

AIZANOI FINANCE REVIEW

ISSUE:8 / 2026
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GREEN FINANCE, GREEN INNOVATION, AND SUSTAINABILITY UNCERTAINTY: EVIDENCE FROM THE G7

YEŞİL FİNANS, YEŞİL İNOVASYON VE SÜRDÜRÜLEBİLİRLİK BELİRSİZLİĞİ: G7 ÜLKELERİNDEN BULGULAR

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ARTICLE INFO	ABSTRACT
<p>Received 07.08.2026</p> <p>Revized 16.09.2026</p> <p>Accepted 03.10.2026</p> <p>Article Classification: Research Article</p> <p>JEL Codes F30 F40 F65</p>	<p>This study examines the effects of green finance and green innovation on ESG-related sustainability uncertainty in G7 countries over the period 2002–2021. Long-run relationships are investigated using the Durbin–Hausman and Westerlund–Edgerton cointegration tests, while coefficients are estimated through the Augmented Mean Group (AMG) and regularized Common Correlated Effects (rCCE) estimators. The findings reveal significant cross-country heterogeneity. Green finance reduces sustainability uncertainty in the UK and Canada but increases it in Germany, Italy, and the USA. Green innovation lowers uncertainty in Canada and the USA. The interaction between green finance and green innovation mitigates uncertainty in Italy and the USA but intensifies it in Canada. Overall, the effectiveness of green finance and innovation depends on country-specific institutional and policy frameworks, highlighting the need for coordinated and innovation-oriented sustainability strategies.</p> <p>Keywords: Green Finance, Green Innovation, ESG-related Uncertainty Index, Westerlund and Edgerton Cointegration Test, Durbin-Hausman Cointegration Test</p>

MAKALE BİLGİSİ	ÖZ
<p>Gönderilme Tarihi 07.08.2026</p> <p>Revizyon Tarihi 16.09.2026</p> <p>Kabul Tarihi 03.10.2026</p> <p>Makale Kategorisi Araştırma Makalesi</p> <p>JEL Kodları F30 F40 F65</p>	<p>Bu çalışma, 2002-2021 dönemi boyunca G7 ülkelerinde yeşil finans ve yeşil inovasyonun ESG ile ilgili sürdürülebilirlik belirsizliği üzerindeki etkilerini incelemektedir. Uzun vadeli ilişkiler, Durbin-Hausman ve Westerlund-Edgerton eşbütünleşme testleri kullanarak araştırılırken, katsayılar AMG ve rCCE tahmincileri aracılığıyla hesaplanmıştır. Bulgular, ülkeler arası önemli bir heterojenlik ortaya koymaktadır. Yeşil finans, İngiltere ve Kanada'da sürdürülebilirlik belirsizliğini azaltırken, Almanya, İtalya ve ABD'de artırmaktadır. Yeşil inovasyon, Kanada ve ABD'de belirsizliği azaltmaktadır. Yeşil finans ve yeşil inovasyon arasındaki etkileşim, İtalya ve ABD'de belirsizliği azaltırken, Kanada'da artırmaktadır. Genel olarak, yeşil finans ve inovasyonun etkinliği, ülkeye özgü kurumsal ve politika çerçevelerine bağlıdır ve koordineli ve inovasyon odaklı sürdürülebilirlik stratejilerine duyulan ihtiyacı vurgulamaktadır.</p> <p>Anahtar Kelimeler: Yeşil Finans, Yeşil İnovasyon, ESG ile ilişkili Belirsizlik Endeksi, Westerlund ve Edgerton Eşbütünleşme Testi, Durbin-Hausman Eşbütünleşme Testi</p>

Atıf (Citation): Bektur, Ç. (2026). "Green Finance, Green Innovation, and Sustainability Uncertainty: Evidence from the G7", *Aizanoi Finance Review*, (8): 54-77



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Introduction

The increasing importance of sustainable development on a global scale raises concerns about national ESG performance and the uncertainties surrounding it, which is a key indicator in this process (Chow and Fung, 2025). National ESG performance measures a country's level of economic development by considering its performance in environmental protection, social development, and good governance (Niu, 2024). Improving countries' ESG performance contributes to international competitiveness and sustainability by accelerating the green transition and the shift to a low-carbon economy at national and global levels (Tan et al., 2025). Furthermore, country ESG assessments provide valuable information for policymakers and investors by identifying potential risks and opportunities associated with a country's ESG profile (Jiang et al., 2022).

Country-level ESG performance is increasingly exposed to various uncertainties and risks that threaten sustainability (Ongan et al., 2025a). ESG-related uncertainty stems from developments in disclosure standards, local and global policy discourses, investor activism, and reputational shocks. Therefore, its critical impact on financial markets and sustainability makes this uncertainty a decisive factor across a wide range of areas, including capital allocation, corporate innovation, strategic positioning, and global competitiveness (Sultana, 2026). While national ESG scores reflect countries' sustainability efforts, ESG-related uncertainty captures the risks and vulnerabilities that hinder the realization of these efforts (Doğan and Zeren, 2025). Ongan et al. (2025b) have developed an index (ESGUI) to measure uncertainty regarding sustainability which combines text mining techniques applied to the Economist Intelligence Unit's monthly country reports with the World Uncertainty Index. ESGUI allows for a multidimensional and integrated measure of risk, stability, and reliability related to sustainability within the environmental, social, and governance elements of ESG. A higher ESGUI value is associated with impediments to sustainability, while a lower index corresponds to more rapid sustainable development (Dou et al., 2025).

Numerous studies in recent literature have investigated the relationship between ESGUI and energy transition, economic activities, financial markets, and risk factors. ESGUI is associated with renewable energy dynamics (Zhao et al., 2025), critical mineral markets (Özkan et al., 2025b), clean energy market (Aydoğdu and Doğan, 2026; Akadiri and Özkan, 2026), cryptocurrency volatility (Dutta, 2026), fossil fuel prices (Olanrewaju et al., 2025), oil prices (Qin et al., 2025a), and stock market returns (Abbas and Adebayo, 2025). In addition, ESGUI has been shown to influence monetary policy effectiveness (Huang et al., 2026), global ESG equity market risks (Cui and Maghyreh, 2025), energy preferences (Anbea et al., 2025), green asset returns (Wang et al., 2026a), and portfolio management (Müller and Joubrel, 2025). Dou et al. (2025) have explored the role of artificial intelligence and green finance in shaping uncertainty. Moreover, Khan et al. (2025) examine the effects of green innovation, financial reform, and effective governance on ESGUI, while Zeren et al. (2025) investigate the influence of financial indicators, such as gold and oil prices, on ESGUI. Qamruzzaman et al. (2025) have shown that ESGUI adversely affects green growth by hindering policy stability and sustainable investments. Furthermore, Sultana (2026) highlights that sustainability-related uncertainty transcends national borders, with global ESG sensitivity and international policy commitments significantly influencing national ESGUI scores. Consistent with this view, Nyakurukwa et al. (2025) have reported the presence of regional and inter-country diffusion of sustainability uncertainty.

