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Eco-investment efficiency and sectoral dynamics: Insights into sustainable finance strategies for emerging economies

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ABSTRACT

This study evaluates eco-investment efficiency across Singapore's key economic sectors using a refined general residual investment model. Drawing on 215 firm-year observations from 43 enterprises that issued green bonds between 2017 and 2021, the analysis assesses whether eco-investment levels align with optimal benchmarks. The model integrates conventional financial indicators (e.g., return on equity), sustainability-related metrics (e.g., green bond yield-to-maturity, carbon emissions), and governance mechanisms (e.g., audit quality, board structure, ownership concentration) to capture investment behaviour comprehensively. Findings reveal persistent underinvestment in eco-friendly initiatives within the telecommunications, residential, and international trade sectors, while the banking and finance sector exhibits signs of overinvestment. By disaggregating results by sector, the study highlights how institutional capacity, policy enforcement, and financial maturity shape eco-investment outcomes. Although Singapore is a high-income economy, its structured approach to green financing, regulatory governance, and sustainability disclosures offers transferable insights for emerging economies. Many emerging markets face barriers such as weak environmental regulation, limited access to green capital, and fragmented policy implementation. This study demonstrates how a coherent policy-finance-governance framework can address these challenges, improve investment efficiency, and support low-carbon development. The study contributes a replicable analytical framework and sectoral evidence that can inform policy and financial reform in emerging economies pursuing climate-aligned investment strategies. It also draws attention to the need for targeted financial instruments and governance mechanisms to overcome eco-investment gaps and enhance avenues for sustainable development.

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1. Introduction

As the global push toward decarbonization intensifies, aligning economic growth with environmental sustainability has become a critical policy priority. In this context, eco-investment, defined as the allocation of capital to environmentally responsible projects, has gained prominence as both a corporate strategy and a national development imperative.

1.1 The role of eco-investment in sustainable development

As the global community accelerates efforts to mitigate climate change, eco-investment, also known as green or environmentally responsible investment, has emerged as a cornerstone in national development strategies aimed at achieving a low-carbon economy. Eco-investment plays a crucial role in reducing carbon emissions, conserving natural resources, and fostering environmentally sustainable economic growth. Although there is no universally accepted definition in economic literature, eco-investment broadly refers to capital allocation toward pollution reduction, clean energy, and green infrastructure. It represents a convergence of environmental responsibility and financial decision-making at the enterprise level.

Across economies, both developed and emerging, enterprises are increasingly central to driving this investment. However, firms often face structural and operational challenges, including high R&D costs, limited access to capital, and internal governance constraints. These limitations are particularly acute in emerging economies, where financial and regulatory ecosystems may be underdeveloped. In this context, assessing eco-investment not only in absolute terms but also in terms of its efficiency, the degree to which eco-investment yields optimal environmental and financial returns, becomes essential for ensuring impactful policy and private-sector alignment with sustainability goals.

1.2 Singapore as a policy benchmark for emerging economies

Singapore offers a unique reference point. While it is a high-income economy, its compact, regulated, and innovation-driven financial ecosystem provides a policy benchmark for emerging economies seeking to build or strengthen their green investment infrastructure. Singapore has actively pursued eco-investment through instruments such as green bonds, corporate sustainability disclosures, and stringent environmental regulations. Between 2017 and 2021, eco-investment in Singapore reached S$1.75 billion, concentrated in sectors such as banking, telecommunications, residential construction, and international trade. Despite these efforts, eco-investment outcomes remain uneven across sectors, with overall carbon emissions increasing by 4.27% over the last two years (Energy Market Authority, 2023).

This raises important questions not only about the scale of eco-investment but its efficiency, whether enterprises are overinvesting, underinvesting, or optimally allocating capital toward sustainability. These concerns are equally, if not more, pressing in emerging economies where resource constraints are greater, and investment inefficiencies can have amplified consequences.

By analysing eco-investment efficiency in Singapore, this study provides evidence-based insights that can inform financial strategies and governance reforms in emerging markets. The mechanisms evaluated, such as yield-to-maturity of green bonds, ownership structures, and regulatory enforcement, are highly relevant to economies at different stages of development seeking to catalyse sustainable growth.

1.3 Gaps in existing research on eco-investment efficiency

While research in green finance and sustainable investment is expanding, several gaps remain. First, many studies focus on aggregate investment levels or returns on green assets, but fewer assess eco-investment through the lens of investment efficiency, particularly at the firm level. Second, existing research rarely applies a structured residual model to isolate inefficiencies (Richardson, 2006), nor does it

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disaggregate performance across economic sectors. Third, empirical studies that link eco-investment to both financial indicators (e.g., ROE) and sustainability-oriented metrics (e.g., green bond yields, environmental regulations) are limited, especially in emerging market contexts.

Furthermore, while several studies have explored the impact of environmental policy or ESG disclosure on investment behaviour, few have examined the interaction between governance mechanisms and eco-investment efficiency across sectors. This interaction is crucial in settings, common in emerging markets, where institutional capacity varies significantly between industries.

