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The Asymmetric Drivers of Sustainable Economic Growth in North Macedonia: A NARDL Approach

Elizabeta Djambaska[1*] | Aleksandra Lozanoska[1] | Irina Piperkova[1] | Vladimir Petkovski[1]

[1] University Ss. Cyril and Methodius in Skopje, Institute of Economics – Skopje, Skopje, North Macedonia

ABSTRACT

This paper investigates the asymmetric drivers of sustainable economic growth in North Macedonia, addressing the critical policy dilemma of balancing rapid macroeconomic convergence with the stringent environmental conditionalities of the European Union's "Green Agenda." Utilizing an extended Cobb-Douglas production function, the research incorporates gross fixed capital formation, labor force dynamics, and annual CO2 emissions into a unified econometric framework. To capture the structural rigidities and vulnerability to exogenous shocks inherent in transition economies, the study employs the Non-linear Autoregressive Distributed Lag (NARDL) bounds testing approach. The empirical results indicate the presence of long-run asymmetric cointegration among the variables. The decomposition of macroeconomic shocks reveals profound structural asymmetries: while positive shocks to capital investment remain the dominant engine of long-run economic expansion, the economy exhibits remarkable resilience to investment contractions, which exert no statistically significant permanent drag on aggregate output. Furthermore, the analysis exposes a persistent human capital "productivity trap," demonstrating that raw labor force expansion, devoid of skills upgrading, fails to stimulate structural growth. Most crucially, the study provides robust econometric proof of a "Green Dividend" in the Western Balkans. The NARDL estimation rejects the traditional industrial paradigm, revealing that while escalating pollution no longer fuels economic expansion, permanent reductions in CO2 emissions actively and significantly stimulate long-term GDP. These findings confirm that transitioning toward sustainable development and active decarbonization does not impose a "green penalty" on developing nations. The paper concludes that North Macedonia has a valuable opportunity to reframe environmental sustainability as a robust macroeconomic driver, strategically aligning capital investments and labor market reforms with the principles of the circular economy to ensure long-term national resilience.

Keywords: s*ustainable economic growth; NARDL model; Green Dividend; Asymmetric Cointegration; transition economy; environmental decoupling; North Macedonia*

JEL Classification: O44, Q56, C22, P20

INTRODUCTION

The economic trajectory of North Macedonia over the past three decades represents a compelling case study of a small, open transition economy determined for convergence with European living standards. Since gaining independence and crossing through the turbulent transition from a socialist to a market-based economy, the country has faced several challenges.

* Corresponding author, e-mail: beti@ek-inst.ukim.edu.mk

The country has undergone a complex transition characterized by the need to rebuild its physical infrastructure and rapid modernization, high structural unemployment, the need to upgrade human capital, and the imperative to align with EU environmental standards.

The path to prosperity has been uneven, characterized by periods of solid growth disrupted by internal political crises and external shocks, such as the 2008 financial crisis, the COVID-19 pandemic and the war in Ukraine. Because these shocks create structural rigidities, traditional linear economic models often fail to capture the true dynamics of the economy. Unlike developed nations, where growth is driven by continuous innovation, North Macedonia's trajectory has largely been a "catch-up" process, heavily reliant on capital deepening. Historically, the country has struggled with "jobless growth" and the significant emigration of its skilled workforce. Simultaneously, the Green Agenda for the Western Balkans has introduced sustainability as a baseline condition for future competitiveness.

This paper addresses this specific Western Balkan "development puzzle" by anchoring its theoretical framework in neoclassical and endogenous growth theories, while employing a Non-linear Autoregressive Distributed Lag (NARDL) approach to capture real-world asymmetric shocks. According to the Solow-Swan growth model (Solow, 1956; Swan, 1958), which remains a dominant explanatory framework for the region, physical capital accumulation should drive economic growth. As a capital-scarce economy relative to the EU, North Macedonia's marginal product of capital is theoretically high. Consequently, gross fixed capital formation—encompassing foreign direct investment (FDI) in technological zones (TIDZ) and public infrastructure projects like Corridor 8 is expected to be the primary engine of GDP growth. However, by utilizing a non-linear framework, this study tests whether the economy reacts symmetrically to investment booms versus capital contractions during crisis periods.

Furthermore, while Endogenous growth theory (Romer, 1989; Lucas, 1988) focuses on education as a primary source of growth, this assumption often breaks down in transition economies suffering from severe skills mismatches. In North Macedonia, the rapid expansion of tertiary enrollment has not been matched by job creation in high-value sectors. The persistent "brain drain" suggests that human capital formation locally often benefits destination countries, such as Germany, rather than the domestic economy. This study explicitly tests this constraint, evaluating whether raw labor expansion translates into genuine productivity gains.

