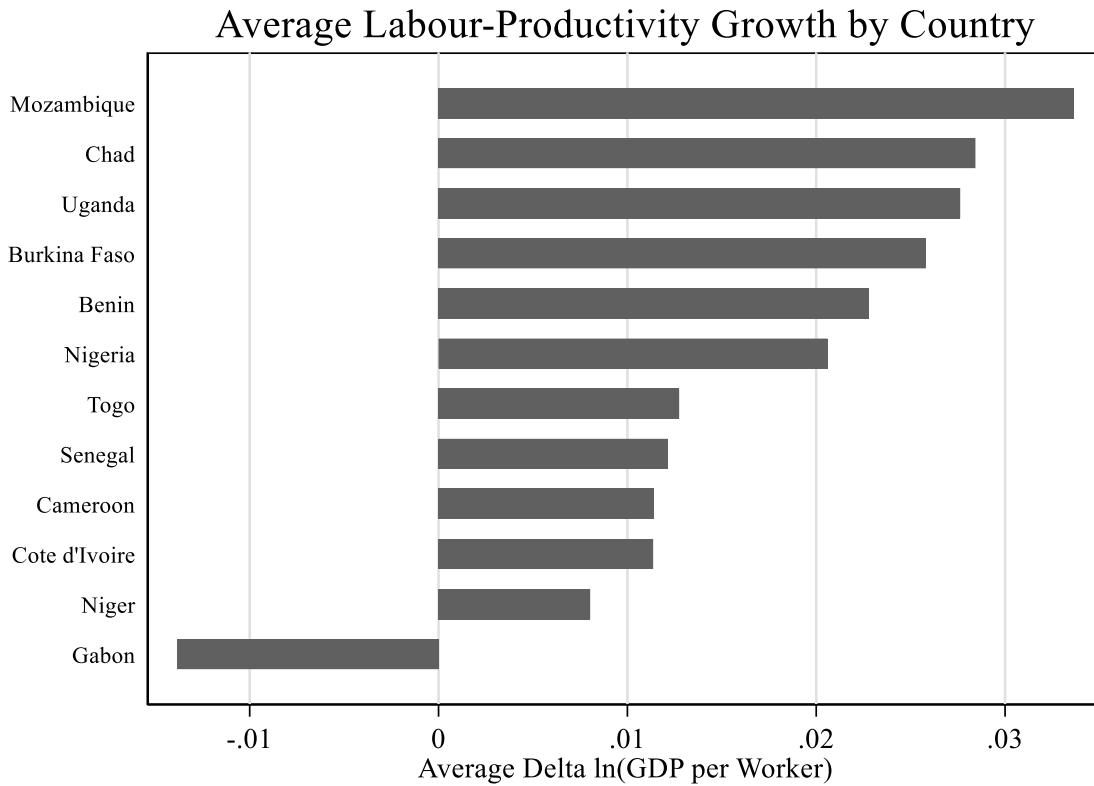


Figure 1. Average labour-productivity growth by country

Note: Bars show the country average of annual Delta ln(GDP per worker) over the estimation period. The figure is descriptive and does not represent an rCCE coefficient.

Figure 1 shows marked cross-country differences in average labour-productivity growth. Mozambique, Chad, Uganda and Burkina Faso record the highest averages, whereas Gabon records a negative average over the sample. These differences are consistent with the formal rejection of slope homogeneity and caution against imposing one common production response on all economies.

Table 7 shows a strong positive descriptive association between labour productivity and capital intensity. The correlation between $\ln(\text{GDP per worker})$ and $\ln(\text{Capital per worker})$ is 0.906, while $\ln(\text{Energy per worker})$ is also positively correlated with labour productivity ($r = 0.756$). Capital and energy per worker are positively related as well ($r = 0.674$), suggesting that more capital-intensive economies also tend to use more energy per worker. These correlations are consistent with the broad production-function expectation that productive inputs and output per worker move together. They are not, however, treated as evidence of a structural or causal relationship because the level variables are non-stationary. The formal empirical conclusions therefore rely on stationary first differences and estimators that account for both common shocks and heterogeneous country responses.

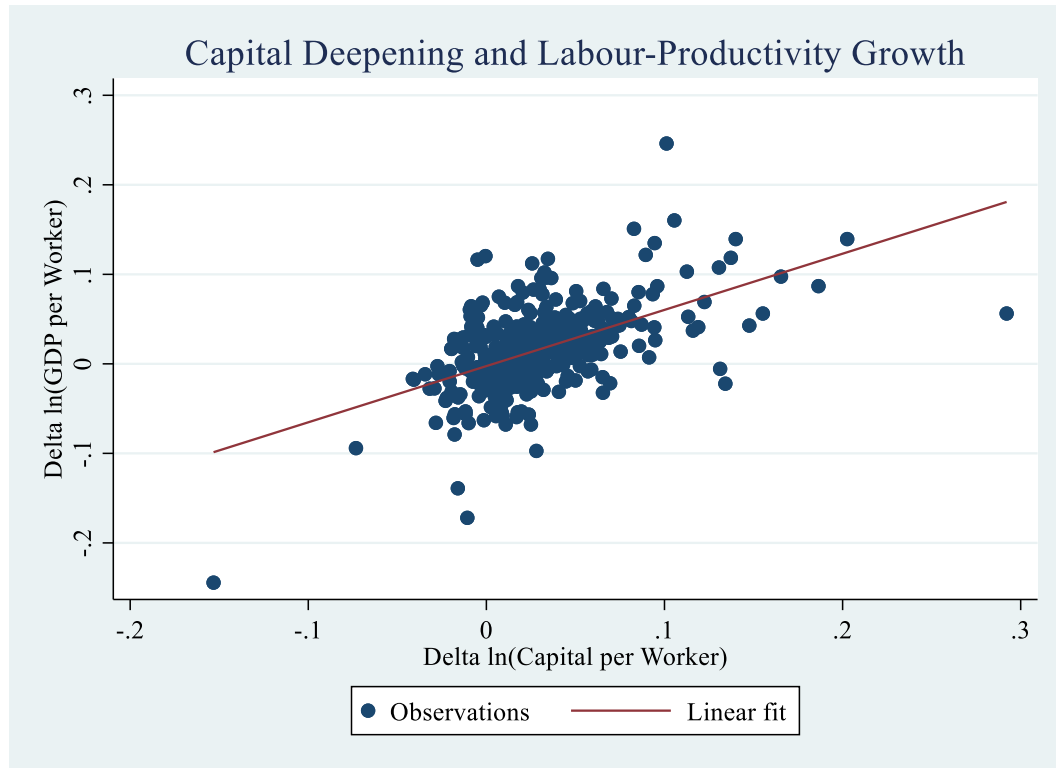


Figure 2. Capital deepening and labour-productivity growth

Note: Each point is a pooled country-year observation in first differences. The fitted line is a simple bivariate linear fit and should not be interpreted as the preferred rCCE estimate or as causal evidence.

Figure 2 provides a descriptive visualization of the positive pooled relationship between capital deepening and labour-productivity growth. However, the dispersion around the fitted line and the presence of several influential observations reinforce the need for heterogeneous common-factor estimation. The formal inference therefore relies on the rCCE model rather than on this pooled bivariate fit.

4.3 Main rCCE Mean Group estimates

Table 8. Main rCCE Mean Group estimates: energy-augmented productivity model

Variable	Coefficient	Bootstrap SE	z	p-value	95% CI
$\Delta \ln(\text{Capital per worker})$	0.452***	0.135	3.36	0.001	[0.188, 0.715]
$\Delta \ln(\text{Energy per worker})$	0.007	0.050	0.13	0.894	[-0.092, 0.106]

Model diagnostics

Observations	Countries	Regularized factors	CD (p)	CDw (p)	CDw+ (p)	CD* (p)
384	12	3	-0.40 (0.691)	-0.62 (0.536)	56.28 (<0.001)	2.42 (0.016)

Source: Author's calculations.

Table 8 presents the preferred rCCE Mean Group estimates. The estimated elasticity of capital per worker is 0.452, with a bootstrap standard error of 0.135 and a p-value of 0.001. Because both the dependent variable and capital intensity enter as first differences of natural logarithms, this coefficient indicates that a 1% increase in capital per worker is associated, on average, with an approximately 0.45% increase in real GDP per worker