The present study addresses these gaps by assessing eco-investment efficiency across Singapore's key economic sectors using a refined residual investment model. The model integrates traditional financial indicators (e.g., return on equity), green financing tools (e.g., yield-to-maturity of green bonds), and governance variables (e.g., board size, audit quality, ownership concentration), alongside environmental controls (e.g., carbon emissions, regulatory density). Specifically, the paper seeks to:

- Evaluate whether firms in key economic sectors are underinvesting, overinvesting, or operating at optimal eco-investment levels.
- Identify the internal (firm-level financials, governance structures) and external (policy, emissions, green bonds) factors influencing eco-investment efficiency.
- Provide sector-specific analysis to highlight variations in performance and policy alignment.
- Offer practical lessons and a replicable analytical framework for emerging economies seeking to enhance their sustainable finance capabilities.

While Singapore is not an emerging economy, this study is highly relevant to emerging market policymakers and stakeholders. The country's eco-investment experience, anchored in strong institutions, financial innovation, and regulatory clarity, offers transferable insights into how emerging economies can develop and regulate green bond markets, improve the transparency and governance of corporate investment decisions, and align sectoral policy with national sustainability goals.

By showcasing how eco-investment efficiency varies across sectors even within a high-capacity environment, the present study also cautions against simplistic policy transplantation and emphasises the importance of contextualized governance reforms.

2. Literature Review

A growing body of research has explored the role of environmentally focused investment in supporting sustainable development and climate action. However, eco-investment remains inconsistently defined, and its efficiency at the firm or sectoral level has not been sufficiently examined. This section of the paper synthesizes current knowledge across three interrelated domains: (i) conceptual definitions of eco-investment, (ii) the theoretical and empirical grounding of investment efficiency, and (iii) key factors influencing eco-investment efficiency. This review also identifies gaps that this study seeks to address, particularly in relation to modelling sector-specific eco-investment performance using firm-level data.

2.1 Defining eco-investment

Eco-investment, often used interchangeably with terms such as green investment or environmentally responsible investment, is conceptually situated within the broader domain of Socially Responsible Investing (SRI), a strand of Corporate Social Responsibility (CSR) that integrates ethical, social, and environmental considerations into investment decisions (Allevi et al., 2019). Although eco-investment has gained traction since the early 2000s, the term remains inconsistently defined in the economic literature (Sparkes & Cowton, 2004). Some studies define SRI as the construction of investment portfolios that incorporate social and environmental risks alongside traditional financial returns (Sparkes, 2008), while others describe it as a process of value-based screening and active engagement (Chatzitheodorou et al., 2019).

Eco-investment narrows this focus to emphasize the minimization of ecological footprints, often by investing in pollution control, carbon reduction technologies, and environmental innovation (Carfora et al., 2021; Climent & Soriano, 2011). As Bhuiyan et al. (2021) observe, eco-investments typically include expenditures on environmental remediation, product redesign for sustainability, and pollution prevention infrastructure. Other studies, such as Bostian et al. (2016) and Costa-Campi et al. (2017), view eco-investment more broadly in terms of environmental R&D and innovation-led production improvements. A more holistic view frames eco-investment as capital allocated with environmental, economic, and social value creation in mind (Feng & Sun, 2020; Becchetti et al., 2022).

Despite this growing body of literature, there remains a lack of consensus on a unified definition. This ambiguity complicates both measurement and cross-sectoral comparison. For the purposes of this study, eco-investment is defined as capital allocation explicitly aimed at decarbonization and environmental sustainability, particularly within the context of national commitments such as the Paris Agreement.

Recent global frameworks have sought to standardize the concept. The European Commission's Taxonomy for Sustainable Activities and the United Nations Environment Programme's (UNEP) sustainable finance principles provide operational guidance for identifying and classifying eco-investments. Notably, Singapore has adopted components of UNEP's framework, launching policies in 2021 that consolidate clean energy adoption, decarbonization, eco-finance infrastructure, and green innovation under a unified transition agenda. Given the steady rise in national carbon emissions, an increase of 4.27% over two years (Energy Market Authority, 2023), Singapore's approach to eco-investment represents both a national imperative and a potential global benchmark for policy modelling.

The present study adopts the above conceptualization to anchor its investigation of sector-level eco-investment efficiency. While the Singaporean context is specific, its structured investment regime provides useful insight for emerging economies seeking to implement or strengthen eco-financing mechanisms and environmental governance systems.

2.2 Eco-investment efficiency: Concepts and gaps

Investment efficiency, in general, refers to the degree to which firms allocate resources toward projects that maximize value without incurring excess or misdirected capital expenditure. At the firm level, efficiency is often evaluated using Tobin's Q ratio, where a value greater than one suggests investment opportunities exceed their cost (Kaplan & Zingales, 1997). However, discrepancies between theoretical and actual investment levels are common, often resulting in overinvestment or underinvestment, both of which constitute inefficiencies (Biddle et al., 2009; Richardson, 2006).

