

ENVIRONMENTAL EFFICIENCY, FINANCING COSTS, AND MARKET
DYNAMICS: A PANEL AND TIME SERIES APPROACH

by

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Dedication

I would like to dedicate this work to my late grandfather and grandmother, whose guidance and support helped me become the person that I am today.

Acknowledgement

I would like to express my sincere gratitude to my thesis supervisor, Dr. Giovanni Calice, for his invaluable guidance, encouragement, and support throughout this research journey. His expertise, insightful feedback, and constructive criticism have been instrumental in shaping this thesis and strengthening its academic rigor.

ABSTRACT

ENVIRONMENTAL EFFICIENCY, FINANCING COSTS, AND MARKET
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This thesis examines whether adopting circular economy practices lowers the weighted average cost of capital (WACC) for European firms, and through which mechanisms this effect operates. It addresses a gap in the sustainable finance literature by focusing on operational circular economy metrics rather than broad ESG scores.

The analysis is conducted at two levels. At the firm level, a between-effects panel regression is applied to 475 listed firms in France, Germany, and the UK over 2015–2024 (22,206 observations). At the market level, a Vector Error Correction Model (VECM) is used to study long- and short-run relationships among four green financial variables: 10-year Treasury yields, the S&P Green Bond Index, the Wilderhill Clean Energy Index, and EU ETS CO₂ prices using 2,575 daily observations (2014–2025).

Results show that the Refinitiv Resource Use Score significantly reduces WACC: firms in the top quartile have an average WACC of 6.48% versus 8.23% in the bottom quartile. In contrast, the Waste Recycling Ratio is not significant, suggesting markets value broad

efficiency measures rather than narrower indicators. Market Beta is the dominant driver: a one-standard-deviation increase raises WACC by 1.90 percentage points, far exceeding the 0.24 reduction linked to resource efficiency. A sign reversal between fixed- and between-effects estimates indicates that markets price persistent structural efficiency rather than short-term improvements.

The VECM identifies two cointegrating relationships, with Treasury yields acting as the primary exogenous driver. Green bond prices do not significantly adjust following interest rate shocks, implying persistent losses.

These findings underpin the Circular-Financial Integration Framework (CFIF), a three-phase tool guiding firms from resource auditing to scaling circular practices. A Renault case study shows that sector Beta, not environmental performance, is the main constraint on lowering financing costs.

Overall, the thesis provides new evidence on the circular economy–WACC link and bridges empirical results with practical capital strategy.

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CHAPTER I: INTRODUCTION

1.1 Background and Motivation

The global economy faces a convergence of environmental and financial pressures that is reshaping the strategic calculus of manufacturing firms. On the environmental side, the depletion of natural resources, rising commodity prices, and the tightening of regulatory requirements under frameworks such as the European Union's Circular Economy Action Plans of 2015 and 2020 are compelling firms to fundamentally reconsider their relationship with materials, energy, and waste. On the financial side, the rapid growth of sustainable finance and emergence of instruments such as green bonds, sustainability-linked loans, ESG-screened equity portfolios is creating new channels through which environmental performance can translate into measurable capital market outcomes. At the intersection of these two forces lies a question of significant theoretical and practical importance: does the adoption of circular economy practices affect the cost at which firms can access capital?

The circular economy is defined as an industrial system that is restorative and regenerative by design, replacing the linear extract-produce-consume-dispose model with closed-loop material flows (Ellen MacArthur Foundation, 2012) has attracted substantial academic and policy attention over the past decade. Yet despite the proliferation of circular economy frameworks, maturity models, and implementation guides, the empirical evidence on their financial consequences remains fragmented and inconclusive. Most existing research addresses the operational and environmental benefits of circularity: reduced material costs, lower waste disposal expenses, improved regulatory compliance

without connecting these benefits to the capital structure outcomes that ultimately determine whether circular investments are financially self-sustaining.

