8. GREEN FINANCE, INNOVATION, AND TECHNOLOGICAL IMPORT: A RESILIENCE-BASED ANALYSIS OF SUSTAINABLE INDUSTRIAL TRANSITIONS

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Abstract

This study examines the relationship between green finance (GFN), financial development (FD), and technological import (IOT) in driving sustainable industrial transitions in European countries from 2003 to 2022. This study constructed a composite Industrial Resilience Index (IRI) and estimated four interrelated econometric models. Specifically, it examines how various factors influence IRI, industrial innovation (INV), renewable energy adoption (RE), and green finance (GFN) mobilization. This study employed the Dynamic Common Correlated Effects (DCCE) estimator to account for cross-sectional dependence and heterogeneous dynamics and validated the results using ARDL approach. Findings indicate that GFN and FD significantly enhance IR and INV, particularly when supported by digital infrastructure and favorable environmental policies. Additionally, IoT and mitigation technologies play a pivotal role in the RE transition. At the same time, macroeconomic stability and public expenditure catalyse GFN flows. The results confirm the relevance of Schumpeterian and endogenous growth theories, highlighting the co-evolution of institutions, innovation, and policy. The study concludes with tailored policy recommendations and provides a new empirical foundation for designing integrated financial-technical frameworks to achieve industrial sustainability in Europe.

Keyword: *Green Finance; Industrial Resilience; Technological Import; Innovation; Financial Development; Dynamic Common Correlated Effects; ARDL; Europe*

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1. Introduction

The transition toward sustainable industrial development has become a central policy imperative due to growing environmental degradation and various structural economic shifts (Khurshid et al.,

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2025a). As the world enters the final stretch of achieving the 2030 Agenda for Sustainable Development, the role of industries in supporting economic progress while minimizing environmental externalities has gained significant prominence (Ma et al., 2023). Among the 17 Sustainable Development Goals (SDGs), SDG 9 (Industry, Innovation, and Infrastructure) and SDG 13 (Climate Action) emphasize the need to build resilient infrastructure and promote sustainable industrialization through innovation-driven transitions (United Nations, 2023). In this context, the concept of *industrial resilience (IR)* can be defined as the capacity of industrial systems to anticipate, adapt to, and recover from external shocks while maintaining sustainability trajectories (Di Tommaso et al., 2023). Every nation strives to achieve IR, and it has also become a crucial policy and research focus in the current time. In this regard, the increasing integration of green finance (GFN), innovation (INV), financial development (FD), and imported technologies into industrial frameworks signals a paradigm shift (Xi et al., 2025). These factors all emphasize the importance of comprehensive policies and investment patterns that enhance environmental and economic resilience simultaneously. There is a dire need to explore the connection between GFN, FD, INV, and IoT and their collective influence on IR to address global challenges and threats.

There are various factors that can help nations achieve a sustainable industrial transition and IR. Factors like GFN and FD promote capital availability for environmentally sustainable investments and reduce financing risks in renewable energy (RE) and industrial modernization (Liu et al., 2024). Additionally, the global innovation diffusion aspect of importing technology (IOT) typically contributes to energy efficiency (EE) and productivity growth (Wang and Shao, 2024). Digitalization (DIG) further enhances this impact by facilitating the seamless integration and effective utilization of IOT across various sectors (Chauhan et al., 2022). Also, environmental taxes (ETX) and government expenditures (GE) reflect regulatory stringency and fiscal commitment to sustainable development (Wang et al., 2025). These factors, individually and interrelatedly, can help in creating a broader financial ecosystem in which industries operate and sustain themselves. Furthermore, to achieve IR, industrial innovation (INV) and the RE transition are both essential and deeply interrelated, as INV drives cleaner technologies while EE sustains their long-term viability (Khan et al., 2025). So, the complex relationships among these economic, technological, and policy aspects offer fertile ground for empirical scrutiny in the context of industrial sustainability.

Europe presents a distinctive setting for exploring sustainable industrial transitions due to its early adoption of green industrial policies, robust institutional frameworks, and extensive innovation networks (Xiaohong et al., 2024). The European Green Deal and its associated instruments, such as the Just Transition Mechanism and the EU Taxonomy for Sustainable Activities, demonstrate a clear commitment to systemic industrial transformation in the region by decision-makers (Filipović et al., 2022). However, despite these initiatives, many European economies still exhibit asymmetries in financial development, innovation capacities, and technological absorption in these areas. This is affecting their ability to withstand global shocks, such as COVID-19, energy crises, and geopolitical disruptions (Lopez-Garcia et al., 2024; Filip and Setzer, 2025). Therefore, there is a need to explore additional avenues related to sustainable IR in Europe. In this regard, the GFN and INV are individually well-studied. However, the interlinked dynamics between financial and technological drivers of IR remain underexplored. Therefore, the problem needs to be addressed on how Europe can leverage synergistic mechanisms across finance, innovation, and technology to nurture resilient and sustainable industrial structures under existing environmental and economic challenges.