Recent research has broadened the scope of investment efficiency analysis. Ellili (2022), for example, explored how ESG disclosures and financial reporting quality influence investment decisions. Wu et al. (2022) examined the role of geographic proximity, while Zhao et al. (2023) considered how tax enforcement affects investment behavior. Lu and Li (2023) investigated institutional herding as a determinant of investment inefficiency. However, despite the rising prominence of environmental finance, eco-investment efficiency remains an underexplored area, particularly at the micro level. Most empirical studies in this space examine returns on green assets or the viability of renewable energy projects (e.g., Czakó, 2012; Karásek & Pavlica, 2016; Valentová et al., 2019), but few assess whether these investments are optimally allocated within firms or sectors. Some researchers, such as Chen et al. (2023) and Du et al. (2019), have examined drivers of eco-investment using neoclassical frameworks, while others have focused on specific technologies such as solar and wind (Farangi et al., 2020; Rozentale et al., 2018). Yet, few

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studies address the efficiency dimension, whether green investment levels are appropriate relative to financial and environmental goals.

The present study attends to this gap by operationalizing eco-investment efficiency through a refined residual model and applying it to sector-level data. It responds to the need for empirical frameworks that link eco-investment outcomes to measurable financial and environmental variables, especially in economies where sustainable finance is still evolving.

2.3 Drivers of eco-investment efficiency

Investment efficiency is influenced by a mix of internal and external factors, especially in imperfect capital markets. There are two primary mechanisms, namely, investment constraints, where firms are unable to fund positive net present value (NPV) projects due to capital limitations, and decision-making inefficiencies, often tied to agency problems or poor governance (Ha & Feng, 2018; Jung et al., 2014).

These mechanisms are highly relevant to eco-investment contexts. First, investment constraints often stem from stringent environmental regulations or high up-front costs for compliance, leading firms to delay or forego necessary environmental projects. Such constraints are common in emerging economies, where pollution control is mandated but financing tools remain underdeveloped. Policies that incentivize low-cost capital for green projects, such as tax credits or grants, are thus critical in aligning firm behavior with environmental objectives (Peneder et al., 2022).

Second, eco-investment decisions involve both internal (retained earnings, operational cash flows) and external (debt, equity, bonds) financial sources. Modigliani and Miller (1958) assert that, under perfect conditions, internal and external funds are interchangeable. However, in practice, information asymmetry and credit risk make external financing more expensive, particularly in the context of green projects. Recent literature emphasizes the growing role of green bonds in overcoming such barriers (Chatziantoniou et al., 2022; Sartzetakis, 2021). Firms that issue green bonds benefit from lower capital costs (Zhang et al., 2021), improved hedging capacity (Dong et al., 2023), wider investor bases (Flammer, 2021), and enhanced support for innovation (Wang et al., 2022). As such, green bonds serve not only as a financing instrument but also as a mechanism for increasing eco-investment efficiency (Gianfrate & Peri, 2019).

Governance mechanisms also matter. Variables such as board independence, ownership concentration, and audit quality influence capital allocation and risk management. Studies show that better-governed firms are more likely to pursue long-term investments, including in sustainability initiatives (Ahmad et al., 2023; Menshawy et al., 2023).

2.4 Advancing the conceptualization of eco-investment efficiency

Existing studies provide a strong foundation for understanding eco-investment as a concept and for analysing green finance mechanisms. However, gaps remain in how eco-investment efficiency is conceptualized, measured, and analysed across sectors, particularly in data-rich yet policy-dynamic contexts like Singapore. The present study therefore addresses gaps in literature in three ways. First, it offers a clear, operational definition of eco-investment grounded in authoritative taxonomies and aligned with decarbonization goals. Second, it applies a firm-level residual model to assess efficiency, offering a methodologically rigorous yet adaptable framework suitable for replication in emerging markets. Third, it explores how eco-investment efficiency varies by sector and across time, using a comprehensive set of financial, environmental, and governance indicators.

Although the data are drawn from Singapore, the findings are highly relevant to emerging economies seeking to build institutional capacity in green finance. Lessons from Singapore's eco-investment performance, both its successes and inefficiencies, can help inform policy design, regulatory reform, and sustainable investment strategies in lower- and middle-income contexts.

3. Method

The present study employs a firm-level panel data approach to assess eco-investment efficiency across Singapore's key economic sectors. The methodology covers the sample and data sources, variable definitions, and the specification of two residual-based models adapted from investment efficiency literature.

3.1 Sample and data

Singapore's eco-investment landscape has undergone significant transformation, driven largely by regulatory reforms aimed at enhancing environmental accountability. Initial policies in 1992 promoting a "clean and green city" lacked strong compliance mechanisms and produced limited firm-level data. However, a turning point came in 2010 when the Singapore Exchange (SGX), in collaboration with the Ministry of the Environment, mandated sustainability reporting for listed firms. This regulatory shift substantially improved data accessibility and quality.

Building on these advances, this study draws on panel data spanning the period 2017 to 2021, comprising 215 firm-year observations from 43 enterprises that issued green bonds. Due to the absence of a centralized green investment database, data collection was manually undertaken from company annual and sustainability reports, the SGX database, and government sources. Despite this constraint, the 2010 reporting reform enabled sufficient longitudinal and sectoral coverage for the study.