Regarding environmental sustainability, this paper tests the validity of the "Porter Hypothesis" (Porter, 1991; Porter & Van Der Linde, 1995) within a transition context. Porter suggests that strict environmental standards and decarbonization efforts drive efficiency, attract higher-quality FDI, and ultimately yield a positive impact on GDP. To evaluate this, CO_2 emissions are utilized as the primary sustainability proxy. By decomposing this environmental trajectory into positive and negative partial sums, the NARDL model isolates the precise macroeconomic impact of pollution. This allows the research to answer whether North Macedonia can achieve economic stability without sacrificing the environment, and empirically proves whether reducing emissions imposes a developmental penalty or yields a structural "Green Dividend."

Following a literature review, the paper establishes its theoretical framework and methodology by detailing the data preparation, stationarity analysis, and the specification of the asymmetric NARDL model. The paper then presents the empirical results evaluating unit root and bounds tests for cointegration and discusses the long- and short-run economic asymmetries before affirming model stability and offering concluding remarks.

LITERATURE REVIEW

Theoretical and empirical analyses estimating the drivers of economic growth and GDP per capita traditionally focus on physical capital, human capital, and other parameters that govern productivity and technological progress. In recent years, however, the academic consensus has shifted toward evaluating specific factors related to sustainable development. Contemporary

studies increasingly incorporate education, population health indicators, research and development (R&D), institutional parameters, and environmental metrics into growth accounting. Consequently, sustainability has emerged as a universally accepted paradigm, attracting immense scholarly interest across both developed and developing nations.

Recent literature provides robust evidence of this paradigm shift. A study by Keerthana et al. (2025) focuses on environmental performance in leading OECD economies (the United Kingdom, France, Germany, and Italy) over a 25-year period (2000–2024). Utilizing a Panel Autoregressive Distributed Lag (ARDL) model, the authors find a significant positive linkage between environmental performance indicators (such as air quality and greenhouse gas emission reductions) and GDP growth. The study emphasizes that investments in green technologies are highly lucrative, proving that "green growth" is a statistically valid phenomenon in advanced economies.

The research “Empirical study towards the drivers of sustainable economic growth in EU-28 countries” analyses the EU-28 countries to identify determinants of sustainable economic growth. It identifies that R&D expenditure and employment of graduates contribute significantly to sustainable development. (Armeanu, Vintilă & Gherghina, 2018) Crucially, it finds that governance factors (measured by the Corruption Perception Index) are strongly linked to growth performance.

Iuga and Lazea's (2023) study focuses on the Sustainable Development Goals and income. The study investigates the link between sustainable development indicators and GDP per capita across European countries. The regression models show that sustainable development variables are significant predictors of income levels in the EU-19 and EU-27 groups. The study confirms that there is no change in the behavior of these variables in the long run, suggesting a stable, structural positive relationship between sustainability metrics and economic wealth in Europe.

The study of Wang et al. (2023) analyzes factors affecting economic growth in a panel of developed countries. The research empirically proves that renewable energy consumption has a significant positive impact on real GDP. Specifically, a 1% increase in renewable energy consumption was associated with a 0.12% increase in real GDP. The authors conclude that sustainable energy transition is not a burden but a catalyst for economic expansion in developed nations, alongside scientific progress and economic freedom.

Shifting to the context of developing nations, the literature on North Macedonia presents a critical assessment of the country’s economic development. Research indicates that while the economy has achieved moderate growth through physical capital accumulation, this expansion faces severe structural limits. Specifically, growth is constrained by low total factor productivity (TFP), a persistent mismatch between education and labor market demands, and demographic trends that endanger fiscal sustainability (Djambaska, Lozanoska & Piperkova, 2022; Djambaska & Petkovski, 2024; Petkovski, Djambaska & Lozanoska, 2024). Moreover, regional scholarship increasingly challenges standard policy assumptions. Authors question the heavy reliance on foreign direct investment (FDI) as the primary solution to unemployment (Djambaska & Lozanoska, 2013). Furthermore, contemporary research emphasizes that transitioning to a green, circular economy is a fundamental prerequisite for long-term resilience (Mashovic, Ignjatovic & Kisin, 2022).

Despite these conceptual advancements, a significant methodological limitation persists in the literature regarding transition economies: a heavy reliance on linear econometric frameworks. Traditional ARDL and multiple regression models inherently assume symmetric macroeconomic responses. They presume that the economic boost from capital accumulation is exactly proportional to the damage caused by capital contraction, and that increases in environmental degradation affect growth identically- albeit inversely - to environmental improvements.

To address this flaw, top-tier environmental economics literature increasingly advocates for the Non-linear Autoregressive Distributed Lag (NARDL) approach. Recent scholarship

demonstrates that symmetric models systematically miss crucial sustainability outcomes (Qureshi et al., 2025). For instance, recent applications of NARDL methodologies provide empirical evidence that positive and negative shocks in energy consumption and CO2 emissions exert fundamentally asymmetric effects on aggregate output across both advanced OECD economies (Song et al., 2024; Artekin, 2024) and developing regions (Yang et al., 2022). These studies confirm that modeling the complex nexus between economic growth and environmental degradation requires non-linear frameworks to capture real-world structural rigidities.

This methodological evolution is highly pertinent to the Balkan region. Early regional scholarship argued that green growth must be viewed not as a regulatory constraint, but as a primary generator for overcoming economic crises and structural stagnation (Jovanovic, Gavrilovic & Minic, 2012). More recently, research analyzing the intersection of emerging technologies and sustainable growth in Serbia and North Macedonia underscores that transition economies require highly tailored policies to overcome institutional barriers and realize the economic benefits of environmental modernization (Velichkovska, Mitić & Kojić, 2025).

Building directly upon this regional foundation, the objective of this paper is to bridge the gap between traditional symmetric growth accounting and the modern imperative for asymmetric environmental policy. By applying the NARDL approach to an extended Cobb-Douglas production function for North Macedonia, this research isolates the asymmetric nature of physical capital and empirically tests for a "Green Dividend." Ultimately, this non-linear framework provides robust empirical validation for sustainable decoupling, demonstrating how transition economies can navigate the complex drivers of sustainable development.

DATA AND METHODOLOGY

Theoretical Framework and Data Preparation

The empirical approach of this study is anchored in an extended Cobb-Douglas production function. This approach builds upon the traditional neoclassical framework by augmenting the standard macroeconomic inputs of physical capital and labor with an environmental sustainability parameter. In this augmented model, the environmental metric functions as an integrated structural constraint—or potential driver—of aggregate production, acknowledging that modern economic output is inextricably linked to ecological trajectories.

Guided by this framework, the core variables of the model are defined as follows: Y (Gross Domestic Product), K (capital stock), L (labor), and CO2 emissions. Initially, the empirical strategy of this study sought to incorporate a broader, multidimensional sustainability framework by including supplementary environmental metrics such as renewable energy consumption, resource productivity, and aggregate energy use. While theoretically advantageous for capturing the comprehensive scope of the "Green Agenda," the inclusion of these additional variables was ultimately precluded by severe empirical constraints inherent to transition economy datasets.

The primary limitation was the restricted temporal availability of these supplementary time series. For North Macedonia, data on resource productivity and specific renewable transitions suffer from short historical spans. In time-series econometrics, small sample sizes strictly limit the number of parameters that can be reliably estimated. Because Autoregressive Distributed Lag (ARDL) and NARDL models require the estimation of both short-run and long-run dynamic lags for every included variable, introducing multiple environmental metrics rapidly depletes the model's degrees of freedom, rendering the regression mathematically inestimable.

Furthermore, preliminary unit root testing on these supplementary variables revealed problematic integration orders, including severe non-stationarity that could not be resolved without losing critical data points. The ARDL bounds testing methodology strictly prohibits the inclusion of variables integrated of order two, I(2). Consequently, to preserve the structural integrity and statistical validity of the econometric model, annual CO2 emissions were retained as

the sole, highly robust proxy for environmental sustainability. This specific variable provided the longest consistent time series and successfully satisfied the strict I(1) first-difference stationarity prerequisite, allowing for a precise and unbiased estimation of the asymmetric 'Green Dividend.'"

Annual time-series data covering a continuous 25-year period from 2000 to 2024 were systematically compiled. Specifically, the time series were sourced from the State Statistical Office of North Macedonia, the National Bank of North Macedonia, the World Bank Open Data platform, Eurostat, and the International Energy Agency (IEA). The dataset encompasses four core macroeconomic variables: Gross Domestic Product (Y) is expressed as an absolute value in current prices, measured in millions of denars; Labor (L) is represented by the total number of employees, while annual CO2 emissions (CO2) are measured in tons. By applying a natural logarithmic transformation to this multiplicative function, the theoretical output elasticities are mathematically converted into linear coefficients that can be econometrically estimated.

Stationarity Analysis and the Capital Proxy

Originally, the empirical approach intended to estimate the model utilizing the accumulated macroeconomic capital stock (K), calculated from gross fixed capital formation via the Perpetual Inventory Method (detailed in Annex 1). The dataset was transformed into natural logarithms (Ln), followed by unit root testing to assess the stationarity of the variables, which is a primary prerequisite for selecting the appropriate econometric model.

However, preliminary test results indicated that the calculated capital stock exhibited second-order stationarity, I (2). Because the Autoregressive Distributed Lag (ARDL) and NARDL bounds testing methodologies strictly mandate that all variables must be stationary at level, I(0), or order one, I(1), the inclusion of an I(2) variable is econometrically invalid. To resolve this mathematical limitation, the framework substitutes the non-stationary accumulated capital stock with gross fixed capital formation (I), utilizing the annual investment flow to represent capital. Following its logarithmic transformation, this substituted variable successfully satisfied the required criterion of first-order stationarity I(1). This stationary, log-linearized foundation provides the exact baseline required for the final regression model.

Model Specification: The Asymmetric NARDL Approach

To capture the potential asymmetric macroeconomic responses within the North Macedonian economy, this study employs the Non-linear Autoregressive Distributed Lag (NARDL) approach developed by Shin, Yu, and Greenwood-Nimmo (2014). Traditional linear models assume symmetric output elasticities, implying that an increase or decrease in an independent variable will exert an identical, albeit inverse, proportional effect on aggregate output. However, recognizing the structural rigidities of transition economies, the NARDL framework relaxes this assumption by decomposing the core independent variables into their respective positive and negative partial sums.

For the purpose of this empirical investigation, two specific variables from the extended Cobb-Douglas production function were decomposed to test for asymmetric shocks: gross fixed capital formation (ln_I) and CO2 emissions (ln_CO2). Labor (ln_ L) was retained as a symmetric control variable to isolate the structural effects of the capital and environmental vectors.

The asymmetric variables are mathematically defined as the cumulative sums of positive and negative changes in the respective time series. For capital investment (ln_I), the positive and negative partial sums are generated as follows:

$$I_t^+ = \sum_{j=1}^{t} \Delta I_t^+ + \sum_{j=1}^{t} \max(\Delta I_j, 0) \qquad (1)$$

$$I_t^- = \sum_{j=1}^{t} \Delta I_t^{-+} + \sum_{j=1}^{t} \min(\Delta I_j, 0) \quad (2)$$

Similarly, to isolate the environmental trajectory and test the hypothesis of a "Green Dividend," the sustainability proxy - annual CO2 emissions (ln_CO2) is decomposed into positive accumulations (polluting more) and negative reductions (polluting less):

$$CO2_t^+ = \sum_{j=1}^{t} \Delta CO2I_t^+ + \sum_{j=1}^{t} \max(\Delta CO2I_j, 0) \quad (3)$$

$$CO2_t^+ = \sum_{j=1}^{t} \Delta ICO2_t^+ + \sum_{j=1}^{t} \min(\Delta CO2_j, 0) \quad (4)$$

Econometrically, this non-linear decomposition serves a dual purpose. First, splitting the capital investment variable allows the model to ascertain whether capital contractions (e.g., during economic crises) permanently damage aggregate output to the same degree that capital accumulation (investment booms) stimulates it. Second, decomposing the environmental variable allows for a precise test of the sustainable transition, rather than merely measuring total emissions, the model independently tests whether reducing CO2 emissions actively harms economic growth (the "green penalty") or stimulates it (the "green dividend").

Following the decomposition of the capital and environmental variables, the extended Cobb-Douglas production function is transformed into an unrestricted Non-linear Autoregressive Distributed Lag (NARDL) Error Correction Model (ECM). This specification allows the model to empirically isolate how asymmetric shocks independently govern long-term economic growth, facilitating the simultaneous estimation of both short-run asymmetric dynamics and long-run asymmetric cointegrating relationships.

To estimate the final NARDL equation, the optimal lag structure was determined utilizing the Akaike Information Criterion (AIC). Given the annual frequency of the dataset and the necessity to preserve degrees of freedom within the sample size, the maximum lag length was strictly restricted to one. Out of 32 evaluated combinations, the AIC algorithm identified the ARDL (1,0,0,1,1,1) specification as the most robust fit for the macroeconomic data.

The statistical reliability and validity of this chosen specification were subsequently verified through a series of residual diagnostic tests. To ensure the efficiency of the estimators, the Breusch-Pagan-Godfrey test was employed to confirm the presence of homoskedasticity. Furthermore, the Breusch-Godfrey LM test was utilized at two lags to strictly reject the presence of serial correlation within the error terms, confirming that the dynamic lag structure adequately captures the time-series properties of the North Macedonian economy.

Finally, the dynamic structural stability of the model's parameters over the entire sample period was evaluated using the Cumulative Sum of Recursive Residuals (CUSUM) and the CUSUM of Squares tests. Assessing structural stability is critically important when modeling transition economies, as it verifies whether the estimated long-run elasticities hold true despite exogenous macroeconomic shocks, such as the 2008 global financial crisis or the COVID-19 pandemic.

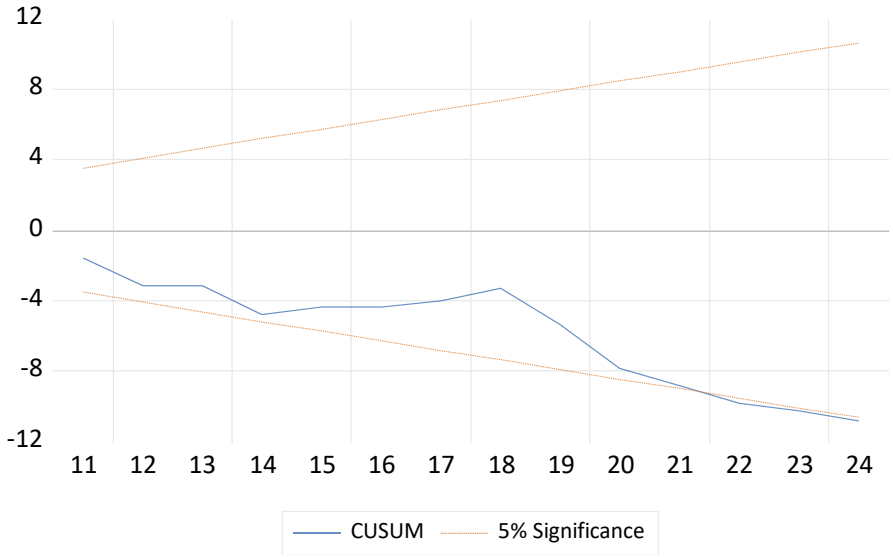

Figure 1 Plot of the Cumulative Sum of Recursive Residuals (CUSUM) for parameter stability

As illustrated in Figure 1, the plot of the CUSUM statistics remains strictly confined within the 5% critical bounds (represented by the red significance lines) throughout the entire estimation period. This is a highly significant finding for the North Macedonian context. The graph supports the interpretation that the fundamental relationship between aggregate output, capital accumulation, and the "Green Dividend" did not suffer from structural breaks during periods of acute regional or global distress. Consequently, the asymmetric elasticities derived from this model are not just statistically significant, but highly stable, making them reliable instruments for long-term macroeconomic policy formulation.

RESULTS AND DISCUSSION

Unit Root Tests and Stationarity

Prior to estimating the asymmetric elasticities, the integration order of the variables was evaluated to prevent the incidence of spurious regression and to satisfy the mathematical prerequisites of the bounds testing methodology. The Augmented Dickey-Fuller (ADF) unit root tests (summarized in Table 1) confirm that none of the core variables, natural logarithms of real GDP (LN_Y), gross fixed capital formation (LN_I), labor (LN_L), and annual CO2 emissions (LN_CO2) are stationary at their level form, as all p-values exceed the 0.05 threshold.

However, upon taking the first difference, all variables become highly stationary at the 1% significance level (p-values < 0.01). Consequently, the entire dataset is uniformly integrated of order one, I(1). This uniform first-difference stationarity perfectly satisfies the strict rules for NARDL estimation, clearing the model for the bounds testing procedure.

Table 1. Augmented Dickey-Fuller (ADF) Unit Root Tests

Variable	ADF Statistic (Level)	Probability	ADF Statistics (1Difference)	Probability	Integration Order
LN_Y	0.553	0.9850	-4.007***	0.0056	I(1)
LN_I	-0.349	0.9031	-3.953***	0.0064	I(1)
LN_L	-1.296	0.6141	-5.146***	0.0004	I(1)
LN_CO2	-1.406	0.5621	-5.683***	0.0001	I(1)

*Note: *** denotes statistical significance at the 1% level.*

The Bounds Test for Asymmetric Cointegration

The existence of a permanent, structural relationship among the variables within the extended Cobb-Douglas framework is verified through the NARDL bounds test. As reported in Table 2, the calculated F-statistic of 11.893 significantly exceeds the 1% upper bound critical value of 4.150. Therefore, the null hypothesis of no level relationship is rejected. This mathematical proof confirms that there is a permanent, long-run cointegrating relationship between aggregate output, capital accumulation, human capital, and environmental trajectories in North Macedonia.

Table 2. Bounds Test for Asymmetric Cointegration

Test Statistic	Value	Significance level	I(0) Bound	I(1) Bound
F-statistic	11.893*	10%	2.08	3.00
k (variables)	5	5%	2.39	3.38
I	1%	3.06	4.15	

*Note: *** denotes that the F-statistic exceeds the 1% upper bound, strongly rejecting the null hypothesis of no cointegration.*

Discussion of long-Run and Short-Run Asymmetries (The Economic Story)

The extraction of the state-dependent coefficients (Table 3) reveals profound structural asymmetries in the drivers of economic growth, challenging traditional symmetric growth accounting and offering clear policy insights.

Mathematical Stability (ECT): The model's stability is corroborated by the Error Correction Term (COINTEQ), which exhibits a highly significant and negative coefficient of -0.361 (p = 0.000). This indicates that following a short-term macroeconomic shock, the North Macedonian economy corrects approximately 36.1% of the disequilibrium within a single year, proving that the system is stable and converges steadily back to its long-run steady state.

The Capital Asymmetry: The decomposition of gross fixed capital formation yields a highly significant, highly elastic positive coefficient for investment booms (LN_I_POS = 1.040, p = 0.006). In the long run, a 1% sustained expansion in capital investment drives a massive 1.04% increase in aggregate GDP, confirming that capital injection remains the dominant engine of growth. However, the coefficient for negative investment (LN_I_NEG) is statistically insignificant (0.034, p = 0.971). This proves that while capital drives growth, the economy is highly resilient to investment contractions, effectively buffering against permanent structural damage during crises.

The "Green Dividend": The most pivotal finding is the asymmetric macroeconomic sensitivity to environmental trajectories. The coefficient for increasing CO2 emissions (LN_CO2_POS) is statistically insignificant (-0.924, p = 0.232), proving that escalating pollution no longer helps fuel the economy. Conversely, emission reductions (LN_CO2_NEG) exhibit a significant and negative coefficient (-0.781, p = 0.055). Because the variable itself tracks negative changes (reductions), multiplying it by the negative coefficient yields a positive macroeconomic multiplier. Explicitly, a 1% reduction in emissions stimulates a 0.78% increase in long-run GDP. These findings provide empirical support for the hypothesis that green transitions actively generate economic wealth, validating the "Green Dividend."

The Labor Constraint: The labor variable (LN_L) exhibits a negative and statistically insignificant long-run coefficient (-1.580, p = 0.159). This finding empirically proves that simply creating jobs or increasing raw headcount without upgrading underlying skills (human capital) does not generate structural economic growth, highlighting a persistent skills mismatch in the labor market.

Table 3. Short-Run and Long-Run Asymmetric Coefficients

	Variable	Coefficient	t-Statistic	Prob.
Long-Run Elasticities	LN_I_POS	1.040***	3.085	0.0064
	LN_I_NEG	0.034	0.036	0.9715
	LN_L(-1)	-1.580	-1.466	0.1597
	LN_CO2_POS(-1)	-0.924	-1.235	0.2324
	LN_CO2_NEG(-1)	-0.781*	-2.045	0.0557
	Constant	33.375**	2.337	0.0312
Short-Run Dynamics	D(LN_I_POS)	0.375***	4.139	0.0010
	D(LN_L(-1))	-0.511**	-2.791	0.0144
	D(LN_CO2_NEG(-1))	-0.321*	-1.776	0.0973
	CoinEq(-1)(ECT)	-0.361*	-10.905	0.0000

Note: *, **, and * denote significance at the 1%, 5%, and 10% levels, respectively. Statistically insignificant short-run lags were omitted for brevity.*

Diagnostics and Stability

To ensure the statistical validity of these findings, the model was subjected to a series of standard residual diagnostic tests (Table 4). The model successfully passed all checks. The Breusch-Pagan-Godfrey test yielded a p-value of 0.1218 (exceeding 0.05), confirming that the residuals are homoskedastic. Furthermore, the Breusch-Godfrey LM test at two lags yielded a p-value of 0.6874, strictly rejecting the presence of serial correlation. Consequently, the estimated coefficients and corresponding p-values are unbiased and mathematically sound.

Table 4. Residual Diagnostic Tests

Test	F-Statistic	Prob. (p-value)	Conclusion
Breusch-Pagan-Godfrey	1.978	0.1218	Homoskedasticity (No heteroskedasticity)
Breusch-Godfrey LM (2 lags)	0.386	0.6874	No Serial Correlation

Figure 2 and Figure 3 visually corroborate the estimated long-run asymmetric elasticities for the North Macedonian economy. The dynamic multiplier graphs map the cumulative response of real GDP to unitary shocks in the independent variables over a 15-year horizon. The solid black line represents the positive shocks, the dashed black line represents the negative shocks, and the dashed red lines denote the 95% confidence intervals.

Figure 2 visually confirms the "Green Dividend" hypothesis (LN_CO2). The dashed black line (LN_CO2_NEG), representing reductions in CO2 emissions, exhibits a clear downward trajectory that stabilizes significantly below the zero line. Because this variable tracks negative changes, this downward trajectory mathematically translates to a strictly positive macroeconomic multiplier, proving that sustainable decarbonization structurally stimulates long-term economic growth.

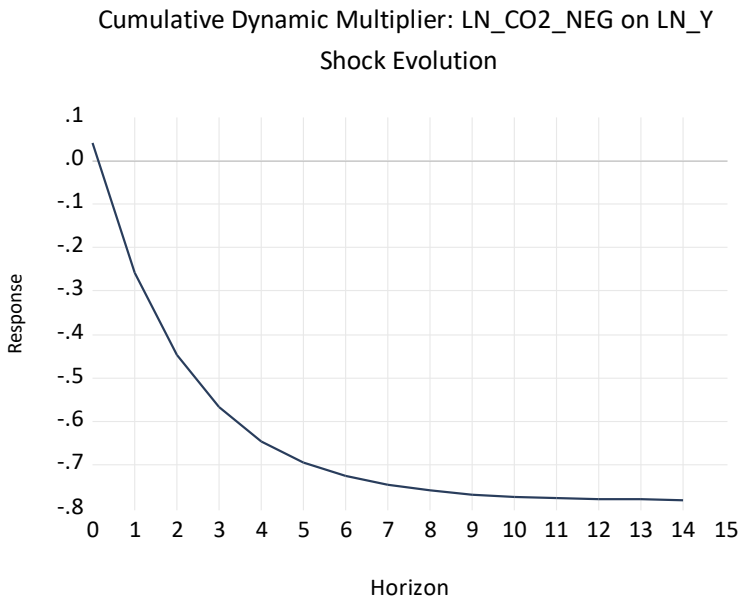

Figure 2. Dynamic Asymmetric Multipliers of the NARDL Model over a 15-Year Horizon (CO2)

Furthermore, Figure 3 visualizes the asymmetric capital shock (LN_I). The solid black line (LN_I_POS) demonstrates a permanent upward trajectory, confirming that positive shocks to capital investment rapidly translate into significant macroeconomic expansion.

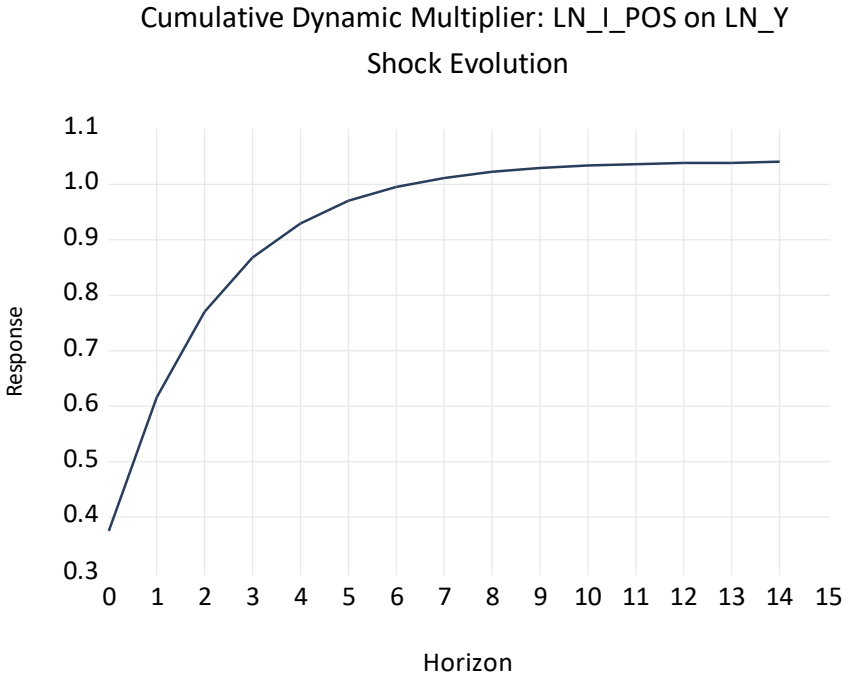

Figure 3. Dynamic Asymmetric Multipliers of the NARDL Model over a 15-Year Horizon (I)

In summary, the empirical estimation of the NARDL model provides robust, statistically significant evidence that the drivers of sustainable economic growth in North Macedonia are fundamentally asymmetric. The extraction of these dynamic multipliers successfully validates the existence of both structural capital resilience and a definitive 'Green Dividend,' empirically resolving the core development puzzle outlined in this study. Having established this econometric

foundation, the analysis now turns to synthesizing these mathematical findings into actionable macroeconomic policy implications. These recommendations are specifically tailored to help policymakers navigate the country's dual imperatives of European convergence and environmental modernization

CONCLUSION

This study investigated the asymmetric drivers of sustainable economic growth in North Macedonia, a transition economy navigating the dual imperatives of European macroeconomic convergence and the structural requirements of the "Green Agenda." By augmenting the traditional Cobb-Douglas production function with environmental sustainability metrics and employing a Non-linear Autoregressive Distributed Lag (NARDL) framework, this research empirically isolated the state-dependent responses of aggregate output to capital, labor, and environmental shocks.