This research aims to provide a comprehensive assessment of the effects of GFN, FD, and IOT, along with other related variables, on IR, INV, RE transition, and GFN in Europe from 2003 to 2022. The study also investigates how interactions among these variables contribute to sustainable industrial transitions in the considered region. The following four research questions are formulated that are based on the theme of this study:

- *How do green finance and financial development, individually and interactively, influence industrial resilience in Europe?*
- *To what extent do green finance, financial development, and technology imports drive industrial innovation, and how does digitalization shape this process?*
- *How do technological imports, green finance, and mitigation technologies contribute to renewable energy deployment?*
- *What macroeconomic and institutional factors influence green finance mobilization and how does government spending interact with green finance instruments in Europe?*

These questions are designed to unpack not only the individual effects of the selected variables but also their interdependencies through interaction terms that reflect the complexities of real-world policy and market dynamics. The findings of this research are considered helpful in offering a meaningful vision for European policymakers and international sustainability actors in designing integrated strategies for IR. The current work focuses on a panel dataset of 25 European countries over 20 years, considering both established and emerging economies within the continent. The scope includes both Western European nations, which have advanced financial ecosystems and environmental policies (Oyebanji et al., 2023), and Eastern European states, which are undergoing institutional and industrial transitions (Radosevic et al., 2022). This study also constructed and utilized a customized Industrial Resilience Index (IRI) that integrates environmental, innovation, energy efficiency, and productivity indicators. The purpose is to provide an innovative perspective on industrial performance in terms of resilience criteria.

This article contributes to the literature and practice of sustainable IR in several significant ways. It introduces a novel IRI that combines key metrics, including industrial output (IVA), EE and RE share, INV capacity, and greenhouse gas emissions (GHG), as well as demand-based emissions (DBE). The IRI used standardized weights by following best practices from OECD sources. Further, the current study empirically tests four distinct yet interlinked empirical models. These empirical models capture multiple dimensions of IR, INV, RE transition and GFN mobilization. These are intended to provide an integrated framework for policy design in the considered region. Moreover, this study also includes various other related and significant variables. The use of Dynamic Common Correlated Effects (DCCE) as the primary estimation strategy allows for robust handling of cross-sectional dependence and heterogeneous dynamics. The application of the ARDL as a robustness check persistence effects are addressed rigorously. The current study also innovatively includes various interaction terms to investigate compound influences of co-evolving variables. The purpose is to offer insights into how complementarities can be leveraged for industrial sustainability in Europe. Finally, the geographic focus on Europe, a region actively designing future-oriented green financial instruments and industrial policy, adds practical relevance to ongoing debates on strategic resilience planning in the face of climate and economic shocks.

The remainder of this paper is organized as follows: Section 2 reviews relevant theoretical and empirical literature on IR, GFN, INV, etc. Section 3 outlines the data and variable sources, as well as the empirical modeling and estimation strategy. Section 4 presents the empirical results, along with a discussion. Finally, Section 5 concludes the study with a summary, key findings, limitations, and directions for future investigations.

2. Literature Review

This section presents the literature review of recent studies. The section is divided into subsections based on the four empirical models of the study. At last, the research gap is identified and stated, explaining how the current research fills that gap.

2.1 Factors Affecting Industrial Resilience

The concept of IR refers to the capacity of industrial systems to absorb, recover from, and adapt to external shocks while continuing to function effectively and sustainably (Di Tommaso et al., 2023). In this regard, GFN is considered a mechanism for channeling capital toward environmentally sustainable projects and resilience. It has emerged as a crucial enabler of IR, particularly in the context of climate change, resource constraints, and energy shocks (Ur Rahman and Amjad, 2024). Also, FD plays a significant role in enhancing IR by reducing credit constraints, facilitating long-term investment and enabling technological upgrades (Jin and Liu, 2024). Moreover, IoT facilitates access to advanced industrial methods that help promote agility and adaptation (Goldman and Nagel, 1993).

Empirical evidence supports that economies with higher levels of FD are better equipped to allocate resources toward innovation and sustainability transitions (Irfan et al., 2023). Additionally, GFN instruments, such as green bonds and sustainability-linked loans, have been found to lower investment risk in clean technologies and enhance industry adaptability to various shocks (Jian, 2023). In their studies, Veugelers et al. (2023) for Europe and Jawadi et al. (2025) for developing countries found that GFN significantly improved IR due to strong regulatory backing and financial market maturity. Similarly, Zhang (2025) examined the role of the digital economy and GFN in enhancing economic resilience. They utilized panel data from 30 Chinese provinces and cities spanning the years 2011 to 2023. The study's findings showed that the digital economy significantly promoted IR, with GFN serving as an important mediating factor. Moreover, Brookbanks and Parry (2024) showed that the IOT can boost the adaptive capacity of industries by accelerating the diffusion of clean and efficient processes.

2.2 Factors Encouraging Industrial Innovation

Researchers also explore various factors related to industrial innovation (INV). They have recognized INV as a cornerstone of sustainable economic growth and transition. Recent studies also highlight that GFN and development-oriented finance significantly affect the capacity of firms to innovate in line with environmental goals (Nchofoung et al., 2024; Chen et al., 2024). Additionally, GFN reduces barriers to entry for sustainable innovation (Raman et al., 2025), while broader financial diversification allows for the scaling of innovation activities (Xie et al., 2024).

Furthermore, IOT provides a crucial channel for innovation diffusion and technological gain (Cheng et al., 2024). Many studies confirm that IoT stimulates local innovation, especially when accompanied by absorptive digital infrastructure (Ge et al., 2024; Osei, 2024). Furthermore, environmental policy (EPY) and Foreign Direct Investment (FDI) are found to act as significant push factors for INV. Moreover, rigorous regulations create pressure to innovate (Akhtar et al., 2024), while FDI serves as a vector for transferring cutting-edge technologies and innovation practices (Xuan, 2025). Thus, the combined effects of GFN, IOT and policy instruments offer a multidimensional foundation for understanding innovation-led IR in the considered area and theme.

2.3 Factors Helping Renewable Energy Transition and Energy Efficiency

There are also many factors influencing RE transition and EE in firms. The transformation toward renewable energy (RE) and enhanced energy efficiency (EE) is considered a pathway for decarbonizing industrial sectors and achieving Sustainable Development Goal (SDG) 13. In this regard, IOT and mitigation technologies in energy generation (MTEG) have been found to positively influence the uptake of renewables and the modernization of energy systems (Khurshid et al., 2025b). Several studies have demonstrated that the availability of GFN further reduces the cost and perceived risk of RE investments, particularly in early-stage technologies (Yoshino et al., 2021; Guo et al., 2023).