The sample focuses on four key economic sectors: banking and finance, international trade, residential, and telecommunications. These sectors were selected for their strategic economic importance and differentiated roles in driving eco-investment. Data from the Energy Market Authority (2023) confirms that these sectors collectively account for a substantial share of national energy consumption, underscoring the environmental stakes and the policy relevance of analyzing eco-investment efficiency within them.

3.2 Variable selection

The present study investigates the efficiency of eco-investment, defined as capital allocated toward decarbonization and environmental sustainability, using a refined residual model. The dependent variable, eco-investment (EI), is operationalized as the natural logarithm of a firm's eco-investment scaled by total assets, based on reported expenditures related to decarbonization, R&D, clean energy transition, construction-in-progress, and administrative costs. These data are derived from financial disclosures and sustainability reports, consistent with the approach of Liu et al. (2022).

3.2.1 Independent variables: Investment opportunity proxies

Two proxies were employed to represent investment opportunities, namely, Return on Equity (ROE), a conventional internal indicator of investment performance and firm profitability, and Yield-to-Maturity (YTM) of Green Bonds, representing access to and utilization of external green finance.

This dual approach aligns with prior literature (Modigliani & Miller, 1958; Kumar & Ranjani, 2018) and reflects the growing relevance of sustainable financial instruments. Unlike traditional Q-ratio metrics, which link market valuation to asset base, YTM of green bonds offers a more direct reflection of eco-investment attractiveness to external investors, particularly where environmental performance underpins bond pricing and risk assessment.

While green credit has also emerged as an alternative financing route, its limited scale and shorter credit terms in Singapore render it less suitable as a proxy for long-term eco-investment opportunity. Therefore, ROE and green bond YTM jointly serve as primary independent variables in the investment efficiency models.

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3.2.2 Control variables: Conventional and eco-investment determinants

Two groups of control variables were included. The first, conventional financial and governance determinants, comprising Leverage (LEV), Cash Flow (CF), Firm Size (FSIZE), Operating Return (OR), Asset Turnover (AT), Firm Age (AGE), and Net Income Growth (NIG) (see Richardson, 2006), and Corporate Governance Indicators comprising Board Size (BSIZE), Independent Directors (IDIR), and Audit Quality (AQ) (see Dechow & Dichev, 2002; Francis et al., 2005), and Ownership Concentration (OC). The second group, environmental and policy determinants, comprising Environmental Policy Restrictions (EPR), proxied by the number of environmental regulations enacted annually (Singapore NEA and SSO databases), and Carbon Emissions (GHG_C), measured as the logarithm of sector-level CO_2 emissions. Collectively, these variables capture both firm-level capacity and external regulatory pressure, factors that emerging economies must increasingly consider when designing sustainable investment ecosystems.

A summary of the sources and measurements for each variable are presented in Table 1.

Table 1. Variables, operationalizations and sources

Variable of study	Abbreviation	Variable measure and definition	Data source
Eco-investment	*EI*	The natural logarithm of eco-investment is divided by total assets.	Annual report and sustainability reporting
Investment opportunities	*IO_ROE*	ROE: The Company's net income divided by the value of its total shareholders' equity.	The Marketnode database, SGX database
	IO_GB	YTM: bond's return by comparing its face value to its current market price over its remaining time to maturity.	The Marketnode database, SGX database
Leverage	*LEV*	Total capital to total assets.	Annual report and SGX database
Cash flow	*CF*	The ratio of cash and cash equivalents plus short-term investments are divided by total assets.	Annual report and SGX database
Firm Size	*FSIZE*	The natural logarithm of total assets.	Annual report and SGX database
Operating return	*OR*	EBIT return on assets is EBIT divided by the average total asset.	Annual report and SGX database
Asset turnover	*AT*	(Total sales)/(beginning assets + ending assets)/2	Annual report and SGX database
Firm age	*AGE*	Log (the initial creation of a firm and the present time (in years))	Annual report and SGX database
Net income growth Rate	*NIG*	(Net profit of current year – net profit of last year)/net profit of last year	Annual report and SGX database
Independent directors	*IDIR*	The percentage of total independent directors on the board.	Annual report and SGX database
Board size	*BSIZE*	The natural logarithm of board members' number.	Annual report and SGX database
Audit quality	*AQ*	Accrual quality modification of the model follows Francis et al. (2005) and Srinidhi and Gul (2006).	Annual report
Ownership concentration	*OC*	Initial controlling shareholder's share proportion.	Annual report
Environmental policy restrictions	*EPR*	The number of environmental policies implemented each year	Singapore National Environment Agency (SNEA) database; Singapore Statutes Online (SSO)
Carbon emissions	*GHG_C*	log (Carbon dioxide emission volume)	SNEA database and Statista

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Year indicators	*Year*	Using dummy variables in regression analysis of annual fixed effects.	Created through Stata 17
Economic sector indicators	*Sect*	Industrial dummy variable used in regressions to capture industry fixed effects. Using the key economic sectors. i.e., banking and finance, International trade, residential, and telecommunication.	Created through Stata 17

3.3 Model specification

To assess eco-investment efficiency, the present study adapts the residual investment model developed by Richardson (2006), originally used to detect overinvestment and underinvestment based on deviations from optimal investment levels. In the present study, the model is repurposed with eco-investment as the dependent variable, allowing for identification of underinvestment (negative residuals) and overinvestment (positive residuals) in environmental projects.