Although the existing literature on ESG-related uncertainty demonstrates a link between ESGUI and various economic and financial indicators, the macroeconomic determinants of ESGUI are not fully understood, and international evidence is still required. This study contributes to the literature by addressing the impact of green finance (GRF) and green innovation (GRIN) on ESGUI from a country-level macroeconomic perspective, using an international sample.

To mitigate ESGUI, significant investments need to be made in numerous projects targeting environmental, social, and governance areas. Creating a suitable financial environment and ensuring continuous and adequate financial support for the success of such initiatives is crucial (Zheng et al., 2025). At this point, GRF bridges the financing gap, directing capital towards climate-friendly initiatives and integrating ESG factors into decision-making processes (Edmans and Kacperczyk, 2022). This innovative finance concept is a set of policies encompassing guidelines such as green bonds, green loans, and funds (Cojoianu et al., 2025). GRF, which generally covers financial services provided for the financing and risk management of projects in areas such as environmental protection, clean energy, energy conservation, green transportation and buildings (Liu and Guo, 2025), plays an important role in the country's ESG performance in these aspects (Ma and Chang, 2023). Zheng et al. (2025) have emphasized that GRF can affect national ESG performance by accelerating green technology development.

GRF reduces carbon emissions and improves air quality by increasing resource efficiency through reallocation of financial resources, and strengthening environmental governance (Meng et al., 2025). In addition, GRF supports renewable energy development by alleviating financing constraints and enhancing GRIN capacity (Zhu et al., 2025). GRF and renewable energy are also fundamental elements in ensuring environmental quality (Jarjari et al., 2025). Moreover, GRF, especially when integrated with technologies such as fintech, enhances the level of corporate risk-taking, information transparency, and disclosure quality, thereby facilitating the green transformation of companies and the economy. Access to green loans under favourable conditions is largely contingent upon firms' compliance with ESG requirements (Yao et al., 2025). Furthermore, GRF promotes market transparency through standardized sustainability reporting and benefits efficient capital allocation and effective capital utilization by investors (Zheng et al., 2025). Empirical evidence from Dou et al. (2025) has indicated that GRF reduces ESG market volatility, identifying GRF as a significant hedging mechanism against sustainability uncertainties.

Another key instrument supporting sustainable development is green innovation (GRIN) (Wang and Zhang, 2025). GRIN is a set of green processes that reduce environmental pollution, save costs, increase resource efficiency, and create economic value (Zheng et al., 2023). Therefore, it is closely related to the concept of ESG in terms of undertaking environmental responsibilities not only at the firm level but also at the national level (Ma and Chang, 2023). Furthermore, GRIN significantly impacts the energy sector by increasing clean production processes and more efficient renewable energy systems. GRIN facilitates economic structural transformation, improves national competitiveness and wealth, expands employment opportunities, enhances public health, and reduces environmental management costs. These channels collectively strengthen social welfare and governance levels, thereby enhancing national ESG performance. (Niu, 2024). The existing literature generally confirms a positive relationship between innovation and ESG (Yang et al, 2024; Wang and Zhang, 2025; Long et al, 2023).

In addition, the interaction between GRF and GRIN offers a pathway to strengthen sustainable development. GRF instruments promote eco-innovation by improving access to finance, reducing cost of debt, and expanding the availability of commercial credit (Chi et al., 2025), directing funds towards green technology-focused R&D activities (Li et al., 2025), and providing favourable conditions and advantageous incentives for innovation activities (Xu et al., 2025a). Increased investments in R&D enhances environmental sustainability through the development of sustainable materials, clean technologies, and eco-innovations (Wu and Bianchi, 2026). On the other hand, green technologies, supported by sustainable transformation, drive ESG performance by enabling the development of green financial instruments (Wang et al., 2026a). In recent years, many countries have implemented GRF-oriented policies to direct financial flows to sustainable sectors, green their financial systems, and promote green technology innovation (Jiang and Ma, 2025). Thus, stability is ensured in innovation cycles, and mitigates the detrimental effect of conventional energy price volatility on sustainable investments (Dou et al, 2025). Deng et al (2024) have highlighted that clean technology innovation significantly mediates the positive impact of GRF on green growth. Similarly, Li et al (2025) have demonstrated that the carbon-emission-reducing effect of GRF is substantially increased with green technological innovation.

The positive impacts of GRF and GRIN on sustainability and national ESG suggest that developments in these areas may also contribute to mitigating ESGUI. Given this critical role, it is crucial to examine the link between GRF and GRIN and ESGUI on an international scale, considering the uncertainty dimension alongside ESG factors, an area that remains insufficiently explored in the literature. Therefore, supplementing the existing literature (Nawaz and Su, 2026; Dou et al., 2025), this study presents international empirical evidence on the impact of GRF and GRIN on ESGUI. Nawaz and Su (2026) have found that ESGUI reduces investor confidence in green assets. This study has strengthened our understanding of GRF dynamics by focusing on the effects of ESGUI on GRF. In contrast to their approach, this study discusses the impact of GRF and GRIN on uncertainty by treating ESGUI as the dependent variable. Complementary evidence is offered by Dou et al. (2025), who examined the role of GRF and artificial intelligence in promoting sustainability. Accordingly, the present study investigates the impact of GRF and GRIN on sustainability uncertainty using an ESG-based sustainability uncertainty index, employing a panel of G7 countries for the period 2002-2021. The G7 countries offer particularly suitable research setting for examining the relationship between GRF, GRIN, and ESGUI. As major advanced economies, these nations exert a significant influence on international financial markets, trade, and investment flows, while playing a pivotal role in financing the transition toward low-carbon economies and shaping global sustainability policies. Their sophisticated financial systems and innovation capacities make them an ideal group for investigating whether GRF and GRIN can mitigate ESGUI. Furthermore, despite sharing the characteristics of advanced economies, G7 countries differ in terms of their energy structures, institutional frameworks, regulatory approaches, and sustainability policies. These variations allow for an analysis of whether the impacts of GRF and GRIN on ESGUI differ across these nations. Consequently, the G7 sample is selected—not with the intent of providing a statistical representation of all countries, but rather to facilitate a systematic investigation into the relationship between GRF, GRIN, and sustainability uncertainty within the context of economies that are highly influential on a global scale.

The rest of the study is structured as follows. Chapter 2 reviews the relevant literature on the relationship between GRF and GRIN and ESG. Chapter 3 describes the data and the econometric methodology. Chapter 4 reports the empirical results. Finally, Chapter 5 interprets the results and provides policy recommendations.

1. Literature review

The literature will be reviewed by systematically exploring the links between green finance and ESG, as well as between green innovation and ESG.

1.1. Green Finance and ESG

The impact of GRF on national ESG performance should be evaluated from environmental, social, and governance perspectives. From an environmental standpoint, GRF plays a critical role in reducing carbon and greenhouse gas emissions (Alvi et al., 2025) by promoting environmentally friendly enterprises and directing capital towards environmentally sectors (Hidayat et al., 2024), accelerating industrial sustainability (Lau et al., 2025), strengthening environmental regulations (Meng et al., 2025), and supporting technological R&D, eco-innovation initiatives, and human capital formation (Zhang et al., 2025; Safi et al., 2024). Progress in GRF therefore constitutes a fundamental pillar in achieving carbon neutrality and countering ecological hazards (Nawaz and Su, 2026). Furthermore, through green financial instruments such as green bonds and green loans, renewable energy projects (Omri et al., 2025) can be supported. It alleviates financial constraints by providing necessary funding for energy efficiency infrastructure (Ullah et al., 2025; Chi et al., 2025), renewable energy innovation (Shi and Shi, 2025) and low-carbon renewable energy transition (Gao, 2025). As firms and governments prioritize sustainability, they allocate greater financial resources to renewable energy projects, which increases environmental resilience through lower carbon emissions (Azam et al., 2025). Recent empirical evidence further demonstrates the positive role of GRF in reducing carbon emissions and fostering sustainable development (Lee et al., 2023; Liya et al., 2026). Kwilinski et al. (2025) have documented the positive relationship between GRF and national environmental ESG performance.

From a social perspective, GRF reduces poverty by improving national health and well-being, accelerating technological advancement, and increasing farmers' incomes and energy accessibility (Xu et al., 2025b). Financial resources mobilized through GRF create new employment opportunities by increasing business capacity and green investments and supporting process innovation (Fu et al., 2025). Since the implementation of GRF policies necessitates technical expertise and a skilled workforce compatible with advanced technologies, it will contribute to the social aspect of ESG through education and income growth.

At the governance level, GRF reinforces corporate principles including transparency and accountability. In particular, strict regulations in the issuance of green bonds improve governance frameworks in terms of openness, investor confidence, compliance with standards, and accountability (Azam et al., 2025). The financial discipline embedded in GRF instruments strengthens "Good Governance" principles by increasing stakeholder engagement, inclusive decision-making processes, and the effectiveness of regulatory compliance. The enforcement of environmental and social standards through relevant financial support encourages firms to discipline their internal governance structures, improve governance effectiveness, and aligning them with governance objectives within the ESG framework (Zheng et al., 2025).

Considering the overall impact of GRF on ESG, it is assessed that it has the potential to significantly increase national ESG scores (Sahu et al., 2026). Hidayat et al. (2024) have demonstrated that green bonds issued to finance sustainable projects contribute positively. Zheng et al. (2025) have found that GRF improves national ESG performance through green technology. In addition, Azam et al. (2025) have determined that GRF plays a critical role in improving national ESG preparedness. Liya et al. (2026) have emphasized the positive impact of the combination of these two variables on environmental sustainability, in addition to the contribution of GRF to national ESG performance improvement. Lau et al. (2025) have provided evidence that green bonds accelerate industrial sustainability by reducing carbon emissions, whereas Liu (2024) has demonstrated the relationship between strong national ESG performance and low green bond spreads.

From an uncertainty perspective, Dou et al. (2025) have found that GRF positively influences artificial intelligence, thereby contributing to a reduction in ESGUI. Nawaz and Su (2026) have further confirmed that sustainability uncertainty plays a significant role in the growth and promotion of GRF. Wang et al. (2026a) have identified a negative association between ESGUI and green bond yields in the short term, contrast with a positive relationship in the medium and long term, and additionally found that the hedging effectiveness of ESGUI increased in the long term. Moreover, Das et al. (2025) have demonstrated that the combined effects of geopolitical, climate, and ESG risks are strongly and positively associated with government green bond issuance. Akadiri and Özkan (2026) have confirmed that green bonds and carbon pricing mechanisms mitigate the negative impact of ESGUI on clean energy markets and reduce uncertainty.

1.2. Green innovation and ESG

From an environmental perspective, GRIN plays a pivotal role in reducing carbon emissions by improving the industrial and energy consumption structure, enhancing foreign direct investment quality, and fostering technological development (Xu et al., 2025a; Xie and Jamaani, 2022; Ali et al., 2022). It also increases energy efficiency (Sun et al., 2019) and supports the renewable energy transition (Ramzan et al., 2023). Strong innovation capabilities enable firms to find renewable energy-oriented solutions and adopt green technology-based production methods (Zhang et al., 2019). The primary focus of GRIN is on developing technologies that mitigate environmental damage by advancing in renewable energy, sustainable materials, and energy storage. By adopting green innovation-centered strategies, countries can unlock new economic opportunities and improve energy security and environmental quality through green innovation-focused strategies (Huang, 2024). Renewable technologies and innovation reduce ecological risks, especially under conditions of heightened uncertainty (Alofayson et al., 2026). Technologies that enable green innovations increase the use of environmentally friendly products (Ramzan et al., 2023). Notably, green technologies, such as purification, recycling, and cleaner production innovations, identify the CO₂ emission problem at its source and promote green growth by minimizing environmental impacts (Wei et al., 2025). GRIN, representing technologies, products, or processes that reduce environmental pollution and the intensity of raw material and energy use, enhances environmental efficiency and enables the reallocation of resources. In this regard, GRIN constitutes a fundamental component of improved ESG performance, particularly within the environmental management (Xu et al., 2025a). Recently, the scope of GRIN has expanded beyond traditional pollution-control technologies to include innovative products and processes that reduce ecological footprint and increase economic returns (Bindeeba et al., 2025). Consistent with this evolution, Obuobi et al.

(2024) have found that rising levels of GRIN reshape energy structure, reduce ecological footprint, and play a crucial role in environmental sustainability. Qamruzzaman (2026) has found that GRIN facilitates sustainability and the transition to a circular economy through environmentally friendly technologies and reduces ecological damage.

From a social perspective, GRIN accelerates organizational transformation and social progress by strengthening the green business and social responsibility profiles of firms and increasing employees' environmental awareness (Long et al., 2023). Firms that adopt energy-efficient green technologies in their production processes also protect employee health and help create a more attractive and socially sustainable working environments (Wang and Zhang, 2025). Green technological innovation generates employment opportunities in new green sectors by increasing the demand for highly skilled labor (Javed and Usman, 2025). He et al. (2023) have confirmed that green technological innovation promotes employment through improved air quality and industrial structure optimization. As R&D investments in GRIN increase, employment opportunities also increase (Aldieri et al., 2019). At the firm level, Olekanma et al. (2026) have reported that small and medium-sized enterprises actively engaged in GRIN experience stronger growth in green job creation. Finally, as environmental awareness rises among consumers, they are more likely to pay more for GRIN along with environmentally friendly attitudes and behaviours, which demonstrates the importance of social acceptance of GRIN activities (Chiambaretto et al., 2024). Fan et al. (2025) have confirmed the role of GRIN in advancing environmental justice and improving the well-being of vulnerable communities by addressing social inequalities.