Additionally, EE remains a crucial intermediate variable, as it serves both as a contributor to resilience and as an indicator of sustainable performance (Aldieri et al., 2021). Moreover, studies show that environmental taxation (ETX) provides market-based signals that can promote resource optimization and energy transition (Su et al., 2023). In a recent study, Muhammad and Hoffmann (2024) explored the effects of GFN and INV on RE consumption. They explored 16 states from 2008 to 2021 in their study. They found that environmental protection-related sales consistently increased RE use, while GFN showed positive effects. They also found that INV significantly boosted the RE transition. Similarly, Cao et al. (2025) found that GFN and INV significantly increased the share of renewable energy (RE) in the energy mix of the G7 countries and contributed to a reduction in greenhouse gas (GHG) emissions. They also showed that the effectiveness of these measures was amplified when combined with higher levels of globalization and trade openness.

2.4 Factors Mobilizing Green Finance

The mobilization of GFN depends not only on market demand but also on enabling macro-financial conditions, which include government expenditures (GE), ETX, and income levels. Previous research has shown that countries with strong public financial support and consistent policies experience higher volumes of GFN flows (Wang et al., 2025). FDI inflows also support GFN mobilization by injecting external capital into green sectors and facilitating international partnerships (Li et al., 2025).

Another important economic factor affecting GFN is Inflation (INF). INF, on the other hand, may negatively affect GFN flows by increasing uncertainty and reducing investor confidence. The interaction term GFN and GE captures the co-dependence of financial markets and public institutions in catalyzing sustainable investments. Studies have shown that targeted GE enhances the credibility of GFN and improves long-term, risk-adjusted returns (Steuer and Tröger, 2022; Wu and Song, 2023). Europe has adopted a unique blend of fiscal incentives, carbon taxation, and ESG reporting frameworks, positioning itself as a leader in global green financial governance (Zatonatska et al., 2024). However, disparities in financial systems and institutional capacity across member states present challenges that require further analysis.

2.5 Research Gap and Contribution of this Study

Although a growing body of research exists on GFN, INV, and RE transition, significant gaps remain. First, few studies adopt a resilience-based approach, especially one that constructs a comprehensive IRI, combining environmental, economic, and innovation indicators. Second, most existing research treats GFN, FD, and INV as independent drivers without modeling their interaction effects. However, exploring their interactive influence is critical in real-world systems. Third, empirical studies rarely use multi-equation modeling frameworks that simultaneously explore INV, RE transition, and GFN mobilization within a unified macroeconomic resilience agenda.

This study fills these gaps by constructing a novel IRI to assess IR. This study also incorporates various interaction terms to capture synergistic effects. Applying DCCE to address cross-sectional dependence and ARDL for robustness and endogeneity control is also making this study viable. Moreover, Europe offers a heterogeneous yet data-rich environment for examining green financial-technological transitions in a comparative setting. Lastly, the combination of numerous but relevant variables related to the considered theme makes this study a novel contribution to the subject area.

3. Data and Methods

3.1 Data Details

This study utilizes a panel dataset of 25 European countries covering the period 2003 to 2022. Data is collected from OECD sources. The selection of European countries is deliberate and aligned with the thematic focus of this research, namely, sustainable IR, GFN, and innovation-driven transitions. Europe serves as a highly relevant empirical context due to its leadership in GFN mobilization, the implementation of ambitious carbon-free frameworks, such as the European Green Deal, and the region's advanced digital and financial ecosystems. Additionally, the heterogeneity across European economies provides a rich analytical environment for examining how institutional, financial, and technological variables interact to influence IR and sustainability performance.

3.2 Theoretical and Empirical Modelling

3.2.1 Industrial Resilience Empirical Model

The theoretical foundation of the first empirical model is grounded in the Schumpeterian Growth Theory and the Dynamic Capabilities Framework. According to Schumpeter (1934), INV drives long-term industrial growth and adaptation, while the dynamic capabilities perspective (Teece et al., 1997) suggests that firms and industries can build resilience through the reconfiguration of internal and external competencies in response to external shocks. Moreover, Institutional Theory (North, 1990) highlights the role of financial institutions in shaping the enabling environment for IR. In this context, FD and GFN can serve as catalysts for building adaptive capacity and resilience to shocks in industrial systems. On the basis of this, the first empirical model, that is, the IR model in Equation 1, is formulated as:

$$IRI_{it} = \beta_0 IRI_{it-1} + \beta_1 FD_{it} + \beta_2 GFN_{it} + \beta_3 IoT_{it} + \beta_4 (GFNxFD)_{it} + \gamma Z_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (1)$$

Where Z_{it} represents the control variables (INV, EE, EPY, DIG).

The inclusion of FD is justified by its role in enhancing credit access and risk-sharing, which enables industries to invest in diversification and resilience-building activities (Jin and Liu, 2024). The GFN supports low-carbon investments, enhances environmental compliance, and contributes to structural resilience (Ur Rahman and Amjad, 2024). Furthermore, IOT facilitates access to advanced industrial methods, promoting agility and adaptation (Goldman and Nagel, 1993). The interaction term (GFN*FD) captures synergistic effects that reflect the benefits of GFN being amplified in more developed financial systems. Control variables such as EE and INV are included as they represent core components of resilience through efficiency gains and adaptive innovation (Aldieri et al., 2021; Muhammad and Hoffmann, 2024).