The first model employs ROE as the investment opportunity indicator and integrates conventional financial controls. The model is expressed as:

$$\mathrm{EI}_{i,t} = \alpha_0 + \alpha_1 \mathrm{IO}_{i,t} + \alpha_2 \mathrm{LEV}_{i,t} + \alpha_3 \mathrm{CF}_{i,t} + \alpha_4 \mathrm{FSIZE}_{i,t} + \alpha_5 \mathrm{OR}_{i,t} + \alpha_6 \mathrm{AT}_{i,t} + \alpha_7 \mathrm{AGE}_{i,t} + \alpha_8 \mathrm{NIG}_{i,t} \\ + \alpha_9 \mathrm{EI}_{i,t-1} + \sum \mathrm{Year} + \sum \mathrm{Sect} + \varepsilon_{i,t}$$

Residual values from this model are interpreted as follows:

- Residual ≈ 0: Optimal eco-investment
- Positive residual: Overinvestment
- Negative residual: Underinvestment

This model is run across the full sample and separately for each sector to account for industry-specific effects. Building on Model 1, Model 2 replaces ROE with YTM of green bonds as a proxy for eco-investment opportunity. It also incorporates an expanded set of internal governance and external environmental variables, removing operating return (OR) due to its limited effect in Model 1. The model is specified as:

$$\mathrm{EI}_{i,t} = \alpha_0 + \alpha_1 \mathrm{IO}_{i,t} + \alpha_2 \mathrm{LEV}_{i,t} + \alpha_3 \mathrm{CF}_{i,t} + \alpha_4 \mathrm{FSIZE}_{i,t} + \alpha_5 \mathrm{AT}_{i,t} + \alpha_6 \mathrm{AGE}_{i,t} + \alpha_7 \mathrm{NIG}_{i,t} + \alpha_8 \mathrm{EI}_{i,t-1} \\ + \alpha_9 \mathrm{IDIR}_{i,t} + \alpha_{10} \mathrm{BSIZE}_{i,t} + \alpha_{11} \mathrm{AQ}_{i,t} + \alpha_{12} \mathrm{OC}_{i,t} + \alpha_{13} \mathrm{EPR}_{i,t} + \alpha_{14} \mathrm{GHG\_C}_{i,t} \\ + \sum \mathrm{Year} + \sum \mathrm{Sect} + \varepsilon_{i,t}$$

This model provides a more comprehensive framework for understanding how financial structures, regulatory dynamics, and governance mechanisms jointly influence eco-investment efficiency, factors increasingly relevant in emerging markets building climate finance readiness.

4. Results

The present study employs a firm-level panel data approach to assess eco-investment efficiency across Singapore's key economic sectors. The methodology covers the sample and data sources, variable

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definitions, and the specification of two residual-based models adapted from investment efficiency literature.

4.1 Sectoral eco-investment trends and firm characteristics

Figure 1 presents the trend of eco-investment across four key economic sectors in Singapore from 2017 to 2021. The banking and finance sector consistently recorded the highest investment, peaking at S$21 billion (31.8%) in 2018. By contrast, the residential and telecommunications sectors contributed S$1 billion (14.2%) and S$2 billion (18.2%), respectively, while the international trade sector, despite its economic importance, remained the lowest contributor and even declined by 50% during the observed period.

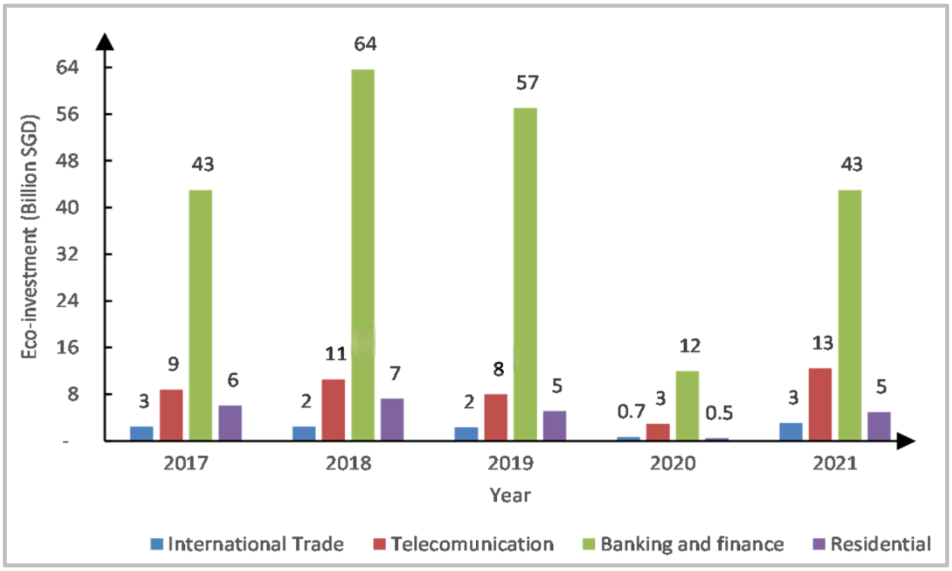

Figure 1. Singapore's key economic sectors of eco-investment (billion-dollar Singapore (SGD)) from 2017 to 2021

Investment levels across all sectors declined in 2019 and 2020, correlating with the national economic slowdown and the impact of the COVID-19 pandemic. For instance, the economy grew by only 0.1% in Q2 2019 before contracting in 2020, which curtailed eco-investment activity across sectors. A recovery trend was observed in 2021 as firms began to re-engage with sustainable finance initiatives post-lockdown.

Table 2. Descriptive statistics of firm-level variables for eco-investment efficiency analysis in Singapore (2017–2021)

Variable	Observation	Minimum	Maximum	Mean	Std. Dev.
EI	165	-1.512	4.776	0.130	1.086
LagEI	163	-1.497	4.776	0.201	0.987
IO _ROE	215	-103.452	57.761	5.450	11.419
IO_GB	215	3.580	18.068	9.231	3.228
LEV	215	0.000	152.17	7.493	10.788
CF	215	0	2	0.121	0.137
FSIZE	215	5.683	19.85	12.213	1.783
OR	215	-19.843	33.017	3.732	4.693
AT	215	0.914	1.671	1.363	0.566
AG	215	-1	22	10.813	3.962
NIG	215	-55.823	308.931	-0.363	27.493

IDIR	215	1	2	0.310	0.460
BSIZE	215	3	16	6.978	2.032
AQ	215	-0.383	-0.017	-0.122	0.069
OC	215	0.037	0.721	0.474	0.105
EPR	17	0	4	2.762	5.313
GHG_C	25	1.457	3.716	1.750	0.460

Notes: "Obs" represents observations; "Min" denotes the minimum value; "Max" refers to the maximum value; "Std. Dev" stands for standard deviation.

Table 2 reveals a broad spread in firm-level financial characteristics. Standard deviations indicate variability across leverage, cash flow, and governance structures, underscoring the need for sector-specific analysis.

4.2 Modelling outcomes

Model 1, which uses Return on Equity (ROE) as the investment opportunity proxy, shows a significant positive relationship with coefficient of eco-investment is 0.178. Significant effects are also observed for asset turnover and net income growth, suggesting that operational and performance metrics influence eco-investment decisions. Meanwhile, coefficient for cash flow and firm size are -1.304 and -0.097, respectively, exhibit negative associations, indicating potential constraints in internal capital allocation for eco-investment.

Model 2 replaces ROE with the Yield-to-Maturity (YTM) of green bonds and incorporates additional governance and environmental variables. The YTM proxy remains significant and positively associated with eco-investment across specifications, affirming the importance of green bond financing as an external driver. Hierarchical inclusion of governance controls, such as board size, audit quality, and ownership concentration, further strengthens model explanatory power.

Environmental controls such as policy restrictions (EPR) and carbon emissions (GHG_C) also display positive associations, though at lower significance levels. These findings suggest that regulatory pressure contributes to eco-investment behaviour, albeit variably across sectors.

The model fit (R^2) increases from 0.701 in Model 1 to 0.753 in Model 2, indicating improved explanatory strength when green finance and environmental controls are considered. Both models estimate the optimal investment level at zero residual, with deviations indicating under- or overinvestment. Negative residuals represent underinvestment, for example, investment below what is expected given firm characteristics while positive residuals reflect overinvestment.

Table 3 shows that underinvestment dominates the dataset. In Model 1, 63% of observations indicate underinvestment, while in Model 2, this drops slightly to 59%. The small standard deviation between the two models confirms their overall robustness.

Table 3. Eco-investment efficiency for statistical indicators

Models	Eco-investment efficiency	Obs	Min	Max	Mean	Std. Dev.
Model 1	Total	165	-0.198	0.202	- -0.040	0.088
	Underinvestment	104	-0.198	-0.001	-0.083	0.060
	Overinvestment	61	0.005	0.202	0.064	0.048
Model 2	Total	126	-0.171	0.169	-0.038	0.092
	Underinvestment	74	-0.171	-0,004	-0.079	0.059
	Overinvestment	52	0.032	0.169	0.086	0.050

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Investment efficiency is further broken down in Tables 4 and 5. The bulk of firm-year observations fall close to zero (i.e., –0.030 to 0.030), indicating marginal misalignment. However, only 15% of firms meet this "near-optimal" benchmark, highlighting significant room for improvement across sectors.

Table 4. Model 1 for detailed eco-investment efficiency distribution results.