From a governance performance perspective, GRIN improves firm performance by strengthening green supply chains and sustainable human resource management (Long et al., 2023). Environmentally friendly products developed through GRIN support corporate visibility and public perceptions of social responsibility, enabling firms to formulate business strategies aligned with green development objectives. The transition towards green and low-carbon production systems shapes corporate governance models and enhances ESG performance (Xu et al., 2025a). Transparency, stakeholder trust, and efficiency can be increased by implementing ESG strategies through innovation (Nagriwum et al., 2025). A green development-oriented culture, characterized by the integration of resource conservation and environmental protection values into business processes, is reflected in internal management and employee behaviour, thus playing a crucial role in corporate governance that supports competitiveness (Wang and Zhang, 2025). Ultimately, GRIN enhances countries' international discourse and influence by promoting green industries, increasing international competitiveness and economic efficiency, and improving the quality of national governance (Niu, 2024).

In summary, given its intrinsic alignment with ESG principles, GRIN drives low-carbon sustainable development and ESG performance by integrating economic performance and corporate value enhancement with social and environmental responsibilities (Wu et al., 2025). Jeon (2025) has demonstrated that national innovation capacity influences national ESG outcomes through three key elements. Specifically, corporate quality is related to governance performance by promoting regulatory compliance with isomorphic pressures, while human capital and digital infrastructure are primarily support social and environmental outcomes by enabling green technologies and providing data-driven ESG monitoring services. Zheng et al. (2025) have demonstrated that GRIN improves national ESG performance with the support of GRF, whereas Niu (2024) emphasizes that

government environmental protection expenditures increase GRIN, thereby improving national ESG performance. Conversely, Fu et al. (2023) have confirmed that stronger national ESG performance positively feeds back into GRIN. Gan and Lee (2025) have also found a positive relationship between high national ESG policy intensity and GRIN. From an uncertainty perspective, the development of GRIN, such as green technology patents, increases stability by reducing uncertainties surrounding future market regulations (Yi et al., 2025). Consistent with this view, Khan et al. (2025) have found that GRIN, along with innovative technologies, mitigates ESGUI by increasing clean energy investments.

1.3. Research gap

This study offers several novel contributions to the existing literature. First, prior research has focused on the relationships between GRF and national ESG performance or sustainability outcomes (Liu, 2024; Zheng et al, 2025; Dai et al, 2025; Lau et al, 2025; Meng et al, 2025; Sadeghi et al, 2025), as well as between GRIN and national ESG performance or sustainability (Gan and Lee, 2025; Islam et al, 2026; Jeon, 2025; Tong et al, 2026). Existing studies have evaluated GRF and GRIN separately. The interaction between these variables, particularly in the context of ESGUI mitigation, can yield different results when considered together. In addition to examining the individual impact of GRF and GRIN on ESGUI, this study provides a broader understanding of how the two variables work together. Most studies examining uncertainty measure sustainability uncertainty narrowly, failing to fully capture the environmental, social, and governance dimensions of uncertainty (Wang et al., 2026a). ESGUI, however, adopts a holistic approach to uncertainty across all three ESG dimensions and enabling the investigation of long-term sustainability impacts (Khan et al., 2025). Instead of analysing the impact of GRF and GRIN mechanisms separately in terms of ESGUI dimensions, this study emphasizes their cumulative effects on ESGUI, providing a comprehensive framework for evaluation.

Second, understanding the drivers of sustainability uncertainty from the perspective of GRF and GRIN through a multi-country analysis makes significant contributions to the literature. Insights derived from such an analysis can shed light on the design of strategic policy recommendations that will optimize the potential of these mechanisms in achieving sustainable development goals. Considering policy uncertainties and geopolitical risks, financial concerns and energy insecurity have increased, indirectly affecting European GRF (Alofaysan et al., 2026). As a result, determining how GRF and GRIN interact with sustainability uncertainty has become increasingly important.

Third, the G7 economies offer suitable research setting for examining the determinants of sustainability uncertainty, given their roles in global cooperation, trade, and economic growth, as well as their leading position in the green transition. These countries have experienced major international shocks, including the European sovereign debt crisis, the Covid-19 pandemic, and geopolitical risks (Wang et al., 2026b), and have shown fluctuations over time in terms of sustainability uncertainty. Moreover, high emissions, challenges in terms of political, social, and governance uncertainties, and ecological pressures pose to the achievement of sustainability goals in these economies (Kahn et al., 2025). The G7, which is expected to play a more active role in increasing its national ESG score and transitioning to a sustainable world (Amin et al., 2025), has ambitious commitments regarding climate, carbon neutrality, energy transition, and biodiversity. The realization of these commitments and the maintenance of ecological stability depend on effective governance, technological innovation, and the availability of appropriate financial

instruments (Qamruzzaman, 2026). In countries with steadily increasing GRF investments (Gu et al, 2023) and strong financial markets and innovation systems, examining the interaction between GRF and GRIN and as well as their implications for ESGUI, fills a significant academic gap in global innovation, finance policies and sustainability transitions. It should be noted, however, that the G7 countries are not viewed as a statistically representative sample of the entire global economy; rather, they serve as a meaningful research group for analysing these relationships within economies that exert significant influence on a global scale.

2. Data and model

The study provides a new perspective on the impact of green finance on ESG-based country sustainability uncertainty. The study considers the G7 countries (Germany, the USA, the UK, Italy, France, Japan, and Canada) and covers the period from 2002 to 2021. The positive effects of GRF and GRIN on sustainability and national ESG performance indicate that advancements in these areas may contribute to a reduction in ESGUI. In order to test this prediction, Model 1 is examined in the study. Furthermore, Model 2 is obtained by adding the $\ln\text{GRFGRIN}$ variable to Model 1, and the interaction between GRF and GRIN is examined. Thus, it is tested whether the impact of GRF on ESGUI changes as the level of innovation increases. Another objective is to analyse and compare the relevant policies, both individually and as a whole.