3.2.2 Industrial Innovation Empirical Model

This model draws on the Endogenous Growth Theory (Romer, 1990), which emphasizes that technological progress and innovation arise from investments in human capital, research, and knowledge spillovers. It also incorporates elements from the Technology Diffusion Theory (Comin & Hobijn, 2004), which recognizes the role of international knowledge transfers via trade and foreign direct investment (FDI) in driving domestic innovation. The integration of financial and environmental policy frameworks into innovation outcomes aligns with the Porter Hypothesis, which posits that well-designed environmental regulations can stimulate INV and competitiveness (Porter and Linde, 1995). Equation 2 presents the second INV model as follows:

$$INV_{it} = \beta_0 + \beta_1 GFN_{it} + \beta_2 FD_{it} + \beta_3 IoT_{it} + \beta_4 EPY_{it} + \beta_5 FDI_{it} + \beta_6 (IoTxDIG)_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (2)$$

The inclusion of GFN reflects its role in enabling the financing of R&D and green technology projects (Jian, 2023). Furthermore, the FD supports broad access to innovation capital. IOT is essential for transferring cutting-edge industrial knowledge, while FDI enhances learning-by-doing and innovation spillovers. The variable EPY accounts for regulatory pressure that can either stimulate or hinder innovation depending on policy design. The interaction term (IoT*DIG) explores how digital infrastructure amplifies the innovation-enabling effects of imported technology. These relationships are consistent with the innovation systems literature, which argues that financial, institutional, and technological variables interact in shaping national innovation performance (Chen et al., 2024; Cheng et al., 2024; Akhtar et al., 2024).

3.2.3 Renewable Energy and Energy Efficiency Transition Empirical Model

The third model in this work is based on the Environmental Kuznets Curve (EKC) Hypothesis and Ecological Modernization Theory. The EKC suggests that environmental degradation initially increases with income but eventually decreases as societies invest in cleaner technologies (Grossman and Krueger, 1995). Ecological Modernization posits that modern industrial societies can decouple growth from environmental harm through INV, EE and GFN (Mol and Sonnenfeld, 2000). The model also reflects the Technology Push Theory, which posits that investment in innovation and clean technologies is central to decarbonizing the industry. The RE transition model is presented in Equation 3.

$$RE_{it} = \beta_0 + \beta_1 IoT_{it} + \beta_2 GFN_{it} + \beta_3 MTEG_{it} + \beta_4 EE_{it} + \beta_5 ETX_{it} + \beta_6 (MTEGxFDI)_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (3)$$

In this model, IoT enables the adoption of efficient and renewable energy (RE) technologies, while GFN channels resources toward sustainable infrastructure. MTEG reflects innovation in the energy generation mix, often driven by research and development (R&D) and public-private partnerships. EE indicates system-wide productivity gains with reduced energy input, which is directly linked to the adoption of renewable energy. Moreover, the ETX serves as a market signal to shift industrial behavior toward renewables. The interaction term (MTEG*FDI) is included to investigate whether FDI enhances the role of mitigation technologies in driving energy transitions, particularly in countries lacking domestic innovation ecosystems. Many researchers support the inclusion of these variables with respect to RE transition (Khurshid et al., 2025b; Guo et al., 2023; Su et al., 2023; Cao et al., 2025).

3.2.4 Green Finance Mobilization Empirical Model

The final empirical model of this work is grounded in Public Finance Theory, Financial Liberalization Theory, and the Climate Finance Framework advocated by multilateral institutions. Public Finance Theory posits that GE and ETX shape the allocation of financial resources by internalizing externalities and directing capital toward socially optimal outcomes (Musgrave and Musgrave, 1989). Financial Liberalization Theory posits that easing restrictions in financial markets enhances access to capital and investment flows, thereby enabling the growth of green financial instruments, such as green bonds and ESG-linked loans (McKinnon, 2010). The Climate Finance Framework emphasizes that both domestic and international capital—enabled through strong institutional quality, supportive fiscal policy, and macroeconomic stability—are crucial for mobilizing green financial flows at scale (UNEP, 2021). Together, these theories provide a foundation for examining how fiscal, regulatory, and economic conditions influence GFN mobilization in Europe. Equation 4 presents the GFN mobilization model.

$$GFN_{it} = \beta_0 + \beta_1 FDI_{it} + \beta_2 GE_{it} + \beta_3 ETX_{it} + \beta_4 RPCI_{it} + \beta_5 INF_{it} + \beta_6 (GFNxGE)_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (4)$$

In all four models, μ_i unit fixed effects, λ_t time-fixed effects, and ε_{it} is the error term.

In this empirical model, FDI is included as a facilitator of external green capital and financial instruments (Ozturk and Acaravci, 2016). The GE on infrastructure and sustainability initiatives creates favorable conditions for private GFN, and ETX reflects the regulatory structure and market-based mechanisms that incentivize environmental investments (Wang et al., 2025). Real Per Capita Income (RPCI) captures the demand-side capacity for green products and services. At the same time, INF is a macroeconomic risk variable that can deter long-term investments. The interaction term GFN*GE tests whether public financial commitments enhance the credibility and volume of private GFN flows. This aligns with empirical findings that co-financing and institutional signaling reduce risks and crowd in private investment (Briera and Lefèvre, 2024).

3.3 Empirical Strategy

The Industrial Resilience Index (IRI) is formulated by a weighted aggregation of six normalized variables, with weights served as by experts based on policy significance and established importance in international frameworks, including OECD (2017)[5] and UNIDO (2021)[6]. This method emphasizes domain-specific priorities over data-driven techniques like PCA. Table 1 presents the details of IRI indicators and their corresponding weights.

Table 1: Details of Industrial Resilience Index Construction

Dimension	Indicators	Acronym	Weights
Productivity	Industrial Output	IVA	0.25
Environmental	Renewable Energy Share	RE	0.15
Efficiency	Energy Efficiency	EE	0.15
Sustainability	Greenhouse Gas Emissions (inv.)	GHG	0.10
Pressure	Demand-Based Emissions (inv.)	DBE	0.20
Adaptive Cap.	Industrial Innovation	INV	0.15

Note: The inverse values of GHG and DBE are used, as higher values imply lower resilience.

For normalization and to bring all variables into the [0,1] range, the min-max scaling based on the formula given in Equation 5 is employed:

$$X_{it}^{*} = \frac{X_{it} - \min(X_i)}{\max(X_i) - \min(X_i)} \tag{5}$$

For indicators exhibiting a negative correlation (GHG and DBE), the subsequent change is implemented:

$$X_{it}^{*} = 1 - X_{it}^{*} \; for \; i \,\epsilon\, \{GHG, DBE\} \tag{6}$$

The relative relevance emphasized in stated and existing literature serves as the basis for the expert judgment used to determine the weights allocated to the Industrial Resilience Index (IRI) components. Industrial Output (IVA) has a higher weight (0.25), which reflects its crucial role in resilience. Emission-related indicators—GHG (inv.) and DBE (inv.)—are assigned a cumulative weight of 0.30 due to their environmental significance, whilst the other dimensions—RE, EE, and INV—are uniformly weighted at 0.15 to reflect their roles in adaptation, efficiency, and sustainable transformation.

[5] *https://www.oecd-ilibrary.org/environment/green-growth-indicators-2017_9789264268586-en*

[6] *https://www.unido.org/sites/default/files/files/2021-11/IDR2022-main-report-web.pdf*

Moreover, six normalized variables are subjected to PCA, which extracts the loadings of the first PC and uses them as weights to calculate the final index. Equation 7 presents those:

$$IRI_{it} = w_1 IVA^*_{it} + w_2 RE^*_{it} + w_3 EE^*_{it} + w_4 INV^*_{it} + w_5(1 - GHG^*_{it}) + w_6(1 - DBE^*_{it}) \quad (7)$$

After the construction of IRI, this work employed a rigorous empirical approach to analyze the factors influencing IR and INV, RE transition, and GFN in European economies. This study used a structured empirical strategy aligned with the characteristics of the panel dataset and the nature of the research questions. The aim is to ensure the robustness and reliability of the econometric analysis. The initial step involved conducting descriptive statistics to examine the distributional properties of the variables.

After calculating the descriptive analysis, this work assessed the presence of cross-sectional dependence (CSD) using the Pesaran (2015) test. This CD test is widely recognized for its effectiveness in detecting contemporaneous correlations across cross-sectional units in macro panels. This test is particularly relevant in the context of this study, specifically for European countries operating within an increasingly integrated economic and financial system. After that, the stationarity properties of the variables were tested using the Levin et al. (2002) panel unit root test. The LLC test assumes a common unit root process across the panel. However, it allows for individual heterogeneity in short-term dynamics. This test was chosen due to its suitability for panels with moderate time dimensions and because it is known for having greater statistical power in small samples compared to other first-generation tests.

Considering that CSD presents and potentially exhibits slope heterogeneity, the primary estimation technique applied in this study is the Dynamic Common Correlated Effects (DCCE) estimator. This technique was initially developed by Chudik and Pesaran (2015). The DCCE estimator is suitable for macro-panel datasets where countries may be exposed to unobserved common shocks, such as global financial crises, coordinated EU policy responses, or technological shifts. It also allows individual countries to respond differently. The DCCE technique controls for these factors by including cross-sectional averages of both dependent and independent variables in the regression, thereby mitigating bias from unobserved factors and capturing heterogeneous dynamics. Moreover, DCCE is well-suited to panels where the time dimension (T) exceeds the cross-sectional dimension (N). This study encompasses 25 countries (Table A, Appendix) over 20 years. Moreover, unit root tests established that all variables, except one, were stationary at level (I(0)), hence reinforcing the validity of our estimations. Similarly, the ARDL method is utilized because the variables are a combination of I(0) and I(1), hence eliminating the necessity for all series to be stationary at the same level. ARDL offers an automatic error correction mechanism (ECM) that measures the rate of adjustment back to equilibrium after cointegration has been verified by bounds testing.

4. Results and Discussion

The descriptive statistics values presented in Table 2 reveal notable variations in the core variables of the study. It is evident that ETX and DBE have the highest standard deviations and mean values. This indicates large disparities in ETX levels and emission intensities across European countries. In contrast, EE exhibits the lowest standard deviation. This implies that countries in the sample have relatively similar energy efficiency (EE) performance per unit of output. The lowest mean is observed in IRI, which suggests that resilience is still a developing attribute in industrial systems. High skewness and kurtosis values are found for INF and INV. This points to non-normal distributions with extreme values, likely due to periodic shocks or uneven innovation capacities across countries. Further details are presented in Table 2.

The CSD test results, based on the Pesaran (2015) CD test, are also presented in Table 2. Results are highly significant for nearly all variables, indicating strong interdependencies among European countries. These results justify the application of the DCCE estimator, which explicitly controls for unobserved common shocks and inter-unit correlations. Furthermore, the unit root testing outcomes are also depicted in Table 2. The results indicate that all variables are stationary at levels except for RE, which becomes stationary after first differencing. This stationarity structure confirms that the majority of variables are suitable for use in level-based panel regressions. The fact that only one variable required differencing reinforces the validity of the dataset for econometric modeling under the DCCE framework, which is a reliable method with mixed-order integration, as long as most variables are I(0).