within the same annual growth interval, conditional on changes in energy intensity and the regularized common-factor controls. The estimate is economically meaningful and statistically different from zero. For the study's central theoretical restriction, the one-sided test of $H_0: \alpha = 1$ is strongly rejected ($z = -4.074$; $p = 0.000023$). Taken together, the positive coefficient and rejection of unit elasticity support $0 < \alpha < 1$ within the maintained Cobb-Douglas framework and are therefore consistent with diminishing returns to capital deepening. By contrast, the energy-per-worker coefficient is close to zero and statistically insignificant ($p = 0.894$), with a confidence interval spanning both positive and negative values. The preferred specification therefore provides no evidence of a robust independent average short-run energy elasticity after capital deepening and common factors are controlled for. This does not imply that energy is technologically irrelevant; rather, its separate average contribution is not statistically distinguishable from zero in this specification. Residual-dependence diagnostics show that rCCE substantially reduces conventional cross-sectional dependence, as CD and CDw do not reject, but CDw+ and CD* remain significant. The residual evidence is therefore best characterized as mixed rather than as complete elimination of cross-sectional dependence. Because the model is observational and rCCE is designed to address common factors rather than establish exogenous variation in capital accumulation, these coefficients are interpreted as conditional associations rather than structural causal effects.

4.4 Robustness and sensitivity analysis

Table 9. Robustness and sensitivity analysis

Specification	Capital elasticity	p-value	Energy elasticity	Energy p-value
Baseline rCCE, $\delta = 5\%$	0.452	0.001	0.007	0.894
rCCE, $\delta = 4\%$	0.470	0.001	0.001	0.991
rCCE, $\delta = 6\%$	0.435	0.001	0.012	0.803
rCCE, alternative K_0	0.401	0.007	0.013	0.774
rCCE, excluding 2020-2021	0.488	0.001	0.010	0.853
AMG	0.632	0.001	0.049	0.163
CCEMG	0.552	0.001	0.053	0.050

Table 9 indicates that the main capital-deepening result is not sensitive to the principal modeling choices considered in the study. The estimated capital elasticity ranges from 0.401 under the alternative initial-capital-stock rule to 0.632 under AMG, and all reported capital coefficients remain positive and statistically significant. Reconstructing the capital stock with depreciation rates of 4%, 5%, and 6% produces closely clustered elasticities of 0.470, 0.452, and 0.435, respectively, showing that reasonable changes in the depreciation assumption do not materially alter the substantive conclusion. The alternative initialization lowers the point estimate to 0.401 but preserves both statistical significance and a confidence interval below unity, indicating that the result is not dependent on the baseline starting-value formula. Excluding 2020-2021 increases the coefficient modestly to 0.488, suggesting that the baseline finding is not driven by the exceptional COVID-19 period. The standard CCEMG and AMG estimators yield somewhat larger elasticities, 0.552 and 0.632, but retain the same positive and less-than-unit pattern. Thus, the evidence for a positive but diminishing capital-deepening elasticity is stable across estimator choice, capital-stock construction assumptions, and sample-period sensitivity. Energy per worker remains statistically insignificant in the rCCE sensitivity specifications and under AMG; the CCEMG estimate is only borderline significant. Accordingly, the energy coefficient is treated as a secondary and non-robust result rather than as a central empirical finding.

4.5 Discussion

4.5.1 Capital deepening and diminishing returns

The preferred estimate indicates that a 1% increase in capital per worker is associated with an average 0.45% increase in real GDP per worker within the same annual interval. The estimate is positive and significantly below

unity, which is consistent with the Solow-Swan diminishing-returns restriction within the maintained production-function framework (Solow, 1956; Swan, 1956). This interpretation is intentionally narrower than a causal claim: the first-difference rCCE specification identifies an average short-run conditional association and does not by itself rule out simultaneity or reverse causality between productivity and capital accumulation. The result nevertheless accords with Kumar and Russell (2002), who identify capital deepening as a distinct source of labour-productivity growth, and with Zoaka and Güngör (2023), who report a positive capital-productivity relationship in Sub-Saharan Africa.

However, the less-than-proportional elasticity also confirms that capital accumulation cannot fully explain productivity performance. Hall and Jones (1999) and Caselli (2005) emphasize that productive efficiency and social infrastructure are at least as important as factor quantities in explaining income differences. Similarly, Koopman and Wacker (2023) show that capital plays a limited average role in initiating growth accelerations but is important for sustaining them, while Eder et al. (2023) find that traditional capital and technological change dominate the contribution of robot capital. The present coefficient therefore reflects an important but bounded productivity mechanism rather than an investment-only growth process.

The stability of the coefficient across 4%, 5% and 6% depreciation rates and the alternative initial-capital-stock rule strengthens this interpretation. The result is not an artifact of one PIM assumption, although the capital stock remains an estimated measure rather than directly observed productive services. Bu (2006) notes that capital in developing countries may depreciate rapidly or remain underutilized because of maintenance and operating constraints. Thus, part of the gap between measured capital accumulation and output growth may reflect the difference between the recorded stock and the effective flow of capital services.