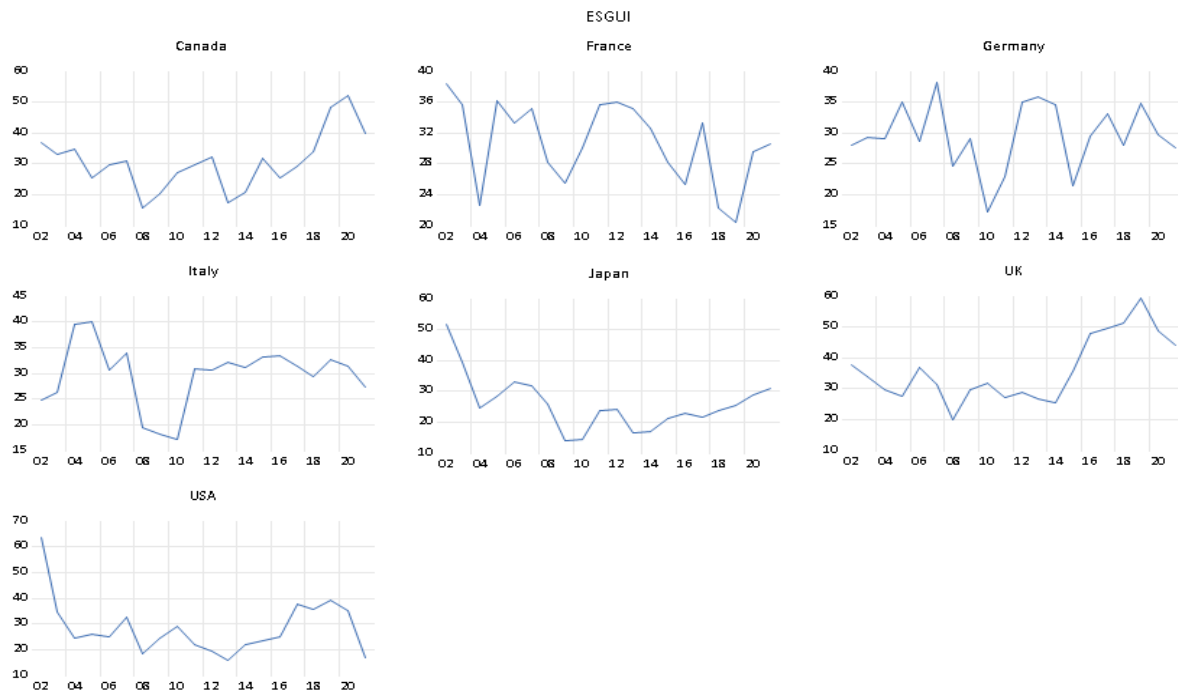
$$\text{Model 1: } \ln\text{ESGUI}_{it} = \beta_0 + \beta_1 \ln\text{GRF}_{it} + \beta_2 \ln\text{GRIN}_{it} + \varepsilon_{it} \quad (1)$$

$$\text{Model 2: } \ln\text{ESGUI}_{it} = \beta_0 + \beta_1 \ln\text{GRF}_{it} + \beta_2 \ln\text{GRIN}_{it} + \beta_3 \ln\text{GRFGRIN}_{it} + \varepsilon_{it} \quad (2)$$

Here, while i denotes the countries, t denotes the time. ε_{it} is the error term. $\beta_0, \beta_1, \beta_2$ and β_3 denote the coefficients of the constant, $\ln\text{GRF}$, $\ln\text{GRIN}$, and $\ln\text{GRFGRIN}$ respectively. All variables are used in natural logarithmic form.

The dependent variable, ESG-Based Sustainability Uncertainty Index, is denoted by ESGUI and is taken from Ongan et al. (2025). This index ranges from the maximum value of 100 to the minimum value of 0. Figure 1 illustrates the time series of ESGUI values for the G7 countries.

Figure 1: ESGUI for G7 countries



“Source: Generated by the author using EViews.”

The GRF and GRIN are independent variables which are taken from OECD Data. The study employs the environment public RD&D budget (% of total energy public RD&D) as a proxy for GRF and the patents on environment technologies (% of all technologies, 2021) as a proxy for GRIN. Based on previous studies, to our knowledge, GRF and GRIN policies have a mitigating effect on ESG-related uncertainty. The empirical literature does not contain studies that consider both variables independently or in interaction with each other.

3. Methodology

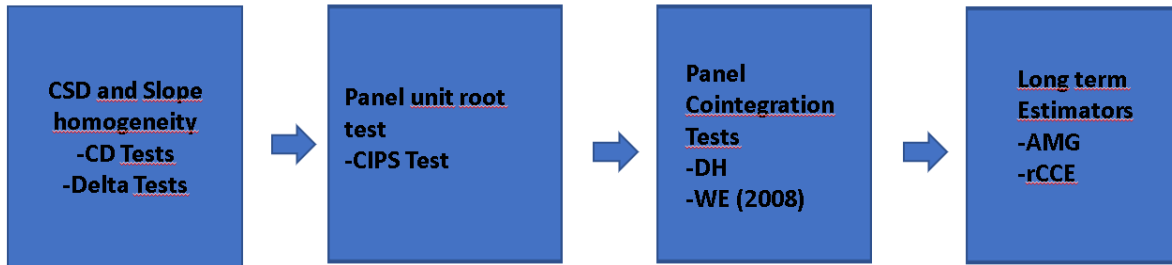
3.1. Priori Tests

In panel data analysis, it is first necessary to conduct preliminary tests, such as cross-sectional dependence (CSD) of variables and heterogeneity of slopes. After analysing the CSD of the model and variables using CDLM1 (Breusch and Pagan, 1980), CDLM2, and Pesaran's CD tests (Pesaran, 2021), the slope heterogeneity test, proposed by Pesaran and Yamagata (2008), is applied. Then, the investigation is conducted to determine whether the variables exhibit a unit root and a cointegration relationship in the panel model. Finally, long-term coefficients are estimated. Firstly, we investigate the CSD using the following test statistics proposed by Breusch and Pagan (1980) and Pesaran (2021).

$$CD = T \sum_{i=1}^{N-1} \sum_{j=i+1}^N \hat{\rho}_{ij}^2 \quad CD_{LM1} = \sqrt{\frac{1}{N(N-1)}} \sum_{i=1}^{N-1} \sum_{j=i+1}^N (T \hat{\rho}_{ij}^2 - 1) \quad CD_{LM2} = \sqrt{\frac{2T}{N(N-1)}} \sum_{i=1}^{N-1} \sum_{j=i+1}^N \hat{\rho}_{ij}^2 \quad (3)$$

where $\hat{\rho}_{ij}$ displays the correlation between errors calculated from Eq. (1) and Eq. (2). The hypothesis valid for all three tests above is as follows: H_0 : there is no CSD and H_1 : there is CSD. Figure 2 illustrates the sequence of methods employed in the empirical analyses conducted in this study.

Figure 2: The Empirical Strategy Steps



“Source: Prepared by the author”

Then, we use two Delta test statistics proposed by Pesaran and Yamagata (2008) to test the homogeneity of the slope coefficient of the model are as follows:

$$\hat{\Delta} = \sqrt{N} \left(\frac{N^{-1} \tilde{S} - k}{\sqrt{2k}} \right) \quad (4)$$

$$\hat{\Delta}_{adj} = \sqrt{N} \left(\frac{N^{-1} \tilde{S} - E(\tilde{z}_{it})}{\sqrt{\text{var}(\tilde{z}_{it})}} \right) \quad (5)$$

where $E(\tilde{z}_{it}) = k$, $\text{var}(\tilde{z}_{it}) = \frac{2k(T-k-1)}{T+1}$ and $\tilde{S}$ is the changed statistics of Swamy (1970). The null hypothesis argues for both tests above is as the slope coefficients are homogeneous.

3.2. Panel Unit Root Test

The second step involves determining whether the variables contain a unit root. The unit root test which belongs to Pesaran (2007) that could be used in the case of CSD. The cross-sectionally augmented IPS (CIPS) test builds on the ADF unit root test and the model is specified as follows:

$$\Delta y_{it} = a_i + b_i y_{i,t-1} + c_i \bar{y}_{t-1} + d_i \Delta \bar{y}_t + e_{it} \quad (6)$$

where, $\bar{y}_t = N^{-1} \sum_{i=1}^N y_{it}$ and $\Delta \bar{y}_t = N^{-1} \sum_{i=1}^N \Delta y_{it}$. Panel-level inference is based on the cross-sectionally augmented ADF (CADF) statistics computed for each cross-sectional unit and aggregated as follows:

$$CIPS(N, T) = N^{-1} \sum_{i=1}^N t_i(N, T) \quad (7)$$

Under the null hypothesis, the series is assumed to have a unit root.

3.3. Panel Cointegration Test

Empirical studies employ various cointegration methods to investigate long-term relationships among variables. Two test statistics for the panel cointegration test called as Durbin Hausman (DH) calculated by Westerlund (2008), which are DH_g and DH_p representing group and panel statistics, respectively:

$$DH_g = \sum_{i=1}^n \hat{S}_i (\tilde{\phi}_i - \hat{\phi}_i)^2 \sum_{t=2}^T \hat{e}_{it-1}^2 \quad \text{and} \quad DH_p = \hat{S}_n (\tilde{\phi} - \hat{\phi})^2 \sum_{i=1}^n \sum_{t=2}^T \hat{e}_{it-1}^2 \quad (8)$$

The null hypothesis of the DH test is that there is no cointegration in the panel.

Among the second-generation tests that account for CSD, there are tests that avoid biased results by taking structural breaks into consideration. Therefore, in this study, the cointegration test with structural breaks proposed by Westerlund and Edgerton (WE) (2008) has been utilized to control the three basic difficulties of panel data, namely CSD, autocorrelation, and structural breaks. The following equation is the cointegration model, which is robust against serial correlation:

$$\Delta \hat{S}_{it} = constant + \phi_i \hat{S}_{it-1} + \sum_{j=1}^{p_i} \phi_{ij} \Delta \hat{S}_{it-j} + error \quad (9)$$

where $\hat{S}_{it}$ is the error term. The two-panel LM-based test statistics defined by WE (2008) are as follows:

$$LM_{\phi}(i) := T \hat{\phi}_i \left(\frac{\hat{\omega}_i}{\hat{\sigma}_i} \right) \quad (10)$$

$$LM_{\tau}(i) := \left(\frac{\hat{\phi}_i}{SE(\hat{\phi}_i)} \right) \quad (11)$$

where, $\hat{\phi}_i$ and $\hat{\sigma}_i$ are the least square estimator and the estimated standard errors, respectively. The test examines the null hypothesis of no cointegration versus the alternative of cointegration. In the remainder of the study, coefficients are estimated both at the panel model and country-specific using the Augmented mean group (AMG) estimator (Eberhardt and Teal, 2010) and the regularized common correlated effect (rCCE) estimator (Juodis, 2022) to ensure robustness.

4. Empirical Results

The CSD and slope homogeneity results are given in Table 1. According to the results, the null hypothesis that there is no CSD is rejected. This means, CSD should be taken into account during the analysis of both the panel model and the variables. Moreover, the obtained results using Pesaran and Yamagata's (2008) homogeneity tests indicate heterogeneous slopes. In other words, country-based analyses should be presented.

Table 1: CSD and Slope Homogeneity Results

CSD			
Variables	CD	CD_{LM1}	CD_{LM2}
lnESGUI	51.82299*(0.0002)	4.756090*(0.0000)	4.458214*(0.0000)
lnGRF	85.26985*(0.0000)	9.917053*(0.0000)	-0.996308 (0.3191)
lnGRIN	335.9456*(0.0000)	48.59717*(0.0000)	18.29632*(0.0000)
lnGRFGRIN	55.45822*(0.0001)	5.317019*(0.0000)	-0.843827 (0.3988)
Slope Homogeneity	Test	Test Stat.	p-value
$lnESGUI=f(lnGRF,lnGRIN)$	$\hat{\Delta}$	1.618***	0.053
	$\hat{\Delta}_{adj}$	1.799**	0.036
$lnESGUI=f(lnGRF,lnGRIN,lnGRFGRIN)$	$\hat{\Delta}$	1.630***	0.052
	$\hat{\Delta}_{adj}$	1.868**	0.031

Note: * $p < 0.01$ and ** $p < 0.05$.

The CIPS unit root test (Pesaran, 2007) considers CSD. As displayed in Table 2, the null hypothesis of a unit root is not rejected at the level however it is rejected at the first differences. Namely, all variables are non-stationary at the level and become stationary in their first differences, i.e., $I(1)$.

Table 2: CIPS Unit Root Test Results

Variables	Level ($I(0)$)	First differences ($I(1)$)
lnESGUI	-2.340	-3.636 *
lnGRF	-2.409	-3.268 *
lnGRIN	-2.628	-4.081 *
lnGRFGRIN	-1.874	-2.907**

Note: * and ** denote the rejection of the null hypothesis at 1% and 5%, respectively.

Based on the unit root test outcomes, the cointegration of the panel model is examined by utilizing DH and WE (2008) cointegration tests. In both tests, the null hypothesis, which argued that there is no cointegration, is rejected based on the probability values, and the existence of a long-term relationship for the models is reported in Table 3.

Table 3: DH and WE (2008) Test Results

DH	Tests	Value	p-value	
Model 1	DH_G	5.055*	0.000	
	DH_P	13.202*	0.000	
Model 2	DH_G	12.941*	0.000	
	DH_P	13.467*	0.000	
WE (2008)	LM_τ	p-value	LM_φ	p-value
Model 1				
Level-shift	-1.772**	0.038	-2.308**	0.011
Model 2				
Level-shift	-1.988**	0.023	-1.766**	0.039

Note: * $p < 0.01$ and ** $p < 0.05$.

Whence, the effect of GRF and GRIN on reducing ESG-related uncertainty is estimated using the AMG method. Similar estimations are also run considering the interaction between GRF and GRIN. Table 4 indicates the estimation results.

Table 4: AMG Long-Run Coefficient Estimation Results

Countries	lnGRF	lnGRIN	lnGRFGRIN
Model 1			
Canada	0.6195334	0.3248848	-
France	-0.0603174	-0.274947	-
Germany	2.261689***	0.7767063	-
Italy	-0.2440459	-0.1276684	-
Japan	-0.0190376	-1.191868*	-
UK	-0.5997184***	0.5833297*	-
USA	0.3354398	0.0075817	-
Panel	0.327649	0.0140027	-
Model 2			
Canada	-22.53359***	-13.31023***	9.206497***
France	-2.87213	-1.305396	1.098743
Germany	-6.397164	-3.005238	3.480557
Italy	11.05737***	4.52977***	-4.807378***
Japan	-1.1229	-1.086889**	0.4311398
UK	0.5205719	.8397223	-0.4270826
USA	12.35981*	-3.552778*	-5.396614*
Panel	-1.284005	-2.413005	0.5122661

Note: * p< 0.01, ** p<0.05, and *** p<0.10.

Table 5: rCCE Long-run Coefficient Estimation Results

Countries	lnGRF	lnGRIN	lnGRFGRIN
Model 1			
Canada	0.616108	0.4633154	-
France	0.0055386	-1.248232	-
Germany	2.466651***	0.3320111	-
Italy	-0.006815	-1.475516	-
Japan	-0.1363406	-0.2245835	-
UK	-0.8313099**	-0.9032576	-
USA	-0.229172	1.622805	-
Panel	0.2692372	-0.2047798	-
Model 2			
Canada	-35.31338**	-18.96386**	14.35519**
France	-1.839073	-1.751458	0.7251706
Germany	-5.583501	-3.166832	3.232134
Italy	10.53958***	2.846989	-4.477694***
Japan	0.8900906	-0.2843333	-0.4131665
UK	-1.28837	-1.158818	0.1886307
USA	11.54994*	-2.911641***	-5.161761*
Panel	-3.006388	-3.627136	1.206929

Note: * p< 0.01, ** p<0.05, and *** p<0.10.

The country-specific results consistently supported by the AMG and rCCE estimators displayed in Table 4 and Table 5 reveal substantial heterogeneity across the G7 economies. Model 1 indicates that the GRF alone increases ESGUI in Germany, while conversely, it reduces it in the UK. Model 2, which includes interaction term, represents that increased GRF increases ESGUI in Italy and the USA,

while the opposite occurs in Canada, where it reduces ESGUI. The fact that GRIN alone reduces ESGUI in Canada and the USA demonstrates that technological outputs prove that countries' environmental promises are not merely advertising. The effect of GRF reducing ESGUI by reinforcing the information transparency created by GRIN is observed in Italy and the USA, while the opposite is true in Canada. This indicates that the aforementioned estimations support each other. In the following section, these findings are discussed in light of the existing literature, and policy recommendations are presented to both policymakers and investors.

5. Discussion

The empirical literature on the impact of GRF and GRIN policies on ESGUI is not sufficiently developed. Therefore, it is difficult to compare the findings of this study with previous research on the effects of these variables. However, some findings reveal the direct effectiveness of GRF on ESGUI and indirectly on the country's ESG score in terms of environment, social, and governance. For instance, the literature confirms the role of GRF and GRIN in reducing ESGUI (Dou et al., 2025; Akadiri and Özkan, 2026; Khan et al. (2025)) and promoting country ESG scores (Zheng et al., 2025; Niu (2024); Kwilinski et al. (2025)). However, unlike the previous literature, this study argues that the interaction of these two variables, finance and innovation as tools, reduces ESGUI. Thus, it addresses a significant research gap regarding whether GRF and GRIN policies, or a combination thereof, are effective in reducing ESGUI.

An examination of the models reveals that GRF exerts varying effects across different countries. G7 countries exhibit a heterogeneous structure in terms of ESGUI. The effectiveness of GRF and GRIN on ESGUI is influenced by differences in economic structure, policy responses, institutional dynamics, energy dependence, conditions of the period, and political stability among countries. The empirical findings indicate that, in Model 1, the Green Regulatory Framework (GRF) alone increases ESGUI in Germany while decreasing it in the UK; in Model 2, it is shown to increase ESGUI in the US and Italy. In the USA, although GRF instruments increased due to differences in interstate ESG standards, the lack of a standard reporting at the federal level caused confusion among investors, thus increasing uncertainty. The counterintuitive results in Germany and Italy can be attributed to high-profile greenwashing cases in these countries. For instance, Eni, a major consumer of green finance in Italy, is penalized by the Italian Competition Authority (AGCM, 2020) for greenwashing. Likewise, an investigation in 2022 into DWS, an asset manager owned by Deutsche Bank, in Germany regarding the exaggeration of its funds' "greenness" has significantly amplified ESG-related uncertainty. Conversely, GRF alone has reduced sustainability uncertainty in the UK and Canada. GRIN, according to both model prediction results, has reduced uncertainty alone in Canada and the USA. When considering the combined interaction of GRF and GRIN, which individually increased ESGUI, it is found to reduce it in Italy and the USA. In Canada, the opposite is true, with increased ESGUI. In Italy and the USA, the combination of GRF and GRIN, as expected, has reduced ESGUI by decreasing market volatility related to ESG and contributed to sustainability. According to this effect, GRF accelerates GRIN, directing funds towards clean energy investments. This, in turn, plays an effective role in increasing stability by limiting uncertainties related to future market regulations. Therefore, GRF and GRIN tools should be considered as a combined policy approach to mitigate ESGUI.

The results obtained for Italy and the USA display that the financial system is more effective in channelling green funds into sustainable environmental, technological, and energy investments.

GRF and GRIN practices have provided a stable environment in conjunction with strong ESG policies in areas such as energy transition, investor confidence, green investment policies, institutional quality, and employment opportunities. This result is consistent with the studies of Dou et al. (2025), Akadiri and Özkan (2026), and Khan et al. (2025) on the mitigating effect of GRF and GRIN on ESGUI. GRF and GRIN play complementary roles in reducing ESG-related uncertainties in the sustainable development process. GRF accelerates the low-carbon transition by shifting investments from carbon-intensive sectors to clean technologies and reduces market concerns about policy risks (Meng et al., 2025; Lau et al., 2025). Furthermore, clear GRF taxonomies and reporting standards reduce uncertainty by creating clear transition paths for companies (Cojoianu et al., 2025). Mechanisms such as climate stress tests and environmental disclosure obligations provide protection against sustainability-related financial risks by addressing stranded asset risks proactively (Jiang and Ma, 2025). On the other hand, GRIN, along with regulatory frameworks and technological advancements, facilitates the monitoring and evaluation of sustainability performance through energy-efficient technologies, low-carbon data center infrastructures, and advanced data analytics. With the mutually reinforcing relationship between GRF and GRIN, GRF supports research and development activities by providing stable funding for innovation and creates new application areas in sustainable sectors. GRIN, using tools such as artificial intelligence, advanced data analytics, and machine learning algorithms, improves the risk assessment of green assets, enabling more effective selection of sustainable projects and supporting the development of GRF markets by reducing transaction costs (Dou et al., 2025; Lee et al., 2025).

