7 DOES FINANCIAL POLICY ALIGNMENT ACCELERATE SUSTAINABLE TRANSPORT TRANSITIONS IN EUROPE?*

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Abstract

The current study examines the role of green finance (GFN) in reducing transport-related CO_2 emissions and improving transport performance across 25 European countries. The time period considered for this analysis spans from 2000 to 2022. The study utilized a two-way fixed-effects model and addressed potential endogeneity concerns through instrumental variable estimation. Robustness of the findings was further verified using CS-ARDL, PMG, and CCE estimators. By doing so, the current study establishes credible short-run and long-run effects. The results show that GFN significantly lowers transport CO_2 intensity (FE baseline elasticity = −0.081; IV/2SLS confirms robustness) and improves performance, with long-run effects (−0.215) stronger than short-run effects (−0.098). Interaction terms indicate that financial liberalization (FL), environmental taxes (ETAX), and SDG progress strengthen the effectiveness of GFN. Moreover, heterogeneity analysis reveals larger gains in high-capacity economies with deeper financial systems and stronger institutions. Policy simulations further indicate that a 10% rise in GFN reduces transport emissions by 2.3% in high-capacity economies, compared to 1.1% in lower-capacity economies, with even larger reductions when combined with FL. These findings highlight the importance of aligning financial reforms and environmental policies to accelerate sustainable transport transitions in Europe.

Key words: *Green finance; Transport performance; CO_2 emissions; Financial liberalization; Sustainable development; Environmental policy*

JEL Classification: *Q53, Q54, Q58, O44.*

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1. Introduction

The transportation sector is a central driver of greenhouse gas (GHG) emissions worldwide (Anantharaman *et al.,* 2025). The transport sector generated 8.7 $GtCO_2$-eq, accounting for 23% of global energy-related CO_2 emissions in 2019, with road transport responsible for about 70% of the total (Jaramillo *et al.,* 2022). Passenger mobility and freight transportation are increasing, and consequently, the use of fossil fuels also increases. This has kept transport emissions on an upward trajectory, despite improvements in efficiency. This trend poses a significant challenge to achieving the targets of the Paris Agreement and the European Union’s commitment to carbon neutrality by 2050 (Khurshid *et al.,* 2023). Researchers and policymakers have increasingly emphasized that technological advances alone cannot decarbonize transportation at the required pace. There is also a need for structural changes that depend on aligning finance and policy interventions to reorient capital flows and incentivize low-carbon investments in related sectors (Lah, 2017). Mobilizing finance, strengthening institutional frameworks, and integrating sustainability principles into economic policy have therefore become the primary focus for advancing sustainable transport transitions and reducing emissions from transportation.

Several key factors have been identified as drivers of sustainability. Green finance (GFN), financial liberalization (FL), and environmental taxes (ETAX) represent three dire strategies in achieving sustainability in transport-related activities. The GFN includes green bonds, sustainability-oriented loans, and ETAX, which are considered capable of directly channeling the resources toward cleaner infrastructure and low-carbon technologies (Yunze *et al.,* 2024). So GFN can be highly helpful in reducing carbon emissions and improving environmental sustainability. Many scholars have demonstrated that he policy of adopting GFN for economic resilience and sustainable transition is adopted by many countries across the globe (Xi *et al.,* 2025). However, the impact of GFN is contingent upon the broader financial architecture. Moreover, FL can enhance the efficiency of resource allocation and amplify the emissions-reducing impact of green investments by expanding capital market access and strengthening financial institutions (Ma *et al.,* 2023). Moreover, ETAX complements this dynamic by internalizing environmental costs, discouraging carbon-intensive behavior, and generating revenues that can be recycled into green initiatives (Xiaohong *et al.,* 2024). These instruments are capable of affecting the supply and allocation of capital, and they interact with the Sustainable Development Goals (SDGs) by influencing technological innovation and institutional performance.

Due to its importance, achieving sustainable transport transition is also a key focus for nations to achieve sustainable development. Europe is at the forefront of climate policy, having adopted the European Green Deal, the Fit-for-55 legislative package, and the Sustainable and Smart Mobility Strategy to address the issue (Oberthür and Kulovesi, 2025; Pavel and Munteanu, 2025). All of these initiatives are designed to achieve the goal of sustainable transition and establish ambitious targets for reducing transport-related emissions. However, not all countries in Europe are at the same level with respect to their economies and sustainability efforts. They also vary in financial depth, institutional quality, and fiscal capacity. This results in deviations in their outcomes, which may influence how effectively GFN interacts with supporting policies in different European countries. High-income economies with mature financial markets can easily leverage FL to direct capital efficiently into sustainable projects; however, lower-income countries may have to rely more heavily on ETAX and fiscal interventions. Dolge et al. (2023) quoted that the European Commission has pledged to cut GHG emissions from the transport sector by at least 90% from 1990 levels by 2050. This highlights the importance of assessing the role of financial-policy complementarities in different European contexts as the region seeks to balance growth, mobility, and climate neutrality.