4.5.2 Allocation, technology and complementary capabilities

The positive but diminishing elasticity is also compatible with sectoral-allocation evidence. Bationo et al. (2023) show that foreign private capital generates different productivity outcomes depending on the recipient sector, whereas Hoekman et al. (2026) find stronger labour-market transformation effects from FDI in manufacturing and high-value-added services. Likewise, Ndubuisi et al. (2026) demonstrate that the structural-change effect of imported capital depends on technological appropriateness and domestic absorptive capacity. These findings suggest that aggregate capital per worker may increase even when a portion of new investment enters activities with limited domestic linkages, technological learning or employment spillovers.

Technology and skills provide a second explanation. Sié (2023) shows that inappropriate technology choices can weaken within-sector productivity, while Karacuka et al. (2025) identify an African digital productivity paradox and substantial sectoral heterogeneity. Similarly, Mazorodze et al. (2025) find that R&D produces larger productivity benefits where skilled workers and technology-intensive production are more prevalent. The result is therefore consistent with a complementarity interpretation: as capital per worker rises, additional gains increasingly require skills, innovation, management, maintenance and organizational adaptation.

Institutional and infrastructure conditions further shape this process. Adu-Darko and You (2025) find that the contribution of institutional quality to African total factor productivity varies over time, while Herrera Dappe and Lebrand (2024) show that electricity, roads and fast Internet generate larger transformation effects when provided jointly. Likewise, Gollin et al. (2026) attribute Africa's modest productivity growth partly to weak physical and social infrastructure. These studies help explain why similar increases in capital intensity can produce heterogeneous outcomes across the 12 economies.

4.5.3 Interpreting the energy coefficient

The preferred energy coefficient is close to zero and statistically insignificant, and it remains non-robust across the sensitivity specifications. This finding differs from the positive manufacturing effect reported by Kebede and Heshmati (2020) and from the positive aggregate growth relationships in Konyeaso et al. (2022) and Jinapor et al. (2025). However, the studies measure different outcomes and mechanisms. Manufacturing energy use is directly tied to machinery operation, whereas the present country-level variable combines agriculture, informal services, public activities and industry. Likewise, inclusive or per-capita growth can respond through channels that are not equivalent to contemporaneous output-per-worker growth.

The result should therefore not be interpreted as evidence that energy is technologically irrelevant. Stern (2011) argues that energy is a genuine production input, but its observed contribution depends on scarcity, substitution and technology. Moreover, Romero-Jordán et al. (2025) find that energy productivity, rather than energy quantity alone, raises total factor productivity. Damane and Ho (2026) similarly report medium-run improvements in energy productivity following renewable-energy shocks despite volatile short-run dynamics. Thus, aggregate energy per worker may be statistically weak when reliability, efficiency, composition and access are not separately measured.

The mixed energy evidence also supports the chosen common-factor approach. Boukhelkhal (2022) shows that African energy-growth results are sensitive to cross-sectional dependence and heterogeneous responses. In the present study, the energy effect remains weak after common shocks and capital deepening are controlled for, suggesting that energy may operate mainly through interaction with capital, infrastructure, finance and technology rather than through a uniform independent annual elasticity.

4.5.4 Heterogeneity and residual common dependence

The slope tests strongly reject a common response across countries, which is consistent with the differences in average productivity growth displayed in Figure 1 and with the diverse structural paths documented in the literature. Pinto et al. (2025) classify African economies into distinct transformation profiles, while Lorato et al. (2025) show how sectoral productivity disparities can generate an unintended service-led transition. Likewise, Dieppe and Matsuoka (2024) and Mensah et al. (2023) demonstrate that the sources of aggregate productivity vary between within-sector gains and labour reallocation. Mean Group estimation is therefore substantively appropriate rather than merely a statistical preference.

Residual diagnostics nevertheless remain mixed. Conventional CD and weighted CD statistics do not reject after rCCE estimation, whereas the power-enhanced and factor-robust diagnostics remain significant. The correct conclusion is therefore that the preferred specification materially reduces conventional dependence but may not capture every common component. This limitation supports cautious association-based language and reinforces the value of comparing rCCE with CCEMG and AMG rather than claiming complete factor removal.