Table 2: Descriptive Statistics, CSD and Unit Root Outcomes

Variables	Abbr.	MEAN	SD	VAR	SKN	KTS	CSD	Unit Root I(0)	Unit Root I(1)
Industrial Resilience	**IRI**	0.302	0.089	0.008	0.238	3.183	46.85***	-10.84***	
Financial Development	**FD**	0.570	0.209	0.044	-0.212	2.003	19.14***	-3.941***	
Digitalization	**DIG**	70.10	16.33	266.6	-0.575	2.722	66.92***	-10.40***	
Green Finances	**GFN**	3.883	0.654	0.428	-0.279	2.336	63.31***	-12.90***	
Renewable Energy	**RE**	7.546	8.134	66.17	1.812	6.712	64.55***	0.045	-6.987***
Environmental Policy	**EPY**	2.287	1.078	1.162	-0.245	2.214	-2.607***	-13.48***	
Import of technology	**IOT**	21.41	1.320	1.742	-0.457	2.873	49.85***	-5.820***	
Government Expenditure	**GE**	25.84	2.509	6.296	1.082	5.404	46.75***	-2.094***	
Environmental Taxes	**ETX**	146.8	195.8	3810	1.940	5.733	51.63***	-8.233***	
Demand-based emission	**DBE**	162.7	212.1	4496	2.199	7.789	35.22***	-2.219***	
Industrial Output	**IVA**	24.74	1.515	2.294	-0.299	2.340	56.88***	-11.08***	
Industrial innovation	**INV**	15.23	7.270	52.86	4.511	44.99	8.422***	-7.574***	
Inflation	**INF**	3.069	4.594	21.10	7.774	106.5	59.57***	-8.130***	
Welfare cost	**WC**	3.961	1.388	1.927	1.324	5.936	51.87***	-5.620***	
Energy Efficiency	**EE**	0.590	0.031	0.001	-0.140	3.313	62.73***	-11.46***	
Real Per Capita Income	**RPCI**	4.370	0.298	0.089	-0.118	2.060	49.54***	-2.334***	
Foreign direct investment	**FDI**	22.75	1.767	3.121	-0.419	3.631	6.110***	-8.358***	
Mitigation tech. Energy generation	**MTEG**	24.45	9.595	92.06	1.129	5.271	27.76***	-2.761***	

*Note: ***(p < 0.01)*

4.1 Dynamic Common Correlated Effects Results

Table 3 contains estimates of DCCE outcomes. In all four models, the lagged dependent variables are positive and are statistically significant, demonstrating temporal persistence. Model 1 (IRI), which indicates moderate route dependence, comes in second at 0.371, after Model 3 (RE), which exhibits the strongest inertia (0.416). Model 4 (GFN) and Model 2 (INV) demonstrate significant persistence, with coefficients of 0.305 and 0.294, respectively, indicating the sustained impact of previous trends on present outcomes.

The first model explains IRI by combining institutional, technological, financial, and ecological components. The positive effects of FD (0.184) and GFN (0.019) show that industrial systems' adaptive ability and shock absorption are supported by access to a range of financing alternatives. This aligns with the green finance strategy and financial integration initiatives in Europe, which aim to reduce financing barriers for investments focused on sustainability. This was also expressed by many researchers, including, Ur Rahman and Amjad (2024), and Jin and Liu (2024). Additionally, INV (0.020) and IOT (0.016) significantly enhance IR. This result highlights the strategic importance of cutting-edge technologies and research and development in modernizing industrial infrastructure. Khurshid et al. (2025a) also demonstrated that innovation drives the development of cleaner technologies and helps firms achieve improved IR. Whereas, Brookbanks and Parry (2024) showed that the IOT can boost the adaptive capacity of industries by accelerating the diffusion of clean and efficient processes and supporting IR. Similarly, DIG (0.022) and EE (0.894) boost resilience by enhancing data-driven decision-making and operational optimization. This was also demonstrated by Zhang (2025). The positive effect (0.060) of the GFN*FD interaction demonstrates the importance of collaboration between GFN and financial market maturity in enhancing IR prospects in Europe. This suggests that IR in Europe is most effectively enhanced when mature and efficient financial systems support green financial instruments. This implies that GFN impact is amplified in economies with well-developed financial markets that can mobilize, allocate, and sustain green investments efficiently.

The dependent variable in the second model is industrial innovation (INV). The findings highlight the significance of both specific green financial tools and the growth of the financial sector as a whole in promoting technological advancement, with GFN (1.321) being identified as key drivers of INV. Raman et al. (2025) found the same results regarding GFN. This also aligns with the plans of EU initiatives such as Invest EU and Horizon Europe, which combine public and private investment to drive INV. In addition to promoting innovation, EPY (0.698) and IOT (1.321) support the Porter Hypothesis, which posits that well-crafted laws encourage the development of technical solutions (Porter and Linde, 1995). Furthermore, access to international knowledge spillover is facilitated by FDI (0.221). Xuan (2025) demonstrated that FDI serves as a conduit for transferring cutting-edge technologies and innovative practices. Furthermore, the importance of absorptive capacity is highlighted by the significant effect of IOT*DIG (0.027). This showed that digital infrastructure enhances the efficient utilization of imported technologies in Europe. This suggests that digital infrastructure enhances a nation's ability to integrate and effectively apply imported technologies. This synergy suggests that digital readiness enhances the productivity and innovation gains derived from technology transfer, making INV more impactful in digitally advanced economies.

The third model investigates the factors influencing the deployment of renewable energy (RE) and was evaluated using the DCCE. The findings presented in Table 3 indicate that the adoption of RE is positively impacted by GFN (0.765) and IOT (1.038). These outcomes demonstrate how European nations rely on both green investments and imported clean technologies to achieve their climate goals. Empirical literature also shows that MTEG has been found to positively influence the uptake of renewables and energy efficiency (Khurshid et al., 2025b). Studies also showed that the availability of GFN further reduces the cost and perceived risk of RE investments, especially in early-stage technologies (Yoshino et al., 2021; Guo et al., 2023). It is also evident from the results that the system's ability to integrate renewables is supported by EE (2.315), although this is only slightly significant. Moreover, ETX (0.0010) is very successful and fits perfectly with the EU's carbon pricing schemes, which encourage investment in renewable energy. Su et al. (2023) also showed that ETX provides market-based signals that can promote resource optimization and energy transition. The interaction term MTEG*FDI also showed a positive impact (0.061). This suggests that FDI enhances the efficiency of clean technologies in renewable energy (RE) transitions. Given the EU's ambitious climate targets under the Green Deal, this finding underscores the importance of maintaining an open and innovation-driven investment environment. It suggests that attracting strategic Foreign Direct Investment (FDI), particularly in green tech sectors, can significantly enhance the diffusion and performance of advanced mitigation technologies across European industries. This definitely helps countries meet their environmental goals more efficiently.

Lastly, the fourth empirical model examines the variables influencing GFN in Europe. Results in Table 3 show that FD (0.041) and GE (0.094) exert significant and beneficial influences. This indicates that a robust financial sector and active fiscal policy are crucial for the development of green financial markets. Results are in line with the findings of Wang et al. (2025). Furthermore, ETX (0.009) increases demand for low-carbon financial instruments, which in turn boosts GFN (Wu and Song, 2023). The stronger demand for sustainability in wealthier societies is evident in the positive correlation between GFN and RPCI (0.039). In contrast, the negative correlation between GFN and INF suggests that macroeconomic instability inhibits long-term investment. A critical component of the EU Recovery and Resilience Framework and larger sustainable finance projects is the multiplier effect of combining public investment with green financial instruments. This is highlighted by the interaction term GFN*GE (0.035). For Europe, this finding supports the idea that coordinated public-private financing can accelerate the green transition by de-risking green projects, encouraging private sector participation, and enhancing the effectiveness of fiscal stimulus in achieving a long-term sustainability agenda.

The model's robustness was validated through a series of post-estimation diagnostic tests following the Dynamic Common Correlated Effects (DCCE) estimation. All models incorporated cross-sectional averages and lagged dependent variables to account for unobserved common factors and dynamic connections. The results of the Pesaran (2004) CD test indicate no significant cross-sectional dependency (p-values > 0.05), demonstrating that the incorporation of cross-sectional averages effectively alleviated residual dependence. The Slope Heterogeneity ($\tilde{\Delta}$) test findings are statistically significant at the 1% level in all models, indicating heterogeneity in slope coefficients and validating the application of a non-pooled estimator. The Westerlund–Edgerton test further demonstrates the absence of structural fractures in the panel data (p-values > 0.10), thereby reinforcing the reliability and stability of the DCCE specification.

Table 3: Dynamic Common Correlated Effects Estimates

Variable	Model 1: IRI	Model 2: INV	Model 3: RE	Model 4: GFN
L.IRI	0.371*** (0.091)			
L.INV		0.294** (0.102)		
L.RE			0.416*** (0.087)	
L.GFN				0.305*** (0.074)
FD	0.184** (0.060)			0.041** (0.012)
GFN	0.019** (0.010)	3.054*** (1.201)	0.765** (0.331)	
IOT	0.016*** (0.002)	1.321** (0.518)	1.038*** (0.465)	
INV	0.020*** (0.008)			
EE	0.894*** (0.090)		2.315* (1.251)	
EPY	0.078*** (0.004)	0.698*** (0.320)		
DIG	0.022** (0.001)			
FDI		0.221*** (0.092)		

GE				0.094** (0.011)
ETX			0.0010*** (0.0002)	0.009*** (0.003)
MTEG			0.136** (0.058)	
RPCI				0.039** (0.018)
INF				–0.031*** (0.015)
IOT*DIG		0.027** (0.011)		
MTEG*FDI			0.061* (0.026)	
GFN*GE				0.035*** (0.004)
GFND*FD	0.057*** (0.015)			
_cons	–0.611*** (0.041)	8.104** (2.742)	–23.54** (7.810)	3.678*** (0.179)

	Model 1	Model 2	Model 3	Model 4
Cross-sectional averages used	Yes	Yes	Yes	Yes
Lag of dependent variable included	Yes	Yes	Yes	Yes
CD Statistic (Pesaran)	1.12	0.87	1.05	0.98
CD Test p-value	0.261	0.384	0.294	0.329
Slope Heterogeneity (Δ̃ test)	6.48***	4.79***	5.62***	5.91***
Break Test (Westerlund–Edgerton)	1.14	0.92	1.06	1.01
Break Test p-value	0.254	0.359	0.291	0.312

*Note: *(p < 0.1), **(p < 0.05) and ****(p < 0.01)

4.2 Robustness Outcomes

According to the robustness check using ARDL estimations (Table 4), all four empirical models yield consistent and theory-aligned findings. In Model 1, IRI is substantially influenced by its historical values (0.244), as well as by FD, GFN, IOT, INV, EE, and DIG, all of which exhibit positive and significant effects. This signifies that in Europe, a synergy of financial and technological preparedness bolstered by INV and sustainable investments fosters IR. The interaction term between GFN and FD (0.132) indicates that GFN is more effective when combined with financial stability. Model 2 substantiates that INV is driven by GFN (2.089), FD (1.116), IOT, EPY, and FDI, with IOT*DIG also exhibiting a substantial positive correlation, indicating that innovation stems from robust financial systems and synergies with digital technologies. In Model 3, RE exhibits significant persistence (0.856) and is influenced by IOT, GFN, MTEG, EE, and ETX. The connection between MTEG and FDI further promotes the use of green energy. Finally, Model 4 identifies GFN as path-dependent and positively affected by FD, GE, ETX, and RPCI while being impeded by INF. The term of interaction GFN*GE (0.041) further emphasizes the significance of public co-financing. The high negative ECT values, together with elevated F-statistics in the Bounds Test, furnish compelling evidence of a viable ARDL model specification, illustrating both short-run dynamics and long-run equilibrium linkages across all four estimated models. These findings highlight the associated roles of finance, policy, and technology in driving sustainable industrial and energy transformations in Europe.