Investment efficiency	Efficiency range	2017	2018	2019	2020	2021	*Sum*
`	(-∞, -0.250]	2	2	1	1	1	*7*
	(-0.198, -0.142]	3	3	1	1	1	*9*
	(-0.142, -0.086]	5	4	6	2	4	*21*
	(-0.086, -0.030]	8	12	4	3	2	*29*
	(-0.030, 0)	9	10	12	3	4	*38*
	Sum	*27*	*31*	*24*	*10*	*12*	*104*
Overinvestment	(0, 0.030)	6	5	2	0	3	*16*
	[0.030, 0.086)	4	4	2	0	1	*11*
	[0.086, 0.142)	3	4	3	0	2	*12*
	[0.142, 0.198)	3	2	2	0	1	*8*
	[0.198, 0.250)	3	1	1	1	1	*7*
	[0.250, ∞)	2	1	2	0	2	*7*
	Sum	*21*	*17*	*12*	*1*	*10*	*61*
	Sum-total	*48*	*48*	*36*	*11*	*22*	*165*

Table 5. Model 2 for detailed eco-investment efficiency distribution results.

Investment efficiency	Efficiency range	2017	2018	2019	2020	2021	*Sum*
Underinvestment	(-∞, -0.250]	1	1	0	0	1	***3***
	(-0.198, -0.142]	1	1	0	0	3	***5***
	(-0.142, -0.086]	1	2	4	9	3	*19*
	(-0.086, -0.030]	1	1	1	1	4	*8*
	(-0.030, 0)	3	9	10	12	5	*39*
	Sum	*7*	*14*	*15*	*22*	*16*	*74*
Overinvestment	(0, 0.030)	1	3	5	1	3	*13*
	[0.030, 0.086)	1	2	7	0	1	*11*
	[0.086, 0.142)	1	3	4	0	2	*10*
	[0.142, 0.198)	1	2	2	1	1	*7*
	[0.198, 0.250)	1	1	1	1	1	*5*
	[0.250, ∞)	1	0	1	0	4	*6*
	Sum	*6*	*11*	*20*	*3*	*12*	*52*
	Sum-total	*23*	*52*	*41*	*32*	*24*	*126*

4.3 Sectoral insights and comparative patterns

Table 6 presents sector-specific distributions. The banking and finance sector shows the highest rate of overinvestment, with 60% of firms exceeding the optimal eco-investment threshold. This could be attributed to stronger regulatory incentives, early adoption of sustainable finance, and proactive disclosure practices within the sector.

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Table 6. Eco-investment efficiency statistical indicators in four key economic sectors.

Key sectors	Efficiency estimates	N	Min	Max	Mean	Std. Dev
Banking and finance firms	Total	43	-0.198	0.202	0.020	0.106
	Underinvestment	13	-0.198	-0.006	-0.114	0.063
	Overinvestment	30	0.006	0.202	0.082	0.048
International trade firms	Total	43	-0.197	0.108	-0.062	0.072
	Underinvestment	33	-0.197	-0.001	-0.089	0.058
	Overinvestment	10	0.008	0.108	0.028	0.030
Residential firms	Total	41	-0.197	0.109	-0.041	0.073
	Underinvestment	31	-0.197	-0.001	-0.069	0.059
	Overinvestment	10	0.005	0.109	0.046	0.035
Telecommunication firms	Total	38	-0.198	0.169	-0.047	0.088
	Underinvestment	27	-0.198	-0.002	-0.089	0.059
	Overinvestment	11	0.010	0.169	0.056	0.055

In contrast, the international trade, residential, and telecommunication sectors reflect significant underinvestment, with underinvestment ratios exceeding 75% in some years. These sectors likely face capital constraints, lower regulatory scrutiny, or fewer sustainability-linked incentives. For example, in international trade, underinvestment accounts for 91.33% of firm-year observations, the residential sector shows consistent underperformance, exacerbated by high development costs and pandemic-induced delays, and the telecommunication sector reflects slightly better performance than the other two, but still displays a 79.59% underinvestment rate.

The patterns reveal substantial sectoral heterogeneity. Banking and finance have leveraged Singapore's green bond market and policy infrastructure to invest aggressively in green projects. In contrast, other sectors show inertia or structural barriers to optimal eco-investment.

5. Discussion

The empirical results demonstrate that eco-investment efficiency in Singapore's key economic sectors remains uneven, with notable underinvestment outside the banking and finance sector. While the banking and finance sector exhibits significant overinvestment, likely due to strong regulatory incentives and early adoption of sustainable finance practices, the international trade, residential, and telecommunications sectors consistently fall short of optimal investment levels. This divergence underscores that while national-level green finance frameworks can be robust, sector-specific constraints can still hinder eco-investment efficiency.

The patterns identified align with earlier findings that financial capacity, governance structures, and regulatory intensity are major determinants of investment efficiency (Biddle et al., 2009; Ahmad et al., 2023). In particular, the positive association between green bond yield-to-maturity and eco-investment found in Model 2 supports the growing body of evidence that sustainable debt instruments can reduce capital costs and expand financing options for environmentally aligned projects (Gianfrate & Peri, 2019; Flammer, 2021). The inclusion of governance indicators such as board size, independent directors, and audit quality further highlights the institutional dimension of eco-investment efficiency, echoing findings from Menshawy et al. (2023) and Ullah et al. (2020).