5. Conclusion and policy implications

5.1 Conclusion

This study examined whether capital deepening is positively associated with labour-productivity growth at a less-than-proportional rate in 12 African OIC economies over 1991-2023. After establishing cross-sectional dependence, first-order integration and slope heterogeneity, the analysis estimated an energy-augmented production-growth equation using rCCE Mean Group with cross-sectional bootstrap inference. The preferred capital elasticity is positive, statistically significant and substantially below unity. Within the maintained production-function framework, the formal tests therefore support the joint restriction $0 < \alpha < 1$. This conclusion remains stable across alternative depreciation rates, an alternative capital-stock initialization, exclusion of the COVID-19 years, and CCEMG and AMG estimators.

The evidence therefore indicates a robust positive but less-than-proportional short-run association between capital deepening and labour-productivity growth in the sampled economies. This pattern is consistent with diminishing marginal returns under the maintained framework and with a broader literature emphasizing productive efficiency, technological capability, sectoral allocation, infrastructure and human skills. Energy use per worker, by contrast, has no robust independent average short-run coefficient. This does not imply that energy is unimportant; rather, aggregate energy quantity may not capture the reliability, efficiency, composition and complementarities through which energy affects productive performance. The findings should be read as conditional associations, not as estimates of structural causal effects.

5.2 Policy implications

The first policy implication, interpreted together with the broader literature rather than as a stand-alone causal prescription, is that investment strategy should emphasize productive capital deepening rather than aggregate investment volume alone. Governments and development-finance institutions should assess whether new assets expand capital available to workers, enter sectors with strong domestic linkages and can be maintained and utilized effectively. Evidence from sectoral allocation and structural transformation suggests that manufacturing, productive agriculture, enabling infrastructure and technology-intensive services may generate broader spillovers than enclave investment with limited local linkages (Bationo et al., 2023; Hoekman et al., 2026; Gollin et al., 2026).

Second, the results are consistent with integrating capital policy with skills, innovation and technology matching. Training, engineering capability, maintenance systems, R&D and managerial adaptation can raise the effective services obtained from the capital stock. Imported equipment should therefore be assessed against domestic absorptive capacity rather than technological sophistication alone (Mazorodze et al., 2025; Ndubuisi et al., 2026).

Third, the weak independent coefficient on aggregate energy use cautions against equating higher energy consumption with higher productivity. Energy policy should therefore combine supply expansion with reliability and efficiency. When electricity is intermittent, transmission losses are high or machinery is inefficient, additional energy consumption may not translate into proportionate productivity gains. Coordinated investment in power, roads and digital connectivity, together with renewable-energy finance and energy-management technologies, is more likely to strengthen capital utilization (Herrera Dappe & Lebrand, 2024; Romero-Jordán et al., 2025; Damane & Ho, 2026).

5.3 Limitations and future research

Several limitations should guide interpretation. First, the capital stock is constructed from aggregate GFCF and does not distinguish machinery, structures, public infrastructure, digital assets or utilization rates. Second, the energy measure captures aggregate consumption rather than access, reliability, renewable composition or energy productivity. Third, the first-difference specification identifies average short-run growth associations rather than long-run level relationships. Fourth, the balanced panel covers 12 economies and therefore does not represent every African or OIC country. Fifth, residual cross-sectional-dependence diagnostics remain mixed. Sixth, although rCCE is designed to account for latent common factors, it does not by itself establish exogenous variation in capital deepening; simultaneity, reverse causality and other forms of endogeneity may therefore remain. For these reasons, the estimates should not be interpreted as structural causal effects.

Future work could disaggregate capital and energy by sector and asset type, test capital-energy interactions, incorporate human capital and institutional measures where balanced data permit, and distinguish within-sector productivity gains from labour-reallocation effects. Longer panels and sectoral datasets would also allow investigation of whether the capital elasticity changes with development level, technology adoption, energy reliability and absorptive capacity.

Declarations

Ethics, Consent to Participate, and Consent to Publish declarations

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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Data availability

The data used in this study are publicly available from the **SESRIC/OICStat database**. The constructed physical-capital-stock series and derived variables were calculated by the authors from the underlying publicly available data. Additional replication materials may be obtained from the corresponding author upon reasonable request.

Code availability

The Stata do-files used for data construction, capital-stock estimation, econometric analysis, robustness checks, and table generation are available from the corresponding author upon reasonable request and may be deposited in a public replication repository upon publication.

Declaration of generative AI use

The authors declare that generative AI tools were used for language editing, writing support, and manuscript refinement. All authors reviewed and approved the final manuscript and remain fully responsible for its accuracy, integrity, interpretation, and originality.

Author contributions

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