Table 4: ARDL Estimation Results

Variable	Model 1: IRI	Model 2: INV	Model 3: RE	Model 4: GFN
L. Var.	0.244** (0.098)	0.192* (0.113)	0.856*** (0.049)	0.067** (0.034)
FD	0.376*** (0.118)	1.116** (0.417)		0.201** (0.078)
GFN	0.156** (0.073)	2.089** (0.892)	0.844*** (0.361)	
IOT	0.022** (0.010)	0.974* (0.501)	0.483*** (0.201)	
INV	0.028*** (0.009)			
EE	1.267** (0.503)		2.009*** (0.729)	
EPY	0.054** (0.027)	0.804** (0.391)		
DIG	0.016*** (0.005)			
GFN*FD	0.132** (0.059)			
IOT*DIG		0.091*** (0.007)		
MTEG			0.099** (0.038)	
ETX			0.108*** (0.005)	0.017*** (0.006)
FDI		0.217** (0.094)		
MTEG*FDI			0.038*** (0.004)	
GE				0.132** (0.061)
RPCI				0.054** (0.025)
INF				–0.087** (0.034)
GFN*GE				0.041*** (0.003)
_cons	0.097 (0.103)	4.72*** (1.819)	0.641 (1.073)	0.056** (0.025)
ECT	–0.397*** (0.129)	–0.284*** (0.097)	–0.421*** (0.101)	–0.311*** (0.088)
Bounds Test (F-stat)	6.182**	5.701**	7.014***	6.405**

*Note: *(p < 0.1), **(p < 0.05) and ****(p < 0.01)

5. Conclusion and Recommendations

This study has examined the role of GFN, FD, and IOT in shaping IR, INV, RE adoption, and GFN mobilization across 25 European countries from 2003 to 2022. Utilizing a robust empirical framework that combines DCCE with ARDL estimation, the analysis provides comprehensive insights into the interconnected drivers of sustainable industrial transitions. The development of a novel IR Index, along with interaction terms, enabled a novel evaluation of how financial, technological, and policy factors collectively influence resilience and sustainability outcomes.

The findings of the current work indicate that both GFN and FD significantly enhance IR and INV. Technological imports and EE are also shown to be strong contributors, not only in improving IR but also in facilitating RE transitions. Interaction effects reveal that the effectiveness of GFN increases when supported by well-developed financial systems. At the same time, the benefits of IOT are amplified in digitally advanced economies. The study further showed that macroeconomic stability, reflected in low inflation and high real income, along with government expenditure and environmental taxes, plays an essential role in stimulating GFN. These results are consistent with Schumpeterian growth theory, the endogenous growth framework, and the dynamic capabilities perspective, all of which emphasize innovation, adaptation, and the co-evolution of institutions and technology as central to sustainable development in Europe.

Several recommendations emerge from these findings. First, there is a need to strengthen GFN ecosystems in Europe through a combination of public and private initiatives. Policies that support the issuance of green bonds incentivize environmental investments and deepen financial inclusion, thereby enhancing the sustainability of industrial systems. Second, promoting technological transfer must be accompanied by investments in digital infrastructure to maximize the innovation potential of the Internet of Things (IoT). This calls for coordinated efforts that align foreign direct investment policies with digital development strategies. Third, governments of European nations should maintain regulatory pressure through stringent EPY and ETX mechanisms that encourage industries to adopt clean production and low-emission energy systems. Fourth, ensuring macroeconomic stability is vital to creating a predictable investment climate that favors long-term green financial instruments. Lastly, the evidence supports the design of synergistic reforms where financial market development, environmental regulation, and innovation policy are implemented as complementary tools rather than isolated interventions.

Limitations and Future Directions for Research

A few limitations of the current study should be acknowledged. The empirical analysis is based on macro-level data that may mask sectoral or firm-level heterogeneity in resilience responses and investment behavior. Additionally, the study captures multiple dimensions of sustainability. However, it does not explicitly account for institutional quality, labor dynamics, or education systems. These factors may also influence the observed outcomes. Future research could expand this framework by incorporating firm-level microdata to assess IR and INV at the enterprise scale. It may also be valuable to introduce governance indicators and explore the moderating role of institutional quality in defining GFN effectiveness. Also, comparative studies across continents could further test the external validity of the IRI and the proposed interaction effects.

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Appendix

Table A: Countries Understudy

Code	Country Name	Code	Country Name	Code	Country Name	Code	Country Name
AUS	Austria	DEU	Germany	LVA	Latvia	SVK	Slovakia
BEL	Belgium	GRC	Greece	LUX	Luxembourg	SVN	Slovenia
CZE	Czech Republic	HUN	Hungary	NLD	Netherlands	ESP	Spain
DNK	Denmark	ISL	Iceland	NOR	Norway	SWE	Sweden
EST	Estonia	ITA	Italy	POL	Poland	CHE	Switzerland
FIN	Finland	LTU	Lithuania	ROU	Romania	TUR	Turkey
FRA	France						