In the case of Canada, however, a contradictory effect is observed, as the interaction between GRF and GRIN exacerbates ESGUI. This result indicates that high sensitivity to GRF and GRIN do not always go hand in hand with ESG. Excessive regulation could weaken the governance score by increasing bureaucracy. The cost of compliance with ESG criteria and strict regulations could divert funds away from social projects and innovation, increasing national ESG-related uncertainty. GRIN is a high-cost and long-term investment process. Fluctuations and declines in national ESG performance can occur due to misallocation of resources, greenwashing risks, or high financial costs suppressing other ESG components. This is particularly evident during periods of financial crisis or in economies with structural fragility. At this point, it should be questioned whether green financial instruments are sufficient to redirect more funds to sustainable investments. For Canada, the implementation of transparent and trust-based GRF policies is important for investor confidence and financial stability. These results highlight country-specific differences in the GRF-GRIN-ESGUI relationship and emphasize the need for balanced environmental and financial policies. The literature discusses how "greenwashing" involves companies manipulating their sustainability claims to misdirect GRF resources, hindering genuine environmental transformation and undermining trust in ESG systems (Xie, 2024; Hu et al., 2025; Wang et al., 2025). Additionally, strict green credit policies push polluting firms out of the system, hindering their capacity to transform into sustainable structures and engage in GRIN. These firms, with limited access to finance, become unable to undertake the environmentally friendly innovations that would transform them (Liao and Zhou, 2024).

When the GRF and GRIN variables examined in this study are considered as a whole, the multidimensional structural challenges faced by G7 countries in sustainability uncertainty processes become more apparent. Recent geopolitical tensions, post-pandemic effects, global financial crises,

and the energy crisis have deepened sustainability uncertainties and revealed the structural vulnerabilities of country ESG scores. Although many G7 countries have set serious targets for renewable energy and carbon neutrality, robust financial support is crucial for achieving these goals. Combined with weak innovation, this situation makes national economies more vulnerable to sustainability uncertainties.

6. Conclusion and policy recommendations

This study utilizes the cointegration approaches of DH and WE (2008) to analyse the role of GRF and GRIN, separately and in combination, on ESGUI in G7 countries during the period 2002–2021. The study aims to determine whether GRF and GRIN policies are more effective independently or interactively. Empirical findings represent that these tools, individually and together, yield statistically significant and consistent results in reducing ESGUI, and that the effect on ESGUI varies by country. In the model including GRF and GRIN, this policy combination demonstrates the importance of designing GRF and GRIN policies as holistic tools. This is a strong finding, as robustness tests also indicate that the effect is significant. For both models, GRF alone is found to have a reducing effect on sustainability uncertainty in the UK and Canada, while it increased uncertainty in Germany, Italy, and the USA. Meanwhile, according to the estimation results for the Model 2, GRIN—when considered independently—reduces uncertainty in Canada and the United States. Considering the interaction between GRF and GRIN, it is observed that the combination reduces ESGUI in Italy and the USA, while it increases uncertainty in Canada. This study displays that, alongside individual policy tools, a GRF-GRIN focused approach is also effective in reducing ESGUI. In light of the results obtained, some policy recommendations could be offered to policymakers and investors to encourage participation. First, robust regulatory frameworks should be established to facilitate the accessibility of GRF and the integration of sustainability practices. Policy tools such as GRF incentives and risk mitigation mechanisms could enhance the positive impact of GRF instruments on stability. G7 countries should evaluate and monitor the outcomes of these funds in terms of ESG dimensions by creating effective GRF and GRIN policies. For this purpose, training and early warning systems should be activated, and incentives should be planned correctly. Comprehensive and comparable data infrastructures need to be established to effectively monitor country ESG and uncertainty scores. Pilot projects should be encouraged in areas such as renewable energy and smart grid management to harness the environmental potential of GRIN. Technologies such as artificial intelligence and big data should be utilized in GRF project management. Furthermore, to enhance the effectiveness of GRF instruments and innovation in reducing uncertainty, regional and sectoral strategies and technology transfer mechanisms should be prioritized. Financial instruments designed specifically according to technological capacity and emission intensity criteria have the potential to both reduce eco-innovation costs and prevent resource waste. Policymakers should expand access to instruments such as green bonds and transition financing to accelerate the transformation of high-emission sectors. However, restrictions on access to these instruments could expose companies to the risk of "greenwashing". Transparency in this process should be ensured through internationally standardized ESG reporting regimes. Moreover, inequalities in the distribution of financial incentives can lead to social unrest and deepen ESG-related uncertainty. In this context, it is crucial for governments to align their financial support and penalty systems with social justice principles. It is critical that global actors, such as the G7 countries, support ESG goals such as emission reduction through regional agreements and collective

strategies. In this process, each country should develop policies according to its own conditions and development priorities. Taking into account the effects of current global uncertainties (COVID-19, geopolitical risks, climate change risks, etc.), future GRF and GRIN policies should be more flexible, resilient, and stable.

This study contributes to the literature examining the role of GRF and GRIN tools in reducing ESGUI in three ways. First, it presents a methodologically robust and versatile empirical framework using AMG and rCCE estimators with a panel dataset from G7 countries for the period 2002-2021. Second, the validation of the impact of GRF and GRIN in reducing ESGUI in both models, specifically for some countries, demonstrates that national GRF and GRIN goals should be addressed concurrently with ESGUI in line with sustainable development strategies. The results reveal the holistic nature of finance and innovation policies, showing that GRF and GRIN are effective both individually and interactively in reducing ESGUI. In light of these contributions, the study not only presents empirical findings on the effectiveness of finance and innovation tools but also reinforces the importance of a holistic perspective on policy design in the literature.

While the findings of this study are based on empirical analyses, they have some limitations. First, the panel dataset used consists of annual macroeconomic indicators at the country level and does not reflect company-level behaviour or sectoral ESGUI. Second, GRF and ESGUI are represented by a single proxy. Future studies could examine the impact of various GRF instruments, such as green bonds, green funds, or insurance, on the ESGUI components separately. Third, the study sample is limited to the G7 group of high-income developed economies. To provide a more comprehensive view, the scope of the study could be expanded with a comparative analysis considering G7 economies, emerging markets, and OECD members, thus capturing cross-country differences in institutional frameworks. Future studies using more detailed datasets and alternative methodological approaches will increase both the depth and applicability of the current analyses.

Generative Artificial Intelligence (AI) Usage Statement:

Generative AI tools were not used in the preparation of this study.

Author Contributions (Yazar Katkı Oranı): Çisem BEKTUR (% 100)

Ethical Responsibilities of Authors (Yazarın Etik Sorumlulukları): This study was prepared in accordance with the rules of the required ethical approval

Conflicts of Interest (Çıkar Çatışması): There is no conflict of interest with any institution related to the study.

Plagiarism Checking (İntihal Denetimi): This study has been checked for plagiarism using a plagiarism scanning programme.

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