The empirical findings challenge several symmetric assumptions prevalent in traditional neoclassical growth accounting. First, the decomposition of gross fixed capital formation confirmed that, while capital accumulation remains the primary engine of long-run economic expansion, exhibiting a highly elastic positive multiplier, the North Macedonian economy demonstrates profound structural resilience to investment contractions. Negative shocks to capital investment do not exert a statistically significant permanent drag on long-term GDP, suggesting the presence of alternative structural or informal buffers during periods of economic crisis.

Second, the analysis provides empirical evidence of a persistent "productivity trap" regarding human capital. The statistically insignificant and negative long-run coefficient for the labor force indicates that raw job creation acts as a structural deadweight when not accompanied by simultaneous upgrades to educational attainment and skill matching. The mere expansion of the labor headcount is insufficient to drive sustainable growth without genuine productivity enhancements and the successful integration of vulnerable demographics into high-value economic sectors.

Most crucially, this research suggests the presence of a "Green Dividend" in the Western Balkan context. The NARDL estimation strictly rejects the traditional industrial paradigm that escalating pollution is necessary for wealth generation. Instead, the model proves that permanent reductions in annual CO2 emissions actively and significantly stimulate long-term macroeconomic output. Consequently, transitioning toward sustainable development and decarbonization does not impose a "green penalty" on the developing economy, but rather serves as a robust catalyst for future prosperity.

Based on these empirical conclusions, several critical policy implications emerge for North Macedonian policymakers:

- **Reframe the "Green Agenda" as an Economic Catalyst:** Policymakers must pivot away from viewing EU environmental conditionalities and circular economy transitions as fiscal burdens. State aid and industrial subsidies should be aggressively redirected away from carbon-intensive industries toward green technologies, resource efficiency, and renewable energy infrastructure. The empirical data prove that targeted decarbonization is a highly lucrative macroeconomic strategy.
- **Shift from Quantitative to Qualitative Labor Policies:** The persistent reliance on attracting foreign direct investment (FDI) solely to reduce raw unemployment numbers is structurally flawed. Policy focus must shift toward mitigating the severe skills mismatch. This requires comprehensive active labor market policies, targeted reskilling programs for structurally vulnerable groups, and the urgent reform of educational outputs to align with the technological demands of a modernizing, green economy.

- **Optimize Capital Investments for Dual Returns:** While the economy is resilient to investment downturns, positive capital shocks still yield the highest growth elasticity. The government must ensure that public infrastructure projects and state-subsidized capital investments are strategically coupled with sustainable development goals, ensuring that physical capital deepening simultaneously accelerates environmental modernization.

Ultimately, this study proves that for North Macedonia, the pathways to economic wealth and ecological sustainability are no longer mutually exclusive. The active decoupling of economic growth from environmental degradation is not only statistically valid but stands as the most mathematically sound blueprint for long-term national resilience and convergence with European living standards.

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ANNEX 1: CALCULATION OF CAPITAL STOCK

To calculate the capital stock first it is necessary to obtain the data about the gross investment. After that the most critical step is to calculate the initial capital stock (K_0). Because the stock of physical capital in any given year is a vast accumulation of past investments minus depreciation, establishing an accurate baseline for the year 2000 ensures the rest of 2000–2024 series. The standard macroeconomic approach for estimating this baseline is the steady-state formula:

$$K_0 = \frac{I_0}{g + \delta}$$

Where:

- K_0 Initial capital stock (for the year 2000);
- $I_0 -$ Initial investment (Gross Fixed Capital Formation in 2000). To calculate the average investment of the first year, according to empirical literature often it is used the average investment of the first 3 to 5 years. In our calculations it is used the average growth rate from 2000 to 2010.
- g - Average annual growth rate of investment (or real GDP) over the period.
- δ - Depreciation rate. A standard assumption in the literature for transition economies is typically 5% (0.05).

The capital stock for the all analyzed period is calculated using the Perpetual Inventory Method (PIM)with the formula $K_t = I_t$+(1-δ) $K_{(t-1)}$

- K_t - Initial capital stock (for the year 2000);
- I_t - Gross fixed capital formation (investment) in the current year
- δ - Depreciation rate
- $K_{(t-1)}$- Capital stock from the previous year.