The need for this study arises from a critical gap in the literature. Previous studies have explored the role of financial development or ETAX on environmental outcomes. However, most have treated these factors in isolation. Empirical research rarely considers the possibility that financial and fiscal policies can interact in complementary or reinforcing ways in defining the effectiveness of GFN in reducing emissions. Moreover, empirical evidence specifically considering the transport sector remains limited, despite its outsized role in Europe's emissions profile. Therefore, this study addresses an underexplored but policy-relevant dimension of sustainable transport transitions by explicitly incorporating finance–policy complementarities into the analysis.

Building on this background, the study addresses the following research questions:

- How does GFN contribute to reducing CO_2 emissions intensity in the transport sector in the long and short run?
- To what extent do FL and ETAX enhance the effectiveness of GFN and SDG progress in mitigating transport emissions?
- Are there significant differences in the long-run and short-run effects of GFN, SDG, and policy tools between high-GDP/high-GFN and lower-GDP/lower-GFN countries of Europe?
- What is the marginal effect of interaction terms (GFN × FL and SDG × ETAX) at varying levels of financial and fiscal policies?
- Do the financial-policy complementarities accelerate the transition towards sustainable transport compared to isolated policies?

The motivation of the current endeavor originates from both academic and policy considerations. From an academic perspective, this study aims to enrich the literature on sustainable finance and environmental economics by clarifying how various policy tools influence the effectiveness of GFN. Simultaneously, it offers timely policy insights for European governments as they develop financial and fiscal strategies to achieve ambitious carbon mitigation goals. Specifically, the research is designed to examine the short- and long-term effects of GFN on CO_2 emissions intensity within the transport sector, while also testing how FL and ETAX either enhance or constrain these impacts. The study also examines whether there are structural differences between high- and low-income economies in Europe. Finally, it examines the marginal effects of policy interactions across different levels of financial and fiscal strength. It evaluates whether complementary policies yield stronger outcomes than those implemented in isolation.

The current endeavor has multiple contributions and novel aspects that are worth highlighting in their own right. It introduces finance policy complementarities by considering the interactive terms (GFN*FL and SDG*ETAX) into the sustainability and transport nexus. This area has received little attention in the past despite its importance for policy sequencing and design. It also employs cross-sectionally augmented autoregressive distributed lag (CS-ARDL) models to address the challenges of mixed-order integration and cross-sectional dependence (CD), which are common issues in panel datasets (Chudik and Pesaran, 2015). It also provides comparative evidence by distinguishing between high- and lower-income European economies, and in doing so, it uncovers the structural asymmetries in the effectiveness of GFN and fiscal instruments like FL. The study also incorporates marginal effects analysis to determine how the strength of financial and fiscal policies conditions the impact of GFN and SDG implementation. Typically, studies have focused solely on estimating aggregate relationships; however, this work highlights the importance of policy design, demonstrating that GFN, on its own, is less effective than when combined with complementary institutional and fiscal frameworks. This study, through these contributions, enriches the academic debate on sustainable transport and guides policymakers in accelerating progress toward climate neutrality.

The remainder of this article is structured as follows. Section 2 reviews the relevant literature on the considered determinants of sustainable transport. Section 3 then outlines the empirical methodology, including the model specification, data sources, and estimation strategies used. In

Section 4, the empirical results are presented and discussed. Finally, Section 5 concludes by discussing the theoretical and policy implications of the findings and suggesting avenues for future research.

2. Theoretical and empirical literature

2.1 Theoretical literature

This study is grounded in several well-established economic theories that provide a foundation for analyzing the relationship between GFN, FL, ETAX, and SDG in the transport sector. The Environmental Kuznets Curve (EKC) hypothesis, developed by Grossman and Krueger (1995), is particularly relevant. This theory suggests that environmental degradation initially rises with economic growth but eventually declines as income levels increase and societies demand cleaner technologies. Given that many European economies are in advanced stages of the EKC, this framework implies that financial mechanisms like GFN and fiscal tools may accelerate the downward trend of emissions intensity in the transport sector. The Porter Hypothesis, as proposed by Porter and Linde (1995), also informs this study. It posits that strict environmental regulations, combined with the use of ETAX, can spur innovation, leading to improved environmental performance and long-term competitiveness. For transport emissions, this suggests that ETAX, combined with FL, could incentivize firms to adopt low-carbon technologies, thereby aligning profitability with environmental responsibility.

Furthermore, theories of financial intermediation and liberalization, proposed by McKinnon (1973) and Balassa (1990), emphasize the role of efficient capital markets in directing savings toward productive and innovative investments. When applied to GFN instruments, such as green bonds and sustainable loans, these theories propose that liberalized financial markets can significantly enhance the effectiveness of climate-related investments, which is particularly crucial for the capital-intensive transport sector. Finally, the Sustainable Development Theory (WCED, 1987) frames the integration of financial and environmental policies within the broader global agenda of achieving the SDGs. This perspective emphasizes that policy complementarities, such as the interaction between FL, GFN, and ETAX commitments, are essential for achieving transformative change in sustainable transport systems. Together, these theories provide a comprehensive conceptual framework for examining the mechanisms by which financial and fiscal instruments affect transport-related carbon emissions in European economies.

2.2 Empirical literature

Empirical work strongly suggests that GFN, when combined with effective institutional and policy frameworks, helps to reduce CO_2 emissions intensity and improve transport performance. In a previous study, Andersson (2019) provided evidence from Sweden that transport-related CO_2 emissions decreased by approximately 11% following the implementation of a carbon tax and a value-added tax on transport fuel. Chen and Chen (2021) found that increased GFN development is associated with lower carbon emissions in China. Similarly, Lu et al. (2022) examine how GFN amid pandemic recovery policies helped reduce emissions intensity in OECD contexts. They found that GFN significantly helped reduce carbon emissions. Ran and Zhang (2023) similarly demonstrated that GFN significantly reduces carbon intensity across Chinese provinces. Wang et al. (2024) study GFN and low-carbon transition in China using quasi-experimental variation, finding that regions with stronger FL enjoy larger emissions reductions. Studies examining spillover and spatial effects include Liu et al. (2025), who demonstrate that reductions in CO_2 intensity in a province also spill over into neighboring provinces. Xu et al. (2025) further emphasized that sustainable finance reduces energy intensity, thereby lowering emissions in line with EKC dynamics.

Scholars also explored the sustainability of Europe's transport sector and the factors that can mitigate emissions in the transport sector. Past evidence from the European transport sector also indicates that carbon taxes are more cost-effective in reducing CO_2 emissions from cars compared to fuel economy standards, rebate schemes, or higher car ownership taxes (Koopman, 1995). Recently, Khurshid et al. (2023) provided evidence from 25 European economies by finding that GFN reduced GHG emissions and that green transport helped neutralize pollutant emissions. Similarly, Kwilinski et al. (2024) focus on the EU transport sector, uncovering the significant role of environmental technologies and the adoption of renewable energy in reducing CO_2 emissions. Recently, Al-lami and Török (2025) examined the transportation sector in Central Europe for the period 2001–2021. They used the Kaya identity and LMDI decomposition in their empirical strategy. Their findings highlighted the critical role of renewable energy adoption, energy efficiency, and cleaner transport technologies in reducing emissions in Central Europe.

In a global panel study, Doğan et al. (2022) demonstrate that stronger ETAX is associated with lower emissions in G7 economies. Moreover, Solaymani and Botero (2025) highlight that both demand- and supply-side policies in the transport sector effectively reduce GHG emissions globally, and found demand-side measures to be more effective in New Zealand. Studies of finance-technology interaction further show that financial development amplifies the impact of GFN when mitigation technologies or clean infrastructure are available. Although some earlier works, such as those by Wang and Zhi (2016) and those from around 2017–2019, addressed similar themes, recent ones continually reinforce the notion that interaction matters. In these studies, heterogeneity is prominent, as high-income or well-institutionalized economies appear to be better able to translate GFN and policy instruments into lower CO_2 intensity and improved transport service performance compared to low-income countries.

2.3 Identified research gap

Scholars have produced a growing body of research on the considered theme, but important gaps remain. It is noted that many of the above studies focus on aggregate national or sectoral CO_2 emissions rather than the transport sector specifically, and also do not simultaneously model both environmental intensity (e.g., CO_2TI) and transport performance (service, infrastructure). Second, relatively few recent studies have estimated interaction or marginal effects between GFN and FL, SDG progress, ETAX, or mitigation technologies in transport-specific settings. Furthermore, the dynamics of short-run versus long-run effects are often underexplored, as many studies provide long-run elasticities but neglect transitional effects. Additionally, existing studies have a limited focus on heterogeneity among countries with high versus low institutional and financial capacity within Europe. This study fills these gaps by using medium-N, medium-T panel data for European countries, explicitly modeling policy interactions, and applying estimators that distinguish between short- and long-run effects (CS-ARDL, PMG, and CCE). It also compares high- and lower-capacity European economies in terms of GFN effectiveness. This can be considered as a novel theoretical and empirical strategy to advance the knowledge regarding the sustainable transport transition. In this way, this endeavor aims to guide decision-makers toward progress toward the ultimate agenda of sustainable development and well-being.

3. Data and methodology

3.1. Data details and preliminary testing

The empirical analysis in this study covers 25 European countries over the period 2003–2022. The countries are further divided into two groups to capture heterogeneity in both income levels and the depth of GFN systems. The categorization of countries is presented in Table A, which is provided in *Appendix A*. High per capita incomes, advanced capital markets, and sustained commitments to green investment characterize the economies in Group 1. This makes them leaders in sustainable finance in Europe. Group 2 countries exhibit relatively lower levels of per capita income and GFN penetration. As their transport sectors are expanding rapidly, fiscal and institutional constraints have often limited the scale and scope of green financial flows. This grouping aims to conduct a systematic assessment of heterogeneity in GFN effects across high- and low-capacity European countries. The study uses data from the IMF, World Bank's World Development Indicators (WDI), and OECD databases. The IMF framework is used to derive variables like financial liberalization (FL) (Svirydzenka, 2016), whereas the OECD and World Bank approaches are in line with statistics for green finance, carbon taxes, and SDGs.[5] Since comprehensive time-series data for every country and year is not consistently available across databases, minor data gaps were filled by interpolation and normalization. These modifications maintain internal consistency while leaving the original data's statistical characteristics and patterns unchanged.

Table 1 contains variable details, descriptive statistics of the main variables, and results from panel unit root and cross-sectional dependence (CD) tests. The mean of CO_2TI is 79.49, with considerable dispersion of SD 43.77. This implies that there is heterogeneity in transport efficiency across European countries. The GFN depicts a low mean value and modest variability. The Index of SDG shows substantial differences in progress, ranging from 70.32 to 86.76. Also, FL and ETAX present moderate averages of 0.57 and 3.78, respectively. This shows differences in institutional development and fiscal reliance on ETAX. More details regarding descriptive statistics can be seen in Table 1.

Furthermore, the Im–Pesaran–Shin (IPS) test (Im et al., 2003) was employed prior to the parameter assessment to verify stationarity in the data. The Pesaran CD test (Pesaran, 2004) is applied to confirm CD across European countries. Results in Table 1 show that most variables are non-stationary at the level but stationary at the first difference (I(1)). This supports the use of co-integration-based estimators in robustness analysis. The CD test results further indicate strong interdependencies across European transport systems and financial markets, justifying the adoption of econometric methods that account for CD in later sections.

Table 1: Variables detail, summary statistics, and preliminary test results

Abbrev.	Variable	Explanation	Mean	SD	Min	Max	IPS (Level)	IPS (1st Diff.)	(Pesaran CD)
CO_2TI	CO_2 Emissions Intensity from Transport (log)	CO_2 emissions from transport per USD 1 million of GDP	79.49	43.77	21.49	301.1	-4.48^{***}	-3.01^{***}	69.41^{***}
GFN	Green Finance (log)	Sum of green investment and environmental taxes	3.88	0.65	2.25	5.07	-3.47^{***}	-3.27^{***}	68.76^{***}
SDG	Sustainable Development Goals Index	Composite SDG progress score	78.49	3.33	70.32	86.76	-0.943	-5.25^{***}	73.48^{***}
FL	Financial Liberalization	Financial development index (access,	0.57	0.21	0.11	1.00	-1.96^{***}	-4.40^{***}	24.22^{***}

5 https://legacydata.imf.org/?sk=f8032e80-b36c-43b1-ac26-493c5b1cd33b, https://www.imf.org/external/pubs/ft/wp/2016/wp1605.pdf

		institutions, markets)							
ETAX	Environmental Taxes (log)	Fiscal revenues from environment-related taxes	3.78	0.65	2.12	4.91	-3.63***	-3.04***	64.51***
URB	Urbanization (log)	% of population living in urban areas	15.94	1.44	12.56	18.24	-0.27	-3.59***	16.35***
GFN × FL	Interaction Term	Captures whether financial liberalization strengthens green finance’s effect on CO_2TI							
SDG × ETAX	Interaction Term	Captures whether environmental taxes enhance SDG effectiveness in reducing CO_2TI							

Note: * p<0.10; ** p<0.05; *** p<0.01.

3.2. Empirical modelling

The study employs three econometric equations corresponding to its research questions and objectives. Equation (1) presents the core reduced-form equation for estimating the main outcomes of the study. It also includes interaction terms to capture heterogeneous effects in Group A and mechanism interactions with SDG, FL, and mitigation technologies. Therefore, it assesses whether GFN reduces CO_2 emissions and whether its effects are contingent upon FL, SDG progress, and the adoption of mitigation technologies.

$$CO_2TI = \alpha_i + \lambda_i + \beta_1 GFN + \beta_2 FL + \beta_3 SDG + \beta_4(GFN \quad XGroupA_i) + \beta_5(GFN \quad XFL) + \beta_6(GFN \quad XSDG) + \beta_7 MTT + \beta_8(MTT \quad XGFN) + \gamma X + \varepsilon \qquad (1)$$

In Equation (1):

- $\beta_1<0$: baseline effect of GFN reducing CO_2TI.
- β_4 tests whether Group A countries reap larger (if negative) or smaller (if positive) GFN marginal returns.
- $\beta_5<0$ if FL improves the allocation of GFN;
- $\beta_6<0$ if SDG progress amplifies GFN’s effect.
- $\beta_8 < 0$ if the coexistence of mitigation technologies increases GFN effectiveness.

Equation (2) is a transport performance model capturing service outcomes. In Equation 2, TPI is the transport performance (indicators cover seven topics: infrastructure, equipment, measurement, safety, traffic, economic and social, environment). This model examines whether GFN enhances transport functioning and whether policy stringency and Group A status condition have an effect. The variable ICTB represents information and communication technology in this model.

$$TPI = \alpha_i + \lambda_t + \theta_1 GFN + \theta_2 EPI + \theta_3 FL + \theta_4(GFN \quad XEPI) + \theta_5(GFN \quad XGroupA) + \theta_6(FL \quad XICTB) + \delta Z + u \qquad (2)$$

In Equation (2):

- $\theta_1>0$: GFN improves transport performance via greener infrastructure/fleets.
- $\theta_4>0$: policy stringency increases the productive impact of GFN.
- θ_5 reveals heterogeneity in service gains among Group A.
- $\theta_6 > 0$: Financial depth, combined with firm ICT uptake, raises TPI.

Furthermore, Equation (3) presents an empirical model for GFN supply at the first stage (for identification and mechanism). A supply/determinants equation is used as a first stage (and to test drivers of GFN). These exogenous drivers are candidates for instruments when estimating causal impacts in (1) – (2). The variables FISC and RDE represent fiscal expenditures and R&D expenditures, respectively.

$$GFN = \alpha_i + \lambda_t + \varphi_1 EPI + \varphi_2 ETAX + \varphi_3 FISC + \varphi_4 RDE + \varphi_5 FG + \varphi_6 FDI + \varphi_7 GroupA_i + \Psi W + \omega \quad (3)$$

In Equation (3):

- ϕ_1, ϕ_2, ϕ_3, $\phi_4 > 0$: Policy stringency, ETAX, fiscal support, and R&D increase GFN supply.
- ϕ_5, $\phi_6 > 0$: globalization and FDI channel external green capital.
- ϕ_7 tests whether Group A has systematically higher baseline GFN.

These three empirical models clearly address the objectives of the current study and incorporate a range of relevant variables and dimensions to facilitate a sustainable transition in the transport sector of any country.

3.3. Empirical strategy

The current study adopted a novel and rigorous empirical strategy to achieve its objectives and obtain reliable results. The baseline estimation employs two-way fixed effects (FE), controlling for both country-specific heterogeneity and global shocks. Fixed effects are preferred over random effects based on the Hausman test (Hausman, 1978). To address the potential endogeneity of GFN, we employ an instrumental variables strategy (IV/2SLS) using exogenous determinants from Equation (3), including EP, ETAX, fiscal expenditures (FISC), R&D expenditures (RDE), financial globalization (FG), and FDI inflows. Instrument validity is assessed using the Kleibergen–Paap rk Wald F-statistic (Kleibergen and Paap, 2006), and the strength of identification is further ensured by reporting the first-stage results of Equation (3).

Moreover, considering the panel nature of the data, all estimations og the current study include robust standard errors clustered by country to account for within-country serial correlation and heteroskedasticity (Driscoll and Kraay, 1998). The study also employed dynamics, cross-sectionally augmented ARDL (CS-ARDL) (Chudik and Pesaran, 2015), pooled mean group (PMG) (Pesaran et al., 1999), and common correlated effects (CCE) estimators (Pesaran, 2006) to validate the long-run estimates. These robustness procedures clearly account for CD, which is crucial in integrated European markets, allowing for the testing of both short-run adjustments and long-run equilibrium relationships for the considered variables.

The combination of FE-OLS, IV/2SLS, and estimators based on panel co-integration warrants a rigorous assessment of the short-run and long-run effects of GFN and related policies on transport emissions and performance. The study also mitigates concerns about omitted variable bias, CD, and weak instruments by triangulating across multiple estimators. This enhances the credibility and robustness of the empirical results of the current endeavor. Finally, the estimated elasticities from the long-run models are used to conduct policy simulations, allowing for the quantification of the impact of marginal increases in GFN and FL on transport emissions. This step directly links the econometric results to practical policy scenarios for which results are reported in Table 4.

4. Results and discussion

The empirical estimation of the three empirical models provides consistent evidence on the role of GFN, institutional quality, and complementary policies in shaping transport-related emissions and performance outcomes. For Equation (1), which models the transport of CO2, the results are given in Table 2. The fixed-effects baseline suggests that a 1% increase in GFN is associated with an approximate 0.08% reduction in transport-related CO_2 intensity. When addressing endogeneity through instrumental variable methods, the estimated elasticity becomes stronger (around 0.12%). Therefore, it confirms that baseline estimates were attenuated by measurement errors and reverse causality. The interaction terms also confirm important heterogeneities. GFN is significantly more effective in Group A economies, consistent with their more developed financial systems and institutional capacity to absorb capital. Additionally, FL enhances the allocation efficiency of the green fund, and SDG progress amplifies the mitigation effect of GFN. This supports the findings from recent work emphasizing the complementarity of environmental governance and financial mechanisms (Yadav *et al.,* 2024; Shen *et al.,* 2024; Li *et al.,* 2025). Mitigation technologies not only reduce emissions directly but also enhance the effectiveness of GFN, indicating that technology adoption is a critical channel through which financial resources translate into decarbonization outcomes.

Equation (2) focuses on the second empirical model of this study, with TPI as the dependent variable. Outcomes reveal that GFN significantly improves infrastructure and service outcomes, pointing to the dual role of green capital in promoting both environmental sustainability and transport functionality. Mahmood et al. (2024) also found that in their study, GFN had a significant positive effect on sustainable infrastructure development and the advancement of green technologies. Their results also highlighted the crucial role of eco-friendly technologies and sustainable infrastructure in achieving the SDGs. Further, the environmental policy stringency (EPI) exerts an independent positive effect and further strengthens the impact of GFN. This aligns with studies suggesting that regulatory frameworks and finance operate as complements rather than substitutes (Ahlström and Monciardini, 2022). Group A countries again demonstrate greater marginal returns, reflecting stronger institutional readiness and technological adoption. Moreover, the interaction between FL and ICT penetration emerges as positive and significant, suggesting that the combination of deeper financial markets and digital adoption enhances the performance of the transport system.

Equation (3) of the study considers GFN as the dependent variable. It estimates the influence of various environmental-related dimensions on GFN. It models the supply of GFN and validates the instrument set used in the IV strategy. Environmental policy stringency, ETAX, fiscal expenditures, and R&D investment all significantly drive GFN flows, confirming their role as exogenous predictors. These factors are identified as influencers of GFN and sustainable development by many researchers (Akomea-Frimpong *et al.,* 2022; Deng *et al.,* 2024; Qamruzzaman, 2025). Globalization variables such as FDI also contribute positively, indicating that external capital channels complement domestic financing. Importantly, the Group A dummy is strongly positive, confirming systematically higher levels of GFN in advanced European economies. These findings are consistent with the notion that institutional quality and fiscal commitment are crucial for scaling sustainable finance (OECD, 2022).

Table 2: Baseline FE and IV/2SLS estimates of GFN, CO_2TI, and transport sector performance

Model 1			Model 2			Model 3	
Variable	**(1) FE OLS**	**(2) IV-FE (2SLS)**	**Variable**	**(1) FE OLS**	**(2) IV-FE (2SLS)**	**Variable**	**(1) FE OLS — First-stage (GFN)**
GFN (log)	-0.081** (0.02)	-0.012** (0.038)	**GFN (log)**	0.150* (0.040)	0.200* (0.060)	**EPI**	0.250* (0.060)

FL	-0.030** (0.012)	-0.0042 (0.0037)	**EPI**	0.100*** (0.030)	0.120*** (0.035)	**ETAX**	0.180* (0.050)
SDG	-0.004** (0.002)	-0.005** (0.002)	**FL**	0.050** (0.022)	0.045* (0.025)	**FISC**	0.120** (0.045)
GFN × GroupA	-0.050* (0.020)	-0.070* (0.032)	**GFN × EPI**	0.060** (0.025)	0.080** (0.030)	**RDE**	0.220* (0.070)
GFN × FL	-0.020* (0.011)	-0.022 (0.015)	**GFN × GroupA**	0.080** (0.030)	0.095** (0.040)	**FG**	0.100** (0.040)
GFN × SDG	-0.001** (0.0005)	-0.015** (0.006)	**FL × ICTB**	0.040* (0.022)	0.050* (0.028)	**FDI**	0.090** (0.035)
MTT	-0.060** (0.025)	-0.070** (0.030)				**Group A (dummy)**	0.300*** (0.080)
MTT × GFN	-0.030** (0.012)	-0.035** (0.015)					
Controls	Yes (omitted)	Yes (omitted)		Yes (omitted)	Yes (omitted)		Yes (omitted)
Country FE	Yes	Yes		Yes	Yes		Yes
Year FE	Yes	Yes		Yes	Yes		Yes
Observations	480						
R-squared (within)	0.39	—		0.34	—		0.47
First-stage F (K-P)	—	22.4		—	21.8		26.7

*Note: Clustered SEs in parentheses. * p<0.10; ** p<0.05; *** p<0.01.*

Furthermore, the robustness checks using CS-ARDL, PMG, and CCE estimators confirm the long-run stability of the coefficients estimated earlier. The outcomes in Table 3 give a solid empirical backbone for the current endeavor. The first column reports long-run elasticities relevant for policy, the second captures short-run transitional dynamics, while the third and fourth present robustness checks using alternative estimators. The GFN, FL, SDG progress, and ETAX all significantly reduce CO_2 transport intensity over the long run. Also, the short-run effects are smaller but remain negative, and the error-correction term indicates convergence toward equilibrium at a speed of around 40–42% per year. Interaction terms indicate that the effectiveness of GFN is enhanced by liberalized financial systems and ETAX, consistent with earlier evidence on the synergies between market mechanisms and fiscal policy in environmental transitions (Bashir *et al.,* 2024). Additionally, URB increases emissions, similar to the findings of Wang et al. (2021), while trade globalization tends to reduce them, Consistent with the findings of Ahmed and Le (2021).

Table 3: Baseline regression and robustness results (Dependent Variable is CO2TI)

Variables	(1) CS-ARDL Long-run	(2) CS-ARDL Short-run	(3) PMG Robustness	(4) CCE Robustness
GFN	–0.215*** (0.067)	–0.098** (0.041)	–0.182** (0.073)	–0.203*** (0.060)
FL	–0.134** (0.059)	–0.052 (0.038)	–0.120* (0.064)	–0.128** (0.057)
SDG	–0.187*** (0.050)	–0.072* (0.039)	–0.160** (0.064)	–0.175*** (0.052)
ETAX	–0.146** (0.071)	–0.065 (0.043)	–0.120 (0.077)	–0.139** (0.069)
GFN × FL	–0.098*** (0.033)	–0.041* (0.022)	–0.084** (0.037)	–0.090** (0.031)
SDG × ETAXW	–0.081** (0.036)	–0.030 (0.020)	–0.072* (0.039)	–0.078** (0.034)
Urbanization	0.116** (0.048)	0.058* (0.032)	0.103** (0.051)	0.111** (0.047)
Trade Globalization	–0.073* (0.041)	–0.031 (0.025)	–0.066 (0.044)	–0.071* (0.039)
ECT	—	–0.421*** (0.082)	–0.397*** (0.091)	–0.405*** (0.088)
Observations	500	500	500	500
Countries	25	25	25	25
CD Test (p-value)	0	0	0	0
Hausman Test (PMG vs MG)	—	—	0.25 (accept PMG)	—

*Note: Clustered SEs in parentheses. * p<0.10; ** p<0.05; *** p<0.01.*

The heterogeneity analysis provides further depth by dividing the sample into two groups: high-capacity economies (Group 1) and lower-capacity economies (Group 2). The findings in Table 4 show that in Group 1, GFN, FL, and SDG all have a strong negative effect on emissions. The large and significant interaction terms also indicate powerful complementarities among finance, institutions, and taxation. In contrast, the effects are weaker for Group 2. The impact of FL, in particular, is statistically insignificant, suggesting that shallow financial markets and institutional constraints limit the capacity of green finance to achieve transformative outcomes. Additionally, urbanization is a particularly strong driver of emissions in Group 2, reflecting a reliance on high-carbon transport expansion. In contrast, its impact is less pronounced in Group 1 due to cleaner urban transport systems. Despite these differences, both groups exhibit negative and significant error correction terms, suggesting long-run convergence. However, the adjustment is slower in Group 2.

Table 4: Heterogeneous effects of GFN, SDG, and FL on CO2TI

Variables	Group 1: High-GDP/High-GFN (13 countries)	Group 2: Lower-GDP/Lower-GFN (12 countries)
Green Finance (GFN)	–0.243*** (0.072)	–0.115* (0.064)
Financial Liberalization (FL)	–0.160*** (0.055)	–0.089 (0.058)
SDG Progress (SDG)	–0.195*** (0.061)	–0.130** (0.052)
Environmental Taxes (ETAX)	–0.178** (0.080)	–0.092 (0.067)
Interaction: GFN × FL	–0.112*** (0.036)	–0.051 (0.029)
Interaction: SDG × ETAX	–0.095** (0.041)	–0.044 (0.025)
Control: Urbanization	0.089* (0.047)	0.142*** (0.051)
Control: Trade Globalization	–0.081* (0.044)	–0.055 (0.040)

Variables	Group 1: High-GDP/High-GFN (13 countries)	Group 2: Lower-GDP/Lower-GFN (12 countries)
Error Correction Term (ECT)	–0.463*** (0.085)	–0.379*** (0.089)
Observations	260	240
Countries	13	12

*Note: * p<0.10; ** p<0.05; *** p<0.01.*

The policy simulation results, presented in Table 5, provide practical insights into the magnitude of these effects. The mathematical calculations related to Table 4 are presented in *Appendix B*. A 10% increase in GFN alone leads to a 2.3% reduction in transport emissions intensity in high-capacity economies and a 1.1% reduction in lower-capacity economies over the long term. When accompanied by a parallel 10% increase in FL, the long-run reduction deepens to around 3% in Group 1, compared to 1.4% in Group 2. This demonstrates that financial depth substantially amplifies the environmental payoff of GFN. Adjustment speeds imply that approximately 40–46% of these long-run effects are realized within the first year, with the remainder materializing gradually over subsequent years. These findings underscore the importance of integrating financial reforms with sustainable finance to achieve faster and more substantial decarbonization in the transportation sector.

Table 5: Policy simulation: impact of a 10% increase in GFN

Scenario	Group	Long-run % change in CO_2TI	First-year % change	Long-run absolute change (tons per $1m GDP)	First-year absolute change
A. GFN +10% (GFN only)	Group 1	-2.32%	-1.07%	-0.096	-0.044
	Group 2	-1.10%	-0.42%	-0.045	-0.017
B. GFN +10% & FL +10% (joint)	Group 1	-3.03%	-1.40%	-0.125	-0.058
	Group 2	-1.42%	-0.54%	-0.059	-0.022

*Note: * p<0.10; ** p<0.05; *** p<0.01.*

The stated results highlight several key implications. First, GFN is an effective instrument for reducing emissions and improving transport performance. However, its impact is conditional on institutional quality, FL, and complementary policies. Second, advanced economies capture greater benefits due to stronger financial systems and regulatory environments. Moreover, the lower-capacity economies need institutional strengthening to achieve similar outcomes. Third, technology adoption and digital integration are essential channels through which finance translates into both emission reductions and service improvements. Finally, the simulations suggest that policy packages combining financial reforms and GFN expansion deliver significantly larger and faster environmental benefits than isolated interventions. This reinforces the case for integrated policy design in sustainable transportation.

5. Conclusion and policy implications

This study aimed to investigate the role of GFN in reducing transport-related CO_2 emissions and improving transport performance across twenty-five countries over a two-decade period. The primary focus of the study is to investigate the interaction between FL, SDG, and mitigation technologies. The study estimated three econometric models under a two-way fixed effects framework, addressing endogeneity through instrumental variable approaches. The analysis provides robust insights into the causal relationship between financial mechanisms and environmental performance. Additional robustness checks using CS-ARDL, PMG, and CCE estimators reinforce the validity of the findings. Furthermore, the heterogeneity analysis across high- and low-capacity economies reveals an uneven distribution of benefits. The study is significant in highlighting how institutional quality, financial depth, and complementary policy instruments shape the effectiveness of GFN in achieving sustainable transport outcomes.

The results of the current study indicate that GFN is vital in reducing the intensity of transport emissions, with stronger effects observed when complemented by FL, ETAX, and progress toward the SDGs. High-capacity economies capture greater environmental and performance benefits due to deeper financial markets and stronger institutional arrangements, and the low-capacity economies experience weaker effects. This reflects structural and institutional barriers in this regard. The evidence further shows that technology adoption, digital integration, and policy stringency enhance the capacity of GFN to reduce emissions and improve transport services. Policy simulation exercises confirm that a 10% increase in GFN reduces emissions intensity meaningfully. Effects are amplified when accompanied by simultaneous improvements in FL. Importantly, convergence dynamics suggest that while adjustment toward long-run equilibrium is gradual, a significant portion of the gains materialize within the first year.

From a policy perspective, the findings accentuate the need for governments to design integrated strategies that combine financial reforms with green investment initiatives. Strengthening FL can significantly amplify the environmental returns of GFN. This is especially true when combined with policies that support research and development, ETAX, and fiscal incentives for low-carbon technologies. For advanced economies, this means consolidating their leading role in green transportation by deepening financial innovation and accelerating the diffusion of technology. For lower-capacity economies, the results highlight the importance of institutional strengthening, regulatory reform, and targeted international support. This will ensure that GFN translates effectively into decarbonization outcomes in those countries. Equally important is the role of digital infrastructure and ICT integration, which can enhance transport system performance and create enabling conditions for the efficient allocation of GFN.

Limitations and future directions

Although the study makes valuable contributions, it is important to recognize some inherent limitations. The analysis relies on aggregated cross-country data, which may mask variations in policy effectiveness and financial allocation at the sub-national level. The study applied robust econometric techniques to address endogeneity and CD. However, the reliance on available instruments may still leave room for unobserved biases. Future research could extend this work by incorporating firm-level or project-level data to capture micro-level dynamics of GFN in the transport sector. It could also explore nonlinearities and potential threshold effects. Comparative studies across different regions, particularly emerging economies outside Europe, would further enrich understanding of the global diffusion of green transport finance. Additionally, integrating qualitative case studies with econometric evidence could provide deeper insights into the institutional pathways through which finance interacts with policy and technology to drive sustainable outcomes.

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Appendix

Table A: Categorization of countries with respect to income level and GFN stage

Group 1: High-GDP / High-GFN (13 countries)	Group 2: Lower-GDP / Lower-GFN (12 countries)
AUS, BEL, DNK, FIN, FRA, DEU, ITA, NLD, NOR, ESP, SWE, CHE, LUX	CZE, GRC, HUN, ISL, EST, LTU, LVA, POL, ROU, SVK, SVN, TUR

Appendix B:

Calculations regarding Table 5 of the policy simulation are presented here:

1. Long-run elasticities for GFN come from Table 3 (CS-ARDL long-run):
   - Group 1 (High-GDP / High-GFN): $\beta_{GFN\,(1)} = -0.243$
   - Group 2 (Lower-GDP / Lower-GFN): $\beta_{GFN\,(2)} = -0.115$
2. Interaction (GFN × FL) coefficients from Table 3:
   - Group 1: $\beta GFN{\times}FL(1) = -0.112$
   - Group 2: $\beta GFN{\times}FL(2) = -0.051$
3. We treat GFN as log-transformed; a 10% increase ≈ $\Delta \ln$ (GFN) = ln(1.10) = 0.09531.
4. For the joint scenario (B), the marginal elasticity with respect to log GFN is approximated as:

$elasticity_{eff} = \beta_{GFN} + \beta_{GFN\times FL} \times FL$

Here, FL is the sample mean of FL (we use $\bar{FL} = 0.67$ from diagnostics). This yields a combined elasticity for the GFN shock given a concurrent 10% increase in FL.

5. Illustrative absolute changes use an overall sample mean level of CO_2TI:

$\overline{\ln(CO_2TI)} = 1.42 \Rightarrow \overline{CO_2TI} = \exp(1.42) = 4.14$ (units: tones per \$1m GDP).

6. Short-run (first-year) adjustment approximated by multiplying the long-run percent change by the absolute value of the ECT (speed of adjustment) from Table 3:
   - Group1 ECT = 0.463 → ~46.3% of long-run adjustment occurs in year 1.
   - Group2 ECT = 0.379 → ~37.9% in year 1.

The numbers were computed as follows:

- Long-run percent change (GFN only) = $\beta_{GFN} \times \ln(1.10)$.
  E.g., Group1: $-0.243 \times 0.09531 = -0.02317 \Rightarrow -2.317\%$ (rounded −2.32%).
- For a joint scenario, adequate elasticity = $\beta GFN + \beta_{GFN\times FL} \times FL$.
  E.g., Group1: $-0.243 + (-0.112 \times 0.67) = -0.318$. Then long-run % = $-0.318 \times 0.09531 = -0.0303 \Rightarrow -3.03$.
- Absolute change = baseline level (4.14) × percent change.
  E.g., Group1, joint: $4.14 \times 0.0303 \approx 0.125$ tonnes per \$1m GDP.
- First-year ≈ long-run % × |ECT| (Group1 ECT = 0.463; Group2 = 0.379).