This research addresses that gap directly. It investigates whether firms that demonstrate superior resource efficiency as measured by the Refinitiv Resource Use Score and Waste Recycling Ratio face lower Weighted Average Costs of Capital than their less efficient peers, controlling for the traditional financial determinants of financing costs. It does so using a between-effects panel regression estimated on 475 firms across France, Germany, and the United Kingdom over the period 2015 to 2024. Simultaneously, it analyses the macro-financial environment within which these firm-level dynamics play out, using a Vector Error Correction Model to characterise the dynamic relationships among green bond markets, clean energy equities, carbon prices, and Treasury yields.

The motivation for this dual-level research design reflects a core insight from the emerging sustainable finance literature: the cost of capital for circular firms is determined not only by firm-level risk characteristics but also by the macro-financial architecture of green asset markets. A manufacturing firm that achieves leading resource efficiency scores may still face elevated financing costs if the green bond market through which it might access preferential capital is itself repricing in response to monetary tightening. Understanding both layers is therefore essential for developing actionable guidance for practitioners.

1.2 The Context: Circular Economy and Sustainable Finance in Europe

Europe provides the most appropriate context for this research for three reasons. First, the EU has developed the world's most comprehensive regulatory framework for both the circular economy and sustainable finance, including the Circular Economy Action Plans, the EU Taxonomy for Sustainable Activities, the Non-Financial Reporting Directive (now superseded by the Corporate Sustainability Reporting Directive), and the Green Bond Standard. These frameworks create both compliance pressures and market incentives that should, in theory, strengthen the relationship between circular performance and financing costs. Second, the three countries selected for this study: France, Germany, and the United Kingdom represent the three largest Western European economies, collectively accounting for a significant share of European manufacturing output and listed equity market capitalisation. Third, Refinitiv Workspace provides comprehensive, consistent ESG data coverage for listed firms in these markets that is unavailable at comparable scale in smaller or emerging European economies.

Within this European context, the data reveal significant heterogeneity in both circular performance and financing costs across the three countries. French firms exhibit the highest mean Resource Use Score in the sample (72.26 out of 100), consistent with the early introduction of mandatory environmental reporting requirements and the strong institutional pressure from French regulatory bodies and institutional investors. German firms occupy a middle position (54.70), reflecting the mixed incentive environment created by Germany's strong industrial tradition but relatively late adoption of mandatory ESG disclosure. UK firms show the lowest mean resource efficiency scores (49.57) and the

highest mean financing costs (7.86%), though their greater market diversity makes direct comparison with the more concentrated French and German samples complex.

The time period of 2015 to 2024 captures a decade of transformative change in both the regulatory and financial environments for sustainability. It spans the introduction of the Paris Agreement (2015), the European Green Deal (2019), the COVID-19 pandemic and green recovery (2020–2021), the energy crisis and inflation shock (2022–2023), and the initial implementation of the CSRD (2023–2024). This breadth makes the sample period both rich in variation and challenging to model, as structural breaks and regime changes in the sustainability policy environment may affect the stability of the estimated relationships.

1.3 Research Problem

Despite the theoretical case for a negative relationship between circular economy practices and the cost of capital grounded in risk reduction, signalling theory, and the growing preferences of ESG-focused institutional investors the empirical evidence for this relationship among European manufacturing firms is limited by three specific gaps.

The first gap is one of measurement specificity. Most existing research on the ESG-WACC relationship uses broad composite ESG scores that aggregate environmental, social, and governance performance into a single index. This approach obscures the specific contribution of circular economy practices i.e. resource efficiency and waste management to financing cost variation. The present research addresses this by using the Resource Use Score and Waste Recycling Ratio as distinct circular economy proxies, allowing separate identification of their effects.

The second gap is one of analytical scope. Existing studies have examined either firm-level determinants of WACC or macro-financial dynamics of green asset markets, but rarely both within a single research design. The financial conditions prevailing in green bond and carbon markets represent the macro context within which firm-level financing decisions are made, and a complete understanding of the circular economy-WACC nexus requires analysis at both levels. This research bridges that gap through its dual-methodology design.

The third gap is one of practical applicability. The academic literature has produced a range of theoretical frameworks linking circular practices to financial outcomes but few tools that practitioners like financial managers, treasury officers, and sustainability directors can use to systematically assess and act on this relationship within their own firms. The Circular-Financial Integration Framework (CFIF) proposed in Chapter 8 of this research addresses this gap directly, translating the empirical findings into a structured, phase-based implementation guide.

1.4 Research Objectives

This research pursues four specific objectives. The first is to empirically establish whether resource efficiency, as measured by the Refinitiv Resource Use Score, is a statistically significant determinant of the Weighted Average Cost of Capital for manufacturing firms in France, Germany, and the United Kingdom, after controlling for traditional financial risk factors. The second is to quantify the economic magnitude of this relationship and compare it to the influence of conventional financial determinants, particularly market beta and firm size. The third is to characterise the macro-financial

dynamics of green asset markets. Specifically the relationships among green bond prices, clean energy equity performance, carbon allowance prices, and Treasury yields and to identify the mechanisms through which macro-financial conditions transmit into the cost and availability of green capital. The fourth is to develop a practical managerial framework, grounded in the empirical findings, that guides manufacturing firms through the process of translating circular economy investment into measurable cost of capital advantages.

1.5 Contribution to Knowledge

This research makes four distinct contributions to the academic and practitioner literatures. First, it provides large-sample, cross-country empirical evidence on the relationship between circular economy indicators and the cost of capital in a European context, extending the ESG-WACC literature from composite sustainability scores to specific circular economy metrics. Second, it identifies and interprets the sign reversal between the between-effects and fixed-effects estimates of the resource efficiency coefficient, that is, the cross-sectional pricing of persistent environmental efficiency versus the absence of within-firm repricing following marginal score improvements as a substantively meaningful finding that advances understanding of how capital markets process environmental information. Third, it establishes the long-run cointegrating relationship among green financial assets and conventional bond markets using a daily VECM over a five-year window, quantifying the interest rate sensitivity of green bonds ($\beta = -0.911$ for a one-unit Treasury yield shock) and the error correction dynamics of clean energy equities and carbon prices. Fourth, it develops the Circular-Financial Integration

Framework as a practitioner tool that connects empirical findings to operational strategy, filling the gap between academic evidence and managerial action.

1.6 Structure of the Thesis

The remainder of this thesis is organised as follows. Chapter 2 presents the research aims, questions, and hypotheses that structure the empirical investigation. Chapter 3 provides a critical review of the literature across five domains: the conceptual foundations of the circular economy, its implementation challenges, the ESG-WACC nexus, the dynamics of green financial markets, and the strategic frameworks for circular transitions. Chapter 4 develops the theoretical framework, integrating the Capital Asset Pricing Model, Signalling Theory, and Information Asymmetry Theory into a coherent account of the mechanisms through which environmental efficiency should influence financing costs. Chapter 5 describes the data sources, sample construction, and presents descriptive statistics. Chapter 6 sets out the methodology, justifying the between-effects estimator for the panel analysis and the VECM specification for the time-series analysis, and presenting all diagnostic test results. Chapter 7 presents and interprets the empirical findings from both analytical parts. Chapter 8 develops the Circular-Financial Integration Framework based on those findings. Chapter 9 applies the framework to Renault SA as a detailed case study. Chapter 10 concludes, discusses limitations, and identifies directions for future research.

CHAPTER II: RESEARCH AIMS, QUESTIONS, AND HYPOTHESES

2.1 Research Aim

The overarching aim of this research is to investigate the relationship between circular economy practices and corporate financing costs among European manufacturing firms, and to develop a practitioner framework that translates this empirical relationship into actionable strategic guidance. This aim is pursued at two analytical levels: the firm level, through a between-effects panel regression examining whether resource-efficient firms face lower weighted average costs of capital than their peers; and the market level, through a Vector Error Correction Model characterising the macro-financial dynamics of green asset markets. The dual-level design reflects the conviction that a complete understanding of the circular economy-financing cost nexus requires analysis of both the firm-specific mechanisms through which environmental performance is priced by capital markets and the macro-financial conditions within which those markets operate.

2.2 Research Questions

The research is organised around four primary research questions, each addressing a distinct dimension of the relationship between circular economy practices and capital market outcomes.

Research Question 1: Is resource efficiency, as measured by standardised ESG metrics, a statistically significant determinant of the Weighted Average Cost of Capital among manufacturing firms in France, Germany, and the United Kingdom, after controlling for conventional financial risk factors?

This question addresses the core empirical claim of the research, specifically that circular economy practices, operationalised through the Resource Use Score and Waste

Recycling Ratio, are priced by capital markets in a way that reduces the cost of capital for more efficient firms. It is addressed through the between-effects panel regression in Chapter 7.

Research Question 2: What is the economic magnitude of the resource efficiency effect on WACC relative to conventional financial determinants such as market beta and firm size, and what does this magnitude imply about the current state of environmental information integration in capital markets?

This question moves beyond statistical significance to economic significance, recognising that a relationship may be real but too small to be actionable for practitioners. It is addressed through the economic magnitude analysis in Chapter 7 and the theoretical interpretation in the discussion section.

Research Question 3: What are the dynamic relationships among green bond markets, clean energy equity indices, carbon allowance prices, and conventional bond yields, and how do macro-financial shocks, particularly interest rate changes, transmit into the cost of green capital?

This question addresses the macro-financial environment within which firm-level financing decisions are made. It is addressed through the VECM analysis in Chapter 7, with particular attention to the error correction mechanism and impulse response dynamics.

Research Question 4: How can the empirical findings on the circular economy-WACC relationship be translated into a structured, phase-based framework that guides

manufacturing firms through the process of converting circular economy investment into measurable financing cost advantages?

This question bridges the academic and practitioner dimensions of the research. It is addressed through the Circular-Financial Integration Framework in Chapter 8 and the Renault case study in Chapter 9.

2.3 Research Hypotheses

The research questions are operationalised through five testable hypotheses, derived from the theoretical framework developed in Chapter 4.

Table 2.1

Hypothesis	Statement	Test
H1	Firms with higher Resource Use Scores have significantly lower WACCs than firms with lower scores, ceteris paribus.	BE regression coefficient on Resource Use Score: expect negative and significant
H2	The Waste Recycling Ratio does not exert a statistically significant independent effect on WACC, due to lower signal credibility relative to the Resource Use Score.	BE regression coefficient on Waste Recycling Ratio: expect insignificant
H3	Market beta is the dominant determinant of WACC variation in the sample, with an effect size substantially larger than that of environmental efficiency variables.	Comparison of standardised coefficients on Beta vs. Resource Use Score

Hypothesis	Statement	Test
H4	The four macro-financial variables (Treasury yield, Green Bond Index, Clean Energy Index, and CO ₂ price) are cointegrated, sharing at least one long-run equilibrium relationship.	Johansen trace and max-eigenvalue tests: expect rejection of $r=0$
H5	Increases in Treasury yields exert a significant negative short-run effect on green bond returns, reflecting the interest rate sensitivity of long-duration green fixed-income instruments.	VECM short-run coefficient on Δ Treasury yield in green bond equation: expect negative and significant

Table 2.1: Research Hypotheses and Empirical Tests

Hypotheses H1 through H3 relate to the firm-level panel analysis and are grounded in the risk-based and signaling channels linking environmental efficiency to financing costs. H1 represents the primary hypothesis of the research. H2 is a differentiated hypothesis that anticipates heterogeneity in the market response to different types of environmental metrics, drawing on signaling theory's emphasis on signal credibility. H3 addresses the relative importance of environmental versus financial determinants of WACC, with implications for where circular economy strategy should focus to achieve the greatest financing cost impact.

Hypotheses H4 and H5 relate to the macro-financial time-series analysis. H4 tests the fundamental prerequisite for the VECM framework: the existence of cointegration

among the four variables. H5 identifies the most theoretically important short-run transmission mechanism in the system: the sensitivity of green bond valuations to monetary policy, which has direct implications for the timing and structuring of green financial instruments.

2.4 Scope and Boundaries of the Research

Several boundaries define the scope of this research. Geographically, the analysis is limited to listed non-financial firms headquartered in France, Germany, and the United Kingdom. While this scope provides a large and diverse sample, it means that the findings may not generalise directly to Central or Eastern European markets, to non-European contexts, or to the post-Brexit UK regulatory environment in the later years of the sample. Sectorally, the research focuses on the manufacturing and industrial sectors, which are the primary targets of circular economy policy and the most data-rich in terms of ESG reporting. The exclusion of financial firms is standard in capital structure research and is maintained throughout.

Temporally, the firm-level panel covers 2015 to 2024, while the time-series dataset covers July 2014 to October 2025. The latter window pre-dates the structural expansion of green finance that followed the COVID-19 recovery and the European Green Deal, which means that the macro-financial findings may not fully capture the current state of green market integration. This temporal boundary is acknowledged as a limitation and motivates the suggestion in Chapter 10 that the VECM analysis be replicated with post-2020 data as a priority for future research.

Methodologically, the research employs observational data and regression-based methods. It does not claim to establish causal relationships in the strict experimental sense. The between-effects estimator identifies persistent cross-sectional associations between environmental efficiency and financing costs, which may reflect a causal effect of circularity on WACC, the influence of unobserved firm characteristics on both, or both simultaneously. The limitations of causal identification are discussed in detail in Chapter 10.

2.5 Definitions of Key Terms

For the purposes of this research, the following definitions apply. The circular economy is defined as an industrial system that replaces the linear extract-produce-consume-dispose model with closed-loop material flows designed to maintain the value of products and materials for as long as possible (Ellen MacArthur Foundation, 2012). Resource efficiency refers to the ratio of economic value generated to natural resource inputs consumed, operationalised through the Refinitiv Resource Use Score. The Weighted Average Cost of Capital (WACC) is the minimum rate of return required by all capital providers (equity and debt holders) weighted by their respective share of total firm value. Market beta is the sensitivity of a firm's equity returns to movements in the broad market index, estimated over a 60-month rolling window. Cointegration refers to the existence of a stable long-run equilibrium relationship among non-stationary time series, such that their linear combination is stationary.

2.6 Summary

This chapter has established the research aims, questions, hypotheses, scope, and key definitions that structure the empirical investigation. The four research questions move from firm-level pricing of environmental efficiency, through economic magnitude assessment, to macro-financial market dynamics, and finally to practical implementation guidance. The five testable hypotheses provide the empirical anchors against which the results in Chapter 7 are evaluated. Chapter 3 now develops the literature review that contextualises these questions within the existing academic debate.

CHAPTER III: LITERATURE REVIEW

The academic discourse surrounding the circular economy, environmental efficiency, and their intersection with corporate finance has expanded considerably over the past two decades. This chapter provides a critical synthesis of the existing literature across five interconnected domains: the theoretical and empirical foundations of the circular economy; the challenges of its implementation in manufacturing; the financial implications of environmental performance for firms' cost of capital; the macro-financial dynamics of green asset markets; and the strategic enablers of circular transitions. By mapping these bodies of knowledge, this review identifies both the theoretical scaffolding upon which this research rests and the empirical gaps it seeks to address.

3.1 The Circular Economy: Conceptual Foundations and Evolution

3.1.1 Defining Circularity: From Concept to Framework

The circular economy has emerged as one of the most influential conceptual frameworks in contemporary sustainability discourse, yet its definitional boundaries remain contested. At its most fundamental level, the circular economy is formally defined

as an industrial economy that is restorative and regenerative by intention and design (Acerbi and Taisch, 2020; Ellen MacArthur Foundation, 2012), representing a systemic departure from the dominant linear paradigm characterised by extraction, production, consumption, and disposal (Ellen MacArthur Foundation, 2013). The seminal work of Pearce and Turner (1990) is widely credited with establishing the ecological economic basis for circularity, drawing on thermodynamic principles to argue that natural resource constraints necessitate a fundamental redesign of industrial metabolism.

Kirchherr, Reike, and Hekkert (2017) conducted a systematic analysis of 114 definitions of the circular economy and found that while the concept is most commonly associated with the reduce-reuse-recycle triad, fewer than a quarter of definitions explicitly address the social dimension, and fewer still establish a clear linkage to sustainable development as a normative objective. The authors also found that CE had historically been associated more with economic prosperity and environmental quality than with broader sustainable development goals. This fragmentation reflects the concept's heterogeneous intellectual heritage, drawing simultaneously from industrial ecology, biomimicry, cradle-to-cradle design philosophy, and performance economy theory. Geissdoerfer, Savaget, Bocken, and Hultink (2017) further noted that while sustainability and the circular economy are often conflated in policy discourse, they are analytically distinct: sustainability concerns the long-run maintenance of environmental, social, and economic systems, while the circular economy is primarily a production and consumption strategy. CE holds four core principles: eliminating waste, circulating materials at their highest value, using materials more than once, and managing products in ways that restore natural

systems (Abdul-Hamid et al., 2021). For the purposes of this research, the circular economy is operationalised in terms of resource efficiency and waste management, consistent with the Refinitiv ESG dataset, with the Resource Use Score and Waste Recycling Ratio serving as proxies for firms' circular performance (Trumpp and Guenther, 2017; De Angelis, 2021).

3.1.2 The Circular Economy in the Manufacturing Sector

The manufacturing sector occupies a privileged position in the circular economy literature, both as a primary contributor to resource consumption and environmental degradation and as a site of significant circular innovation. The EU's Circular Economy Action Plans of 2015 and 2020 have placed increasing regulatory pressure on manufacturing firms to adopt design-for-disassembly principles, extended producer responsibility frameworks, and closed-loop material flows (European Commission, 2020). Locally, countries such as China have incorporated CE into national policies supporting industrial ecology and material re-circulation within industrial sectors. Stahel (2016) argued that the shift to a circular economy in manufacturing requires not merely incremental process improvement but a fundamental restructuring of value chains from product-centric to service-centric business models. This has been empirically supported by studies of the automotive sector (Mathews and Tan, 2016), electronics manufacturing (Bressanelli et al., 2018), and the chemical industry (Antikainen and Valkokari, 2016). Companies such as Philips and Renault have demonstrated the economics of circular economy in practice through design for disassembly and remanufactured products (Ethirajan et al., 2021). Ranta, Aarikka-Stenroos, Ritala, and Mäkinen (2018) found persistent heterogeneity in circular maturity across firms, driven by differences in

technological capability, supply chain governance, and regulatory exposure, directly informing the research design of the present study.

3.1.3 Challenges in the Implementation of the Circular Economy

The challenges of adopting circularity are partially rooted in the historical development of economic systems that prioritised efficiency, mass production, and short-term profitability over long-term resource sustainability (Jaeger and Upadhyay, 2019). Liu and Bai (2014) find that high investment costs and long payback periods discourage firms from implementing CE practices, and also cite the lack of financial support mechanisms and tax incentives as key barriers. Luthra et al. (2022) note that the lack of flexibility and long lead times involved in changing supply chain dynamics require substantial initial investment in circular technologies. Beyond economic barriers, Benton et al. (2015) find a fundamental lack of understanding of CE principles among stakeholders, while Su et al. (2013) identify the absence of a unified standard system for performance assessment as a further structural impediment. One reason defining the circular economy remains challenging is that its definition is based on a heterogeneous mix of scientific and semi-scientific concepts (Corvellec et al., 2021). These implementation challenges have direct financial consequences: firms may incur high initial capital expenditures that increase their debt-to-equity ratio before any long-term WACC reduction is realised, creating what this research terms the financial paradox of circular investment.

3.1.4 Critiques and Limitations of the Circular Economy Paradigm

Despite widespread adoption, the circular economy has attracted substantive academic criticism. Corvellec, Stowell, and Johansson (2021) argued that the circular economy's emphasis on technical material flows obscures deeper questions of consumption levels and social equity: recycling may extend the material life of products while leaving unchanged the volume of production that drives environmental degradation, consistent with the ecological economics literature on rebound effects (Giampietro and Mayumi, 2018). Korhonen, Honkasalo, and Seppälä (2018) raised related thermodynamic concerns, noting that entropy laws impose fundamental limits on recyclability and that a 100 percent circular economy is physically impossible. For the manufacturing firms in this study's dataset, the relevant managerial question is therefore not how to eliminate waste entirely but how to optimise the trade-off between circular investment and residual waste generation.

3.2 The Influence of Circular Economy Strategies on Operational Competence, Environmental Performance, and Financial Results

According to Sawe et al. (2021), the operational competence, environmental performance, and financial results of manufacturing firms are all impacted by circular economy strategies. CE practices achieve operational competence by driving efficiency in resource use: metrics including waste reduction, sustainability of products, and product lifecycle management offer significant prospects for how products are manufactured, resulting in better operations and enhanced productivity. Remanufacturing and refurbishing products generate as good or better outputs from existing materials without

procuring new ones (Janssens, Kuppens, and Van Schoubroeck, 2021), while IoT and data analytics help to monitor materials in real time and optimise operational decision-making.

CE has a direct impact on environmental sustainability indicators, as it entails affording the highest importance to resource use so that resources create value and do not waste, pollute, or unnecessarily consume natural capital (Joensuu, Edelman, and Saari, 2020). Closed-loop systems both reduce the demand for new material and the disposal of waste to landfill. CE strategies also positively impact financial performance: organisations can recover the capital outlay for CE technologies from long-term savings on raw material consumption and disposal costs (Khan et al., 2021), and CE models generate new revenue sources through selling back products or secondary materials, enhancing brand image and market share. However, as this study's panel regression demonstrates, the translation from operational circular performance to capital market outcomes is not straightforward: the Resource Use Score is statistically significant but economically modest in its effect on WACC, reflecting the early stage of integration between environmental performance metrics and financial valuation.

3.3 Environmental Performance and the Cost of Capital: Theory and Evidence

3.3.1 Theoretical Channels Linking Sustainability to Financing Costs

The theoretical case for a negative relationship between environmental performance and the cost of capital rests on several complementary mechanisms. The risk-based channel draws on the CAPM to argue that environmentally responsible firms face systematically lower exposure to physical and transition risks (Pedersen, Fitzgibbons, and Pomorski, 2021). Firms that have reduced their resource intensity are less exposed to

regulatory and commodity price risks, and rational investors should therefore require a lower risk premium (Bolton and Kacperczyk, 2021). The signaling channel draws on Spence (1973): superior environmental performance functions as a credible signal of managerial quality and strategic foresight, reducing information asymmetry and hence financing costs (Ge and Liu, 2015; Bauer and Hann, 2010). Without technological validation, however, environmental claims are often dismissed as greenwashing. The investor preference channel draws on Fama and French (2007) and Pastor, Stambaugh, and Taylor (2021): as ESG-focused institutional capital grows, the equilibrium required return on green assets falls below that of equivalent brown assets. Finally, ecological modernisation theory argues that environmental and economic efficiency reinforce each other, with circular economy indicators reflecting a firm's capacity to innovate within production processes (De Angelis, 2021).

3.3.2 Empirical Evidence on the ESG-WACC Nexus

El Ghouli, Guedhami, Kwok, and Mishra (2011) found that firms with better CSR scores faced significantly lower costs of equity. Cheng, Ioannou, and Serafeim (2014) extended this to a global sample and demonstrated that firms with superior ESG performance face lower capital constraints, attributed primarily to reduced information asymmetry. Bauer and Hann (2010) found that firms with environmental concerns faced higher credit spreads, while Ge and Liu (2015) demonstrated that strong CSR performance is associated with more favourable loan terms. Flammer (2021) provided quasi-experimental evidence that green bond issuance is associated with improvements in environmental performance and stock market valuations. However, Friede, Busch, and

Bassen (2015), in a meta-analysis of over 2,200 empirical studies, found a positive ESG-financial performance relationship in only 63 percent of cases with wide variation in effect sizes, consistent with the modest coefficient on the Resource Use Score identified in this study's panel regression. In the European context, the EU Taxonomy for Sustainable Activities has created a regulatory impetus that is likely to strengthen the ESG-WACC nexus over coming years (Schoenmaker and Schramade, 2019), while Hoepner et al. (2021) found that institutional investor engagement on environmental issues led to subsequent reductions in firms' downside risk exposure.

3.3.3 The Role of Disclosure Quality and Reporting Standards

A critical mediating factor in the ESG-WACC relationship is the quality and credibility of environmental disclosure. The current landscape is characterised by significant heterogeneity across voluntary frameworks including the GRI, SASB, and TCFD. Hawn, Chatterji, and Mitchell (2018) demonstrated that the gap between firms' internal environmental actions and their external reporting significantly affects market valuations, with decoupled firms experiencing lower valuations over time. To the extent that the Resource Use Score in this study reflects reported rather than actual resource efficiency, the measured ESG-WACC relationship may understate the true economic effect of operational circularity. The development of mandatory disclosure standards under the EU Corporate Sustainability Reporting Directive (CSRD) represents a structural improvement in the information environment that may strengthen these relationships in future research.

3.4 Green Financial Markets: Structure, Dynamics, and Integration

3.4.1 The Emergence and Growth of the Green Bond Market

The green bond market has grown from a niche instrument into a significant segment of the global fixed income market since the first labelled green bond was issued by the European Investment Bank in 2007 (Climate Bonds Initiative, 2023). The defining feature is the use-of-proceeds framework: issuers commit to allocating proceeds to eligible green projects and reporting on environmental outcomes, creating ex-ante accountability. Zerbib (2019) found evidence of a small but statistically significant negative yield spread for green bonds relative to conventional bonds, a greenium that appears to have grown as the market has matured (Baker, Bergstresser, Serafeim, and Wurgler, 2022). However, Tang and Zhang (2020) found limited evidence of improvements in subsequent environmental performance following issuance, suggesting the signaling effect may outpace underlying environmental commitment in some cases.

3.4.2 Macroeconomic Drivers and Market Integration

Interest rate dynamics represent the most significant conventional driver of green asset valuations. The empirical analysis of this study confirms that changes in 10-year Treasury yields exert a significant negative effect on green bond returns in the short-run VECM estimates, consistent with the theoretical prediction that tighter monetary conditions reduce the present value of long-duration green assets (Ehlers and Packer, 2017). Carbon market dynamics represent a distinct macroeconomic driver: Koch, Fuss, Grosjean, and Edenhofer (2014) demonstrated that carbon price shocks generate significant sectoral rebalancing in equity markets. Reboredo (2018) found low but increasing

correlation between green and conventional bond returns over 2013-2017, while Pham and Nguyen (2022) found stronger co-movement in the post-pandemic period. The cointegration relationships identified in the VECM analysis of this study are consistent with this long-run convergence narrative, suggesting that the co-movement between green and traditional financial markets is primarily a long-run phenomenon mediated by monetary conditions.

3.5 The Role of Technological Innovation and Stