



Green shifts in foreign capital: asymmetric effects of FDI and income on CO₂ emissions in Bulgaria

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ABSTRACT

This study examines the asymmetric environmental effects of foreign direct investment (FDI) and income growth in Bulgaria, linking the analysis to broader globalization debates on the ecological consequences of cross-border capital flows. Using quarterly data from 2014Q1 to 2024Q2 and a nonlinear autoregressive distributed lag (NARDL) model, we assess how sector-specific FDI in manufacturing and construction affects per capita CO₂ emissions. By decomposing FDI and GDP per capita into positive and negative shocks, we test whether globalization-driven inflows and income expansions support low-carbon development. The results indicate a long-run “pollution halo” effect, with rising FDI and income reducing emissions, while contractions in income elevate them. In contrast, short-run dynamics point to temporary “pollution haven” patterns. These findings underscore the dual role of globalization: cross-border investment can initially intensify environmental pressures but, under robust regulatory frameworks, fosters technological upgrading and green transitions. The study contributes to globalization research by offering asymmetric, sector-specific evidence from an emerging industrial EU economy with a peripheral role in global value chains.

Introduction

Climate change has become one of the defining global challenges of the twenty-first century, compelling governments and societies to reassess the balance between economic growth and environmental sustainability. Greenhouse gas emissions remain closely tied to industrial activity, energy consumption, and international economic integration. While advanced economies have made progress in decoupling growth from emissions, many emerging and transition economies continue to struggle with the trade-off between sustaining growth and meeting climate targets (Nguyen et al., 2025).

Foreign direct investment (FDI) lies at the centre of this dilemma. As one of the principal vectors of globalization, FDI connects national economies to global value chains, transferring capital, technologies, and management practices across borders. On the one hand, these flows can accelerate modernization and improve environmental performance. On the other, they may lock host economies into carbon-intensive trajectories if investment concentrates in polluting sectors or if regulatory institutions are weak (Pham et al., 2025). These competing dynamics underpin the long-standing debate between the “pollution haven” and “pollution halo” hypotheses, which reflect the broader question of

whether globalization worsens or alleviates ecological pressures.

Bulgaria provides a salient case for testing these competing globalization hypotheses. Despite achieving substantial reductions in per-capita emissions since 1990, the country remains the most carbon-intensive economy in the European Union, heavily reliant on lignite coal and energy-intensive industries (European Parliament, 2024). At the same time, Bulgaria is deeply embedded in cross-border capital flows, with FDI inflows shaping the structure of its industrial and construction sectors. This combination of high emissions intensity, EU membership, and exposure to globalization makes Bulgaria an instructive laboratory for studying the asymmetric environmental effects of foreign capital. As the EU’s most carbon-intensive member, Bulgaria’s experience also illustrates challenges faced by other integrated but institutionally weaker economies, making it a useful lens on globalization’s uneven sustainability outcomes.

Against this institutional and economic background, Bulgaria’s decarbonisation pathway is strongly shaped by EU-level climate regulation and national implementation capacity. Bulgaria’s industrial development has long been shaped by emissions-intensive sectors such as metallurgy, petrochemicals, and power generation. Following EU accession, the country has undertaken significant reforms to modernize

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its energy and manufacturing base, yet coal dependence and legacy infrastructure remain major constraints (Ministry of Environment and Water of Bulgaria, 2024). The country's Climate Change Mitigation Act mandates that a significant portion of EU ETS auction revenues be reinvested in carbon abatement projects, such as forest sequestration and geological carbon capture and storage (CCS). However, Bulgaria has not ratified the London Protocol amendment that would allow cross-border CO₂ transport for offshore storage, potentially limiting its CCS options (Carbon Gap, 2025). Bulgaria's central policy document, the Integrated National Energy and Climate Plan (INECP), was updated in 2024 to align with the European Green Deal, the "Fit for 55" package, and Repower EU (Ministry of Energy & Ministry of Environment and Water of Bulgaria, 2024). The plan sets national targets for 2030 across five key areas: decarbonization, energy efficiency, energy security, market integration, and innovation. It commits to a complete coal phase-out by 2038 and net-zero emissions by 2050. These goals are backed by additional instruments. The Energy Efficiency Act mandates energy audits, building energy performance certification, and financial support mechanisms for energy-saving investments across the manufacturing and construction sectors (Climate Change Laws of the World, 2008). In parallel, Bulgaria's National Recovery and Resilience Plan (NRRP) channels EU post-pandemic funds into energy system upgrades, green mobility, and industrial modernization (Ministry of Energy & Ministry of Environment and Water, 2024). The INECP also emphasizes advanced emissions control technologies—including systems that can capture over 90% of harmful gases and particulates—for deployment in key polluting sectors such as metallurgy, energy, and cement production (Ministry of Energy & Ministry of Environment and Water of Bulgaria, 2024).

Despite these policy advances, enforcement capacity and institutional coherence remain variable. While Bulgaria has formally adopted EU climate legislation, implementation across sectors is uneven. The effectiveness of these frameworks in guiding foreign investment toward low-emission outcomes will depend on continued improvements in regulatory enforcement, investment screening mechanisms, and cross-ministerial coordination.

Evidence from other emerging economies underscores that the Bulgarian case is not unique but part of a wider globalization pattern. In the BRICS, for instance, FDI has been found to initially increase emissions before reducing them through efficiency gains (Tripathy et al., 2023). Similarly, studies of Türkiye and Romania reveal a coexistence of haven and halo effects (Tütüncü & Sirkıntoğlu, 2025). Similar evidence has been reported across Central and Eastern Europe, where globalization has reshaped the FDI–emissions nexus after EU accession, with integration into European value chains associated with declining emissions in some contexts (Balsalobre-Lorente et al., 2023). These comparative findings suggest that globalization's environmental impact is neither linear nor uniform but contingent on sectoral composition, institutional quality, and policy frameworks.

For Bulgaria, this contingency is especially important. Deeper integration into global markets can amplify environmental pressures unless accompanied by strong domestic safeguards. As Karimli et al. (2024) demonstrate for European countries more broadly, globalization's ecological footprint depends critically on the interplay of international flows and national-level governance. Understanding this interaction is therefore central to assessing Bulgaria's low-carbon transition within the wider context of globalization.

Moreover, the asymmetric dynamics we explore resonate with globalization's vulnerabilities to shocks. Economic downturns in integrated economies often trigger increases in emissions, as seen during the COVID-19 pandemic and earlier financial crises. This underlines that globalization's environmental impact cannot be understood solely at the national level but reflects how cross-border capital flows and global shocks interact with domestic institutions.

This study addresses these gaps by examining the asymmetric effects of sectoral FDI and income on CO₂ emissions in Bulgaria. By distinguishing between manufacturing and construction FDI inflows and

applying a nonlinear autoregressive distributed lag (NARDL) framework to quarterly data, we provide new evidence on both short-run pressures and long-run adjustments. The findings are relevant not only for Bulgaria's domestic policy choices but also for globalization debates, as they shed light on how foreign investment can either reinforce carbon-intensive development paths or support low-carbon transitions in emerging economies embedded in global value chains.

The remainder of the paper is organised as follows. Section 2 reviews the literature on FDI, growth, and environmental outcomes, with particular emphasis on CEE. Section 3 presents the data and methodology. Section 4 reports the empirical results, and Section 5 discusses their implications for Bulgaria's energy transition and EU climate policy. Section 6 concludes with key findings.

Literature review and policy context

Understanding how FDI and income growth influence carbon emissions requires an integrated view of both the empirical literature and the evolving institutional environment in which these processes unfold. The environmental effects of FDI are shaped not only by sectoral composition and technological content but also by national regulatory frameworks, enforcement capacity, and alignment with supranational climate goals. This section first reviews key empirical findings on the FDI–emissions nexus globally, across emerging markets, and in Central and Eastern Europe (Section 2.1), before turning to the legal and policy context governing climate-related investment in the European Union (Section 2.2).

Empirical evidence on FDI and environmental outcomes

Global and emerging economy evidence

Research on the environmental consequences of FDI has yielded mixed findings across global and emerging markets. Theoretically, FDI can influence emissions through three primary mechanisms: scale effects (increased production and energy use), composition effects (reallocation across sectors with different carbon intensities), and technique effects (transfer of cleaner technologies and practices). The *Pollution Haven Hypothesis* (PHH) emphasises scale and composition, suggesting that multinational firms shift polluting activities to countries with weak environmental regulation. In contrast, the *Pollution Halo Hypothesis* focuses on technique effects, positing that FDI can improve environmental performance through technology spillovers and management upgrades.

Empirical studies confirm the critical role of regulatory institutions and governance quality. Ahmed and Le (2023), using panel cointegration and causality methods, show that in countries with strong governance, FDI reduces emissions, while in weaker environments it raises them. Tripathy et al. (2023), applying an ARDL framework to BRICS countries, find that FDI initially increases emissions but later contributes to reductions via efficiency gains. Wang et al. (2023) stress – through GMM estimation – that economic freedom and legal clarity are prerequisites for FDI to have positive environmental effects. These findings reinforce the conclusion that FDI's environmental impact is not uniform, but highly conditional on institutions, regulatory enforcement, and sectoral targeting.

Central and Eastern Europe and the case of Bulgaria

In the Central and Eastern European context, the environmental impact of FDI has shifted significantly since EU accession. Before integration, FDI often contributed to emissions growth through the relocation of pollution-intensive industries. However, post-accession alignment with EU environmental legislation has altered this dynamic. Balsalobre-Lorente et al. (2023), using dynamic panel estimations, show that CO₂ emissions linked to FDI declined across 11 CEE countries after EU standards were adopted. Campos-Romero et al. (2023) report similar findings from a difference-in-differences approach, showing improvements in countries integrated into European value chains. Butt (2024),

employing panel regression, emphasizes that while pollution haven effects persist in weaker institutional settings, EU-aligned reforms and renewable energy policies have mitigated damage in others.

Country-level differences remain pronounced. [Łacka et al. \(2024\)](#), with ARDL and causality tests, identify continuing haven effects in Slovakia and the Czech Republic, while Poland and Hungary show improvements linked to energy transition. These differences highlight the need for disaggregating FDI by sector and adopting methodologies suited to national contexts.

For Bulgaria, the empirical record is particularly contradictory. [Pavlović et al. \(2021\)](#), using Pearson correlation, polynomial regression, and multivariate linear regression for Balkan economies, find a persistent pollution haven pattern, with FDI linked to higher emissions in energy-intensive sectors. [Huseynli and Comoglu \(2025\)](#), applying Granger causality tests on Bulgarian data from 1998 to 2022, report no direct causal link between FDI and emissions, though they stress that the country remains one of the EU's most carbon-intensive economies. [Marques and Caetano \(2020\)](#), employing a panel ARDL approach across high- and middle-income countries, argue that FDI initially raised emissions but later supported reductions through efficiency gains and sectoral restructuring. [Kamacı et al. \(2021\)](#), working with VECM and cointegration methods, find no significant long-run causal link for Bulgaria, pointing instead to the mediating role of trade liberalization and market structure. Other studies underscore the influence of methodological choices: [Tütüncü and Sirkuntoğlu \(2025\)](#), using cointegration tests with structural breaks and FMOLS estimators, estimate that a 1% rise in FDI increased Bulgarian emissions by nearly 0.5%, while [Hatmanu, Cautisanu, and Iacobuta \(2021\)](#) apply an ARDL framework to Romania and Bulgaria, focusing on income and energy use. The latter confirm the value of ARDL-type models in post-socialist EU economies but do not examine the role of FDI or asymmetries, leaving important gaps for future research.

Governance and institutions also emerge as important explanatory factors. [Stoyanova Asenova et al. \(2024\)](#), drawing on governance indicators, show that regulatory quality and corruption control strongly shape environmental outcomes even when GDP–emissions correlations are weak. Renewable energy investment has likewise been found to mitigate emissions while supporting growth in Bulgaria ([Can & Korkmaz, 2019](#); [Fotourehchi, 2017](#)), both using ARDL bounds testing approaches.

A recurring limitation in much of this research is methodological. Most Bulgaria-focused studies rely on annual data and linear econometric models, which are less able to capture short-run fluctuations or the asymmetric effects of positive versus negative shocks. While ARDL-based studies (e.g., [Hatmanu et al., 2021](#)) demonstrate the value of flexible time-series approaches, they remain limited to aggregate determinants of emissions. By contrast, nonlinear ARDL specifications (NARDL) have proven effective in other emerging and transition economies, as they allow for disaggregating short- and long-run dynamics and identifying asymmetric responses of emissions to FDI and income changes ([Shin et al., 2014](#); [Tripathy et al., 2023](#)). Despite Bulgaria's high policy relevance, no prior study has combined quarterly data, sectoral FDI disaggregation, and an explicitly asymmetric specification.

This paper addresses these gaps by applying a quarterly NARDL framework to test whether the effects of FDI and income on CO₂ emissions differ by direction (positive or negative shocks), sector (manufacturing vs. construction), and time horizon (short vs. long run).

EU regulatory framework shaping the FDI – Environment nexus

The European Union has established one of the most comprehensive climate policy architectures in the world, with direct implications for investment and emissions dynamics across its member states. Central to this framework is the EU Emissions Trading System (EU ETS), in operation since 2005, which covers approximately 40% of the EU's total greenhouse gas (GHG) emissions. The system imposes a price on carbon

emissions from sectors such as electricity generation, heavy industry, and aviation—and since 2024, maritime transport ([European Commission, n.d.-a](#)). The ETS operates across all EU countries and several associated economies, with emissions caps tightening over time to incentivize decarbonization.

The European Climate Law, adopted in 2021, enshrines the EU's target of climate neutrality by 2050 and mandates a minimum 55% reduction in net GHG emissions by 2030 compared to 1990 levels ([European Commission, n.d.-b](#)). These targets underpin the broader European Green Deal, which aims to transform the EU's energy, transport, agriculture, and industrial systems through regulatory reforms and financial instruments ([European Council, 2025](#)).

Complementing these efforts, the Industrial Emissions Directive (IED) governs pollution control in more than 50,000 industrial installations across the EU. A revised version—IED 2.0, adopted in 2024—expands the directive's coverage and strengthens environmental performance standards, particularly in carbon-intensive sectors such as cement, lime, and chemical production ([EEB, 2024](#); [European Commission, n.d.-c](#)). While the construction sector is not directly regulated, the IED covers upstream material producers vital to construction activity. Member States, including Bulgaria, must transpose the directive into national legislation by July 2026.

Support for sustainable capital allocation is further reinforced by EU Regulation 2020/852 (the Taxonomy Regulation), which defines criteria for assessing the environmental sustainability of economic activities ([Green Finance Platform, 2021](#)). The regulation guides private investment toward low-carbon technologies and requires large companies and financial institutions to disclose how their operations align with EU climate and environmental priorities.

Together, these instruments create a regulatory environment that discourages high-emissions activity and incentivizes climate-aligned investment—especially in industries subject to ETS and IED regulation. They also create strong incentives for member states to attract foreign investment into clean technologies, green infrastructure, and low-emission production processes.

To synthesize the diverse empirical evidence, [Table 1](#) summarizes selected studies on the FDI–CO₂ emissions nexus, highlighting differences in regional scope, data characteristics, econometric methods.

Methodology

This section presents the dataset, and model used to test the asymmetric effects of FDI and income on CO₂ emissions in Bulgaria. The analysis is based on the nonlinear autoregressive distributed lag (NARDL) framework ([Shin et al. 2014](#)), suitable for series with mixed orders of integration.

Data

This study investigates the asymmetric environmental effects of FDI and income in Bulgaria, using quarterly data from 2014Q1 to 2024Q2. [Table 2](#) presents the data, their description, unit of measure, and the source. Graphs of variables and correlation matrix are in Appendix (A1).

The selection of manufacturing and construction as sectoral FDI variables reflects both theoretical considerations and the structural characteristics of the Bulgarian economy. Manufacturing FDI is closely integrated into global value chains and is typically associated with technology transfer, productivity upgrading, and exposure to international environmental standards. At the same time, manufacturing activities are energy-intensive, making this sector a key channel through which foreign investment can influence carbon emissions via scale, composition, and technique effects. These features render manufacturing FDI particularly suitable for testing asymmetric environmental responses within the Pollution Haven and Pollution Halo frameworks ([Bagchi and Sahu, 2025](#)).

By contrast, FDI in the construction sector follows a different

economic logic. Construction investment is largely driven by domestic demand conditions, real estate cycles, and EU-funded infrastructure and renovation programs rather than export-oriented production. In Bulgaria, construction-related FDI has increasingly been linked to energy-efficiency improvements, building renovation, and compliance with EU environmental and energy-performance standards. Distinguishing between manufacturing and construction FDI therefore allows the analysis to capture heterogeneous and potentially asymmetric transmission mechanisms through which foreign capital affects environmental outcomes Amir et al. (2025).

The dependent variable is carbon dioxide (CO₂) emissions per capita, the explanatory variables are the net FDI inflows into the manufacturing and construction sectors, and the GDP per capita. Descriptive statistics are provided in Table 3. CO₂ emissions exhibit moderate variation, with a mean of 2.08 tonnes per capita. FDI inflows in both sectors show higher dispersion, reflecting the irregular movements of capital in sectors under review. The income per capita achieved its minimum of 1570 EUR in the initial quarter of observation (2014Q1) while the maximum of 3120 was captured in 2023Q4.

Although the NARDL framework allows using variables irrespective of whether they are I(0), I(1) or mutually cointegrated, the structure does not work with I(2) variables. Therefore, we tested our variables CO₂, FDI in manufacturing, FDI in Construction, and GDP per capita (CON, MAN, CON, and GDPPC) for stationarity using the Augmented Dickey–Fuller (ADF) test introduced by Dickey and Fuller (1979) and Phillips–Perron (PP) test by Phillips and Perron (1988). Both the ADF and PP tests test the null hypothesis that a unit root is present.

Table 1
Summary of prior empirical findings on FDI and CO₂ emissions.

Authors (Year)	Region/country	Data	Methodology	Main findings
Balsalobre-Lorente et al. (2023)	CEE	Panel data (period not specified)	Panel cointegration (FMOLS, DOLS) and quantile regression (EKC framework)	Globalization is associated with higher CO ₂ emissions; economic complexity and renewable energy mitigate this effect; evidence consistent with pollution haven dynamics at early stages.
Campos-Romero et al. (2023)	EU (EU28)	Country –sector panel 1995–2015	MRIO input–output and mixed multilevel model	Inverted U-shaped relationship between FDI and emissions intensity, with pollution haven dynamics more visible in Eastern EU economies and weakening over time.
Hatmanu, Cautisanu & Iacobuta (2021)	Romania and Bulgaria	Annual time series 1980–2019	ARDL bounds testing within EKC specifications and VEC Granger causality	The study focuses on EKC determinants (GDP, energy, urbanization) rather than FDI; it reports long-run relationships in both countries, with an inverted U-shaped EKC in both and an inverted N-shaped EKC additionally in Bulgaria.
Łącka et al. (2024)	Visegrad Group	Annual time series 1991–2021; Czech and Slovakia 1993 – 2021	ARDL bounds testing with ECM and Toda–Yamamoto causality; robustness via panel fixed effects and local projections	FDI is not significant in long-run CO ₂ equations for any country; causality from FDI to CO ₂ is found only for the Czech Republic and Slovakia, indicating a limited and context-dependent link rather than a systematic haven or halo pattern.
Marques & Caetano (2020)	High- and middle-income countries (21 countries)	Panel data annual 2001–2017	Panel ARDL with ECM; fixed effects with Driscoll–Kraay standard errors; short- and long-run analysis; robustness via industry-level CO ₂	The effect of FDI differs by income group: it is associated with lower emissions in high-income countries, while in middle-income countries it increases emissions in the short run but contributes to emission reductions in the long run.
Pavlović et al. (2021)	Balkans (10 countries)	Panel data annual 1998–2019	Correlation analysis, polynomial regression (EKC), and multivariate linear regression	Positive and statistically significant FDI–CO ₂ correlation is reported for Serbia, Albania, Croatia, Romania, Bulgaria, and for the Balkans aggregate; a negative and significant relationship is reported only for Montenegro.
Tripathy et al. (2023)	India	Annual time series 1980–2014	Johansen cointegration, Granger causality, and SUR with mediation analysis	The study finds long-run cointegration and unidirectional causality from FDI to CO ₂ ; the direct FDI effect is positive, while indirect effects through mediating channels vary, so the overall impact depends on the composition of FDI.
Tütüncü & Sirkıntoğlu (2025)	Türkiye, Bulgaria, Romania	Annual time series 1991–2019	Cointegration test with structural change and FMOLS	FDI has a positive and significant effect on pollution in Bulgaria and Romania, while no statistically significant effect is found for Türkiye.
Wang et al. (2023)	67 countries	Panel data 1990–2019	Panel FMOLS and panel threshold regression	The FDI – CO ₂ relationship is nonlinear and depends on income level, with a positive effect at low income, an insignificant effect at middle income, and a negative effect at high income.

Note: The table provides a concise synthesis of selected studies; findings are simplified to ensure comparability.

Model

Following Shin et al. (2014) the long-run regression of the CO₂, MAN, CON, and GDP per capita is the following:

$$CO_{2t} = \beta_1^+ MAN_t^+ + \beta_1^- MAN_t^- + \beta_2^+ GDPPC_t^+ + \beta_2^- GDPPC_t^- + \tau CON_t + \varepsilon_t, \tag{1}$$

Where β^+, β^- , are the associated asymmetric long-run parameters, τ is a long-run parameter and MAN_t and $GDPPC_t$ are $k \times 1$ vectors of regressors decomposed as:

$$MAN_t = MAN_0 + MAN_t^+ + MAN_t^- \tag{2}$$

Where MAN_t^+ and MAN_t^- are partial sum processes of positive and negative changes in MAN_t :

$$MAN_t^+ = \sum_{j=1}^t \Delta MAN_j^+ = \sum_{j=1}^t \max(\Delta MAN_j, 0), \tag{3}$$

$$MAN_t^- = \sum_{j=1}^t \Delta MAN_j^- = \sum_{j=1}^t \min(\Delta MAN_j, 0), \tag{4}$$

$$GDPPC_t = GDPPC_0 + GDPPC_t^+ + GDPPC_t^- \tag{5}$$

where $GDPPC_t^+$ and $GDPPC_t^-$ are partial sum processes of positive and negative changes in $GDPPC_t$:

$$GDPPC_t^+ = \sum_{j=1}^t \Delta GDPPC_j^+ = \sum_{j=1}^t \max(\Delta GDPPC_j, 0), \tag{6}$$

Table 2
Variable definitions.

Variable	Description	Unit of Measure	Source
CO ₂	Greenhouse-gas emissions (CO ₂ , CH ₄ , N ₂ O, HFC, PFC, SF ₆ , NF ₃ in CO ₂ -eq.)	Tonnes per capita	Eurostat
Manufacturing (MAN)	Net inward FDI in the manufacturing sector	Million EUR	CEIC
Construction (CON)	Net inward FDI in the construction sector	Million EUR	CEIC
GDP per capita (GDPPC)	GDP per capita (chain-linked volume, 2020)	EUR per capita	Eurostat

$$GDPPC_t^- = \sum_{j=1}^t \Delta GDPPC_j^- = \sum_{j=1}^t \min(\Delta GDPPC_j, 0), \tag{7}$$

Extending Eq. (1) into nonlinear ARDL model (p,q) following Shin et al. (2014) the NARDL form is the following:

$$CO_{2t} = \sum_{j=1}^p \varphi_j CO_{2t-j} + \sum_{j=0}^q \left(\omega_{1j}^+ MAN_{t-j}^+ + \omega_{1j}^- MAN_{t-j}^- \right) + \sum_{j=0}^q \left(\omega_{2j}^+ GDPPC_{t-j}^+ + \omega_{2j}^- GDPPC_{t-j}^- \right) + \sum_{j=0}^q \zeta_j CON_{t-j} + \varepsilon_t \tag{8}$$

where φ is the autoregressive parameter, ω_j^+ , ω_j^- , are the asymmetric distributed-lagged parameters, ζ_j is a long run parameter and ε_t is an iid process with zero mean and constant variance, σ_ε^2 .

The error correction form of our NARDL model is presented by Eq. (9).

$$\begin{aligned} \Delta CO_{2t} = & \rho CO_{2t-1} + \theta_1^+ MAN_{t-1}^+ + \theta_1^- MAN_{t-1}^- + \theta_2^+ GDPPC_{t-1}^+ \\ & + \theta_2^- GDPPC_{t-1}^- + \nu CON_{t-1} + \sum_{i=1}^{p-1} \gamma_i \Delta CO_{2t-i} + \sum_{i=0}^{q-1} (\pi_{1i}^+ \Delta MAN_{t-i}^+ \\ & + \pi_{1i}^- \Delta MAN_{t-i}^-) + \sum_{i=0}^{q-1} (\pi_{2i}^+ \Delta GDPPC_{t-i}^+ \\ & + \pi_{2i}^- \Delta GDPPC_{t-i}^-) + \sum_{i=0}^{q-1} \eta_i CON_{t-j} + \varepsilon_t \end{aligned} \tag{9}$$

where Δ is the difference operator, CO_{2t} is the carbon dioxide (dependent variable), MAN_t^+ and MAN_t^- are partial sum processes of positive and negative changes in MAN_t ; $GDPPC_t^+$ and $GDPPC_t^-$ are partial sum processes of positive and negative changes in $GDPPC_t$; CON_t stands for FDI into construction; ρ , θ^+ , θ^- , and ν , are the long-run coefficients, γ , π^+ , π^- , and η are the short-run coefficients. $\beta^+ = -\theta^+/\rho$ and $\beta^- = -\theta^-/\rho$, are the asymmetric long-run parameters (see Eq. (1)).

To investigate whether a long-run equilibrium exists among the variables (CO_2 , MAN^+ , MAN^- , GDP^+ , GDP^- , and CON), the Wald F

Table 3
Descriptive statistics.

	CO ₂	FDI Construction	FDI Manufacturing	GDP per capita
Mean	2.0834	21.0310	78.1810	2343.5710
Median	2.0895	4.8000	75.5500	2310.0000
Maximum	2.5590	117.7000	860.8000	3120.0000
Minimum	1.4770	-52.3000	-454.4000	1570.0000
Std. Dev.	0.2529	36.2590	216.6380	386.0925
Skewness	-0.3336	0.8312	0.7501	0.1204
Kurtosis	2.6918	3.2758	6.3502	2.5219
Jarque-Bera	0.9453	4.9697	23.5810	0.5015
Probability	0.6234	0.0833	0.0000	0.7782
Observations	42	42	42	42

statistic was applied. The null hypothesis of no cointegration in Eq. (9) was tested against the alternative hypothesis indicating the presence of cointegration. $H_0: \rho = \theta_1^+ = \theta_1^- = \theta_2^+ = \theta_2^- = \nu = 0$, $H_1: \rho \neq \theta_1^+ \neq \theta_1^- \neq \theta_2^+ \neq \theta_2^- \neq \nu \neq 0$. Pesaran et al. (2001) proposed bounds testing framework to inspect the level relationship between variables. „If the computed Wald or F-statistic falls outside the critical value bounds, a conclusive inference can be drawn without needing to know the integration/cointegration status of the underlying regressors. However, if the Wald or F-statistic falls inside these bounds, inference is inconclusive and knowledge of the order of the integration of the underlying variables is required before conclusive inferences can be made.” (Pesaran et al. 2001p. 290).

The model was tested for normality, autocorrelation, homoskedasticity, and functional form. We used a standard normality test, the Jarque Bera (JB) test (Jarque and Bera, 1980) with the null hypothesis: H_0 : the residuals are normally distributed. Since the autocorrelation is a phenomenon that can only occur in models for time-series data (Vogelvang 2005), the test developed by Breusch (1979) and Godfrey (1978) was applied to test the null hypothesis: H_0 : no residual autocorrelation. The heteroskedastic disturbances were tested by Breusch-Pagan test (Breusch and Pagan 1979) with the null hypothesis: H_0 : homoskedasticity. The functional form of the model was evaluated using the Ramsey RESET test (Ramsey 1969).

Results and discussion

Lag selection is based on the Schwarz Information Criterion, resulting in an ARDL (2,0,4,4,4,4) specification. Tables 4 and 5 deploys the results from the unit root testing of CO₂, FDI into manufacturing (MAN), FDI into construction (CON), and GDP per capita using ADF and PP tests. The ADF test shows that variables CO₂, MAN, and CON are stationary in level, however, GDP per capita becomes stationary after first differencing, it is integrated of the first order I(1). Surprisingly, the ADF test identifies CO₂ as non-stationary with constant and trend when differenced, which is an unusual result. The PP test, however, identifies the CO₂ as non-stationary in levels, but stationary after differencing, which is common for time series.

The conclusion regarding unit root testing is based on the results of the Phillips-Perron (PP) test, which indicates that the dependent variable is non-stationary in levels but becomes stationary after first differencing. Therefore, it is integrated of order one, I (1).

These results satisfy the combination of I(0) and I(1) for the NARDL model and justify the relevance for cointegration and asymmetric procedures. Table 6 presents the outcomes from the NARDL model.

L_{MAN} and L_{GDPPC} denote the long-run coefficients associated with FDI manufacturing (MAN) and GDP per capita (GDPPC) changes calculated as follows: L_{MAN}^+ ($\beta_1^+ = -\theta_1^+/\rho$) and L_{MAN}^- ($\beta_1^- = -\theta_1^-/\rho$) denote the long run coefficients associated with positive and negative changes of Net inward FDI in the manufacturing sector. L_{GDPPC}^+ ($\beta_2^+ = -\theta_2^+/\rho$) and L_{GDPPC}^- ($\beta_2^- = -\theta_2^-/\rho$) denote the long run coefficients associated with positive and negative changes of GDP per capita. L_{CON} denotes the long run coefficient associated with the Net inward FDI in the construction sector. L_{CON} is calculated as $\tau = -\nu/\rho$. $Wald_{LR}$ refers to the Wald test (F-statistics) for the null of long run symmetry in MAN and GDPPC in following way: ($L_{MAN}^+ = L_{MAN}^-$) and ($L_{GDPPC}^+ = L_{GDPPC}^-$) and $Wald_{SR}$ refers to the Wald test for the null of the additive short run symmetry defined as $\sum_{i=0}^q \pi_{1i}^+ = \sum_{i=0}^q \pi_{1i}^-$ and $\sum_{i=0}^q \pi_{2i}^+ = \sum_{i=0}^q \pi_{2i}^-$. F_{PSS} tests the null hypothesis in (9): $\rho = \theta_1^+ = \theta_1^- = \theta_2^+ = \theta_2^- = \nu = 0$. The critical value for the F-statistic in the case of unrestricted intercept without trend is 6.69 for $k = 5$ (without dependent variable). χ_{SC}^2 , and χ_{HET}^2 is the Breusch-Godfrey Serial Correlation LM test, and Heteroskedasticity test Breusch-Pagan-Godfrey.

The bounds test confirms the presence of a long-run relationship, with the computed F-statistic (6.69) exceeding the upper critical value at the 1%, 5%, and 10% level (4.68, 3.79, 3.35). The results indicate the

presence of asymmetric effects of FDI in manufacturing on CO₂ emissions, as well as a non-linear relationship between GDP per capita and CO₂ emissions. The emissions are responding differently to negative and positive changes in FDI into manufacturing and GDP per capita both in the long and short run. This is supported by the Wald test statistics. (Wald_{LR MAN} = 13.489, p-value < 0.01; Wald_{LR GDPPC} = 18.416, p-value < 0.01; Wald_{SR MAN} = 3.358, p-value < 0.10; Wald_{SR GDPPC} = 21.624, p-value < 0.01).

Positive changes in FDI in manufacturing (MAN⁺) are associated with a statistically significant reduction in CO₂ emissions. An increase by one-billion-euro in net FDI inflows into manufacturing is associated with a reduction of nearly half a tonne of CO₂ emissions per person. The MAN⁺ coefficient is significant at 10% level. This finding supports the Pollution Halo Hypothesis, indicating that such inflows may include cleaner technologies and foster modernization in the manufacturing sector. Conversely, negative changes in manufacturing FDI (MAN⁻) are not statistically significant (p-value = 0.912). The result suggests that declines in net FDI inflows do not have a significant long-run effect on the environment.

Regarding income, both positive and negative changes in GDP per capita exhibit statistically significant effects in the long run. GDPPC⁺ is negatively associated with CO₂ emissions, indicating a long-run divergence between income and environmental deterioration. This finding may reflect structural economic shifts, such as a transition from high-polluting industries to service-oriented sectors, with the information technology sector playing a leading role, as well as increased investment in environmentally friendly technologies. The negative sign of GDPPC⁻ indicates that decrease in income is associated with increased CO₂ emissions in the long run. A contraction in GDP per capita may lead to greater dependence on less efficient domestic production processes, mainly in the absence of green capital inflows from abroad. During economic downturns, environmental standards may also be relaxed and as such can contribute to higher emissions. The results indicate that negative changes in income have a greater impact on pollution than positive changes. This implies that policymakers should account for potential environmental externalities which arise during economic downturns (contractions may significantly increase CO₂ emissions in the long run). The long-run coefficient for CON (net inward FDI in the construction sector) is negative (-0.007645) and statistically significant at the 5% level (p-value < 0.05). This result suggests that a one-billion-euro increase (or decrease) in net FDI inflows into construction is associated with approximately a 7-tonne per capita decrease (or increase) in CO₂ emissions.

While GDP per capita and FDI in manufacturing were decomposed into positive and negative changes to capture potential asymmetries in their environmental impacts, FDI in the construction sector was included as a single net variable. This decision reflects both empirical and theoretical considerations. Construction FDI during the sample period exhibits volatile but irregular movements, without consistent patterns of positive and negative shocks that would warrant asymmetric decomposition. Moreover, construction FDI is primarily shaped by domestic demand cycles, real estate activity, and EU-funded infrastructure projects, making it less exposed to the international investment cycles that generate asymmetric effects. In contrast, manufacturing FDI is

structurally more sensitive to global shocks and technological transfers, which justifies explicit treatment of asymmetries.

In the short run, the results show that the contemporaneous effect of FDI⁺ in manufacturing is not statistically significant. However, the influence becomes evident in the lagged terms, with a positive and statistically significant effect in the second quarter (significant at the 10% level) and an even stronger positive effect in the third quarter (significant at the 5% level). Negative changes in FDI in manufacturing do not exhibit statistical significance. These findings imply that increases in net FDI inflows into the manufacturing sector are associated with higher emissions in the short run, supporting the Pollution Haven Hypothesis. These results can be explained in the following way: during the initial stages of investment when operations begin and production increases, the impact on environment may be intensified. However, in the long run, once the investments are fully implemented and possibly upgraded with cleaner technologies, their environmental effects seem to be diminishing. Yet, in the long run, the environmental impact appears to reverse. The long-run coefficient for positive changes in FDI in manufacturing (LMAN⁺ = -0.000511; p-value = 0.065) is negative and statistically significant. This contrast between short- and long-run effects highlights how essential it is to assess the implications of foreign investment dynamics on environment conditions.

The short-run results point to asymmetric and dynamic responses of CO₂ emissions to changes in GDP per capita. For positive changes (ΔGDPPC⁺), the coefficients are all positive and highly significant. The strongest effects occur at one- and two-quarter lags, indicating that emissions respond to economic growth relatively quickly, peaking after a short delay, and gradually diminishing thereafter. In contrast, negative changes (ΔGDPPC⁻) show a more diverse pattern. The contemporaneous effect is negative and significant, indicating that emissions initially increase when income falls. However, the first lag is positive and significant, showing a fall in emissions with one quarter delay. Subsequent lags are not significant. Overall, these results point to a nonlinear and asymmetric relationship, with economic expansions having a strong impact on increasing emissions, while economic contractions show weaker and more unstable effects.

The short-run effect of FDI into the construction sector (CON) is positive and statistically significant at the 10% level in the first lag. The contemporaneous effect and other lags (up to the third) are not statistically significant.

To capture the short-run effects of the COVID-19 pandemic, we used a dummy variable that equals 1 for 2020Q1 and 2020Q2, and 0 otherwise. The coefficient of the dummy variable is positive and statistically significant at the 10% level. This result shows that emissions were increasing during the initial phase of the COVID-19 pandemic (during the first two quarters of 2020). A possible explanation is the jump in the use and disposal of medical supplies and pharmaceuticals, as well as the application of various practices in the waste management that may have been environmentally harmful.

The model passes all diagnostic tests, confirming its robustness and correct specification. There is no evidence of serial correlation (Breusch–Godfrey LM test, p > 0.115), heteroskedasticity (Breusch–Pagan–Godfrey test, p > 0.881), or functional misspecification (Ramsey RESET, p = 0.558). Residuals appear normally distributed

Table 4
Results from ADF test.

	ADF t-Statistic				ADF p-values			
	CO ₂	MAN	CON	GDP/pc	CO ₂	MAN	CON	GDP/pc
c	-4.199313	-6.028726	-5.181384	0.233069	0.0022	0.0000	0.0001	0.9708
ct	-4.015867	-6.275032	-5.417611	-3.477768	0.0179	0.0000	0.0004	0.0567
Δc	-3.194431	-7.802181	-11.30177	-4.323468	0.0300	0.0000	0.0000	0.0017
Δct	-3.200190	-7.764511	-11.17413	-4.270529	0.1029	0.0000	0.0000	0.0096

Note: c – constant; ct – constant and trend; Δ – first difference. Values in **bold** indicate stationarity at the 5% level. Lag length selection: automatic (based on Schwarz Information Criterion, max lag = 12). Results generated using EVIEWS 10.

Table 5
Results from PP test.

	PP t-Statistic				PP p-values			
	CO ₂	MAN	CON	GDP/pc	CO ₂	MAN	CON	GDP/pc
c	-2.761385	-6.028726	-5.240775	-4.468748	0.0728	0.0000	0.0001	0.0009
ct	-2.761108	-6.293855	-5.479068	-10.36037	0.2192	0.0000	0.0003	0.0000
Δc	-6.886259	-33.83375	-12.52173	-14.10562	0.0000	0.0001	0.0000	0.0000
Δct	-7.394653	-33.85101	-12.47995	-13.82563	0.0000	0.0000	0.0000	0.0000

Note: c – constant; ct – constant and trend; Δ – first difference. Values in bold indicate stationarity at the 5% level. Lag length selection: automatic (based on Schwarz Information Criterion, max lag = 12). Results generated using EVIEWS 10.

Table 6
Outcomes from the asymmetric (NARDL) model.

	ΔCO _{2t} NARDL
CO _{2t-1}	-0.527965***
MAN _{t-1} ⁺	-0.000270**
MAN _{t-1} ⁻	-1.32E-05
GDPPC _{t-1} ⁻	-0.003439***
GDPPC _{t-1} ⁺	-0.003032***
CON _{t-1}	-0.004036**
ΔCO _{2t-1}	0.344850*
ΔMAN _t ⁺	-3.34E-05
ΔMAN _{t-1} ⁺	0.000194
ΔMAN _{t-2} ⁺	0.000250*
ΔMAN _{t-3} ⁺	0.000251**
ΔMAN _t ⁻	0.000104
ΔGDPPC _t ⁻	-0.001057**
ΔGDPPC _{t-1} ⁻	0.001080*
ΔGDPPC _{t-2} ⁻	-0.000207
ΔGDPPC _{t-3} ⁻	-0.000491
ΔGDPPC _t ⁺	0.001368***
ΔGDPPC _{t-1} ⁺	0.003880***
ΔGDPPC _{t-2} ⁺	0.003739***
ΔGDPPC _{t-3} ⁺	0.002103***
ΔCON _t	-0.000625
ΔCON _{t-1}	0.002439*
ΔCON _{t-2}	0.001296
ΔCON _{t-3}	0.000737
Dum	0.141706*
Constant	0.726601*
L _{MAN} ⁺	-0.000511*
L _{MAN} ⁻	-2.49E-05
L _{GDPPC} ⁺	-0.005743**
L _{GDPPC} ⁻	-0.006513**
L _{CON}	-0.007645**
R ²	0.98
χ ² _{SC}	7.424 [0.115]
χ ² _{HET}	17.035 [0.881]
Jarque Bera Normality test	3.288 [0.193]
Ramsey Reset Test F statistics	0.368 [0.558]
Wald _{LR} MAN	13.489***
Wald _{LR} GDPPC	18.416***
Wald _{SR} MAN	3.358*
Wald _{SR} GDPPC	21.624***
F _{PSS}	6.69
CUSUM Test	Stable
CUSUM of SQUARES	Stable

(Jarque–Bera = 3.288, p = 0.193), and CUSUM and CUSUM-of-squares tests confirm parameter stability over time (see Appendix A2).

Fig. 1 presents the dynamic NARDL multiplier graph for MAN (Net inward FDI in the manufacturing sector), and GDPPC (GDP per capita).

The NARDL multiplier graph illustrates the asymmetric response of the dependent variable (CO₂ emissions) to positive and negative changes in MAN (FDI into manufacturing sector), and GDP per capita. The dynamic NARDL multiplier graph shows that emissions respond to positive shocks in a modest way, with the effect peaking around the 5th quarter, followed by a gradual decline between the 5th and 8th quarters. After that, the impact stabilizes but indicates a persistent influence of positive manufacturing FDI shocks on emissions. The NARDL multiplier graph

illustrating the asymmetric response of the dependent variable (CO₂ emissions) to positive and negative changes in GDP per capita shows the following: in the initial phase, there is quite a fast increase in emissions in response to negative GDP shocks, peaking around the 5th quarter. A sharp decline follows, and by approximately the 8th quarter, the responses to both positive and negative shocks become less asymmetrical. However, the effect of positive shocks remains dominant in the following quarters.

Before deriving policy implications from the empirical results, it is important to assess the robustness and stability of the estimated asymmetric relationships. The robustness of the estimated asymmetric relationships is assessed through a set of internal validation procedures inherent to the nonlinear ARDL framework. First, unit root tests indicate a combination of I(0) and I(1) variables, confirming the suitability of the NARDL approach (Pesaran et al., 2001; Shin et al., 2014). Second, both the F-bounds and t-bounds tests provide strong evidence of a stable long-run relationship among CO₂ emissions, sectoral FDI inflows, and income dynamics.

Third, Wald tests for long-run and short-run symmetry decisively reject the null hypothesis of linear adjustment, supporting the existence of asymmetric effects in both the short and the long run (Shin et al., 2014).

In addition, the adequacy of the model specification was assessed using a comprehensive set of diagnostic and stability tests. While complementary causality tests could provide further insights into the directionality of the relationships, panel-based approaches such as Dumitrescu–Hurlin causality are not applicable in a single-country time-series context, and time-series causality tests are less informative in short quarterly samples. Such analyses are therefore more appropriately applied in panel or multi-country frameworks with longer time horizons (Dumitrescu & Hurlin, 2012).

The model passes all diagnostic tests, confirming its robustness and correct specification. There is no evidence of serial correlation (Breusch–Godfrey LM test, p > 0.115), heteroskedasticity (Breusch–Pagan–Godfrey test, p > 0.881), or functional misspecification (Ramsey RESET, p = 0.558). Residuals appear normally distributed (Jarque–Bera = 3.288, p = 0.193), and CUSUM and CUSUM-of-squares tests confirm parameter stability over time (see Appendix A2).

With the robustness and stability of the estimates established, the discussion now turns to the interpretation of the identified short- and long-run effects within their institutional and theoretical context. The short-run effects can be interpreted as reflecting the central role of institutional quality and regulatory enforcement in shaping the environmental consequences of FDI. Consistent with CEECs and other emerging economies literature, stronger governance and stricter environmental oversight are associated with lower emissions or slower emission growth, whereas weaker institutional settings can yield upticks in emissions in the short run as polluting activities relocate and immediate efficiencies are not yet realized (Ahmed & Le, 2023; Tripathy et al., 2023; Wang et al., 2023). In the long run, the pollution halo effect, driven by technology transfer and managerial upgrading, appears more pronounced when firms integrate into clean-technology ecosystems and undertake sustained sectoral upgrading. Across Europe and transition economies, longer-run environmental improvements have been linked

to EU-aligned reforms, renewable-energy policies, and diffusion of cleaner production technologies (Balsalobre-Lorente et al., 2023; Campos-Romero et al., 2023; Butt, 2024). Our findings reveal a dual pathway: short-run emissions effects are governed by policy enforcement, while long-run outcomes depend on technological spillovers and institutional coherence (Stoyanova Asenova et al., 2024; Can & Korkmaz, 2019; Fotourehchi, 2017).

Policy implications for Bulgaria

Bulgaria’s policy environment has become increasingly aligned with EU climate objectives, as reflected in its commitments under the European Climate Law, the Industrial Emissions Directive, and the Integrated National Energy and Climate Plan (INECP). These frameworks, together with access to EU funding instruments, provide a solid foundation for steering foreign capital toward sustainable investment.

The results of this study suggest that Bulgaria should prioritize the quality – not merely the volume – of FDI, particularly in sectors with strong emissions-reduction potential such as advanced manufacturing, clean energy infrastructure, and low-carbon construction materials. This requires a shift in investment promotion policy from a horizontal, cost-based model to a targeted, strategic approach. Recent policy analyses emphasize that Bulgaria’s FDI strategy has remained overly passive, with limited institutional capacity for screening, prioritizing, or supporting green and high-value-added projects. As Zhelev and Kussainova (2024) argue, the country has failed to capitalize fully on its EU integration by allowing capital inflows to concentrate in low-productivity sectors, exacerbating regional disparities and missing opportunities for long-term technological upgrading.

To strengthen climate-compatible investment outcomes, Bulgaria should consider:

- Embedding environmental conditionality in investment screening and approval processes;
- Aligning FDI promotion with EU taxonomy standards and national decarbonization priorities;
- Enhancing the strategic capacity of the InvestBulgaria Agency and fostering coordination across ministries and municipalities;
- Expanding green finance mechanisms to de-risk capital flows into climate-aligned sectors.

Ultimately, ensuring that FDI reinforces Bulgaria’s low-carbon transition will depend on sustained institutional reforms, effective enforcement, and the ability to direct capital toward sectors that deliver both economic and environmental returns. The empirical model supporting these conclusions was validated through comprehensive diagnostic testing, confirming its stability and correct specification over the full sample.

Bulgaria’s shift toward a halo-dominated FDI-environment relationship holds lessons for neighbouring CEE countries that have not yet consolidated environmental gains. The results underline the importance of policy coordination, sectoral disaggregation, and asymmetry-aware modelling in diagnosing transition dynamics. They also highlight potential risks. Without continuous investment in institutional quality and industrial upgrading, the carbon benefits of FDI could erode, particularly under macroeconomic shocks or external energy price volatility.

Finally, as the EU tightens its climate regulations and border carbon adjustments take effect, countries like Bulgaria must avoid becoming a secondary pollution haven within the Single Market. Maintaining the observed gains requires that both domestic firms and foreign investors continue to decarbonize operations, supported by stable, forward-looking public policy.

Conclusion

This study examined the relationship between foreign direct investment, income growth, and CO₂ emissions in Bulgaria using a nonlinear autoregressive distributed lag framework and quarterly data from 2014Q1 to 2024Q2. By disaggregating FDI into manufacturing and construction sectors and decomposing income into positive and negative shocks, we identified important asymmetries in how cross-border capital flows and income dynamics influence environmental outcomes.

The results show that in the short run, rising FDI in manufacturing temporarily increases emissions, consistent with “pollution haven” dynamics during the early stages of investment. In the long run, however, both manufacturing and construction FDI reduce emissions, supporting the “pollution halo” hypothesis and suggesting that foreign investment, when embedded in EU regulatory frameworks, contributes to cleaner production and technological upgrading. Similarly, income growth is associated with declining emissions over time, while contractions in income increase them, highlighting the environmental risks that accompany economic downturns in integrated economies.

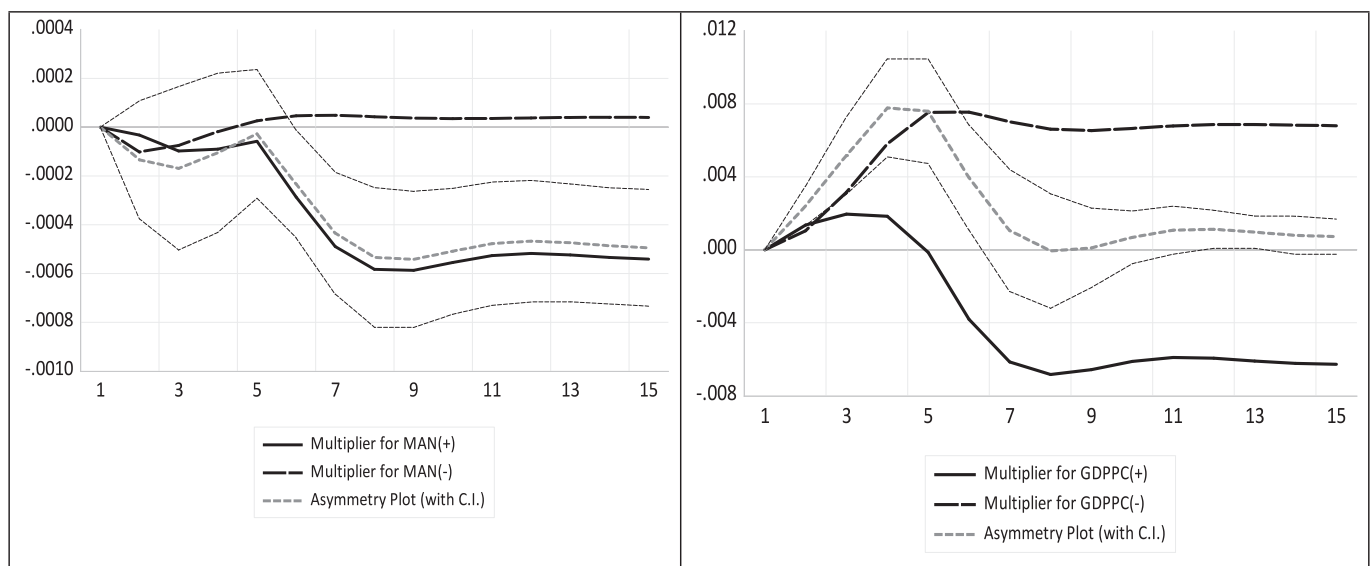


Fig. 1. NARDL multiplier graph.
Source: Author’s elaboration in EViews 10.

These findings extend beyond Bulgaria. Comparable evidence from BRICS, Türkiye, and Romania indicates that the environmental impact of FDI is not uniform but asymmetric, sector-specific, and contingent on institutional quality. Bulgaria's trajectory illustrates how economies at the periphery of global value chains face the challenge of managing the short-run ecological costs of openness while harnessing its long-run potential for green modernization. This highlights the uneven sustainability outcomes of globalization, where the benefits of cross-border investment depend critically on regulatory capacity and institutional strength.

For policymakers, the key implication is that globalization can be steered toward climate-compatible outcomes if foreign investment is directed into sustainable sectors and supported by robust institutional frameworks. For scholars, the Bulgarian case underscores the importance of asymmetric modelling and sectoral analysis in understanding how international capital flows reshape environmental trajectories in emerging industrial economies.

This study identifies several constraints that may influence the Bulgarian case and the external validity of FDI-emissions research. The time span (2014–2024) offers a relatively short window to observe long-run structural changes in environmental policy and macroeconomic conditions. Bulgaria's country-specific focus and lack of cross-country comparison limit the broader regional generalizability of our findings. Sector-level FDI data may mask heterogeneity at the firm or project level, affecting observed technology transfer and upgrading across investments. The absence of explicit environmental policy variables (e.g., carbon pricing, green subsidies, regulatory stringency) may mediate observed relationships between FDI, income, and emissions. The lack of cross-country analysis restricts inference about regional applicability.

Future work could extend to multi-country panels within the EU or transition economies, incorporate longer horizons, and utilize firm- or project-level data. Adding policy indicators and exploring additional environmental outcomes would enhance mechanistic understanding and inform policy design for harnessing globalization toward green transitions. Methodological enhancements, including alternative nonlinear specifications and additional robustness checks, would further strengthen causal inference in future research.

CRediT authorship contribution statement

Paskal Zhelev: Writing – review & editing, Writing – original draft, Supervision, Funding acquisition, Conceptualization. **Julia Kromkova:** Writing – review & editing, Visualization, Resources, Investigation, Data curation. **Sabina Lacusova:** Writing – review & editing, Visualization, Investigation, Data curation. **Renata Pitonakova:** Writing – review & editing, Writing – original draft, Validation, Software, Methodology, Formal analysis.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.resglo.2026.100353>.

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