From a policy perspective, the results in both models indicate that green financing instruments and governance reforms can play a pivotal role in addressing underinvestment. However, the sectoral disparities in efficiency suggest that a one-size-fits-all policy approach may be insufficient. The banking and finance sector's relative success in leveraging Singapore's green finance ecosystem reflects institutional readiness and financial sophistication, conditions that are less developed in other sectors. Emerging economies can

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draw lessons from this by prioritizing phased sectoral engagement, tailoring incentives, and investing in capacity-building for sectors with lower institutional maturity.

Embedding the analysis from Section 4.3, the comparison between Models 1 and 2 confirms that incorporating green bond yields and governance/environmental controls enhances both explanatory power and policy relevance. The improvement in model fit from 0.701 in Model 1 to 0.753 in Model 2 underscores the value of integrating environmental finance variables into traditional investment efficiency models. This has direct implications for emerging economies: developing a green bond market, strengthening environmental policy enforcement, and promoting governance reforms could collectively foster more efficient eco-investment allocation across sectors.

The study's findings also resonate with Peneder et al. (2022), who argue that environmental regulations, when combined with financial incentives, can stimulate efficient capital allocation toward green projects. For Singapore, the challenge lies in extending the effectiveness of its regulatory and financing framework beyond the well-capitalized banking and finance sector. For emerging economies, the lesson is twofold, First, that financial innovation such as green bonds can be instrumental in overcoming investment constraints, and second, that governance mechanisms must be strengthened to ensure that increased funding translates into measurable environmental outcomes.

Finally, the persistent underinvestment in the international trade, residential, and telecommunications sectors suggests the need for more targeted interventions. These may include concessional financing for green technology adoption, tax incentives for sustainable infrastructure development, and stricter sector-specific emissions standards. Such measures could help close the eco-investment gap, thereby supporting broader national and regional decarbonization objectives.

6. Conclusion

This study assessed eco-investment efficiency across Singapore's key economic sectors using an adapted residual investment model that incorporates both conventional financial indicators and sustainability-specific measures such as green bond yields, governance variables, and environmental policy constraints. The analysis revealed that while the banking and finance sector exhibits significant overinvestment in eco-friendly projects, the international trade, residential, and telecommunications sectors remain underinvested relative to their optimal levels. These results underscore the persistent sectoral disparities in eco-investment efficiency despite Singapore's advanced green finance infrastructure.

Although Singapore is a high-income economy, its experience offers valuable lessons for emerging economies aiming to develop sustainable finance ecosystems. The positive association between green bond financing and eco-investment highlights the role of sustainable debt instruments in reducing capital costs and broadening access to funding for green projects (Flammer, 2021; Gianfrate & Peri, 2019). Strengthening governance mechanisms, such as board independence, audit quality, and ownership transparency, can further enhance capital allocation efficiency. For emerging markets, this suggests that green finance initiatives should be coupled with institutional reforms to ensure that increased investment translates into measurable environmental outcomes. Sector-specific strategies, tailored incentives, and capacity-building programs are essential for overcoming structural barriers and achieving balanced eco-investment efficiency across industries.

The study is limited by its relatively small sample size, constrained to Singaporean firms that issued green bonds during the observation period. This may not capture the full diversity of eco-investment behaviours in all sectors. Additionally, the analysis focuses on short- to medium-term dynamics and does not account for potential long-term effects of policy changes, technological adoption, or macroeconomic shifts. Finally, while the residual model captures deviations from optimal investment levels, it does not fully disentangle the causal mechanisms driving under- or overinvestment.

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Future studies could expand the analysis to include firms without green bond issuance to capture a broader eco-investment landscape. Comparative cross-country research, particularly involving emerging economies in Southeast Asia, Africa, and Latin America, would help test the transferability of Singapore's green finance model. Longitudinal studies spanning a decade or more could reveal the sustained impacts of policy interventions and market developments on eco-investment efficiency. Additionally, incorporating qualitative methods, such as interviews with policymakers and corporate decision-makers could provide richer insights into the institutional and behavioural drivers of investment efficiency.

While Singapore's advanced financial ecosystem enables strong performance in some sectors, persistent underinvestment in others signals the need for targeted interventions. Emerging economies can draw from these findings to design integrated policy, finance, and governance frameworks that not only increase green investment flows but also ensure their efficient and impactful allocation.

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Conflict of interest statement

The authors declare that this research was conducted without any self-benefit, commercial, or financial conflicts of interest, and that there are no conflicts with any funder.

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Renato Sitompul conceptualized the study, developed the methodology, conducted the investigation, and performed the formal analysis in consultation with Ramesh Nair. He also prepared the original draft of the manuscript. Zuraidah Mohd Sanusi and Syahrul Ahmar Ahmad contributed to the conceptualization, methodology, and formal analysis, and was involved in supervision, as well as providing critical feedback during drafting. Zuraidah Mohd Sanusi and Syahrul Ahmar Ahmad contributed to the review and editing of the manuscript, validated the analysis, and assisted in the revision process. All authors read and approved the final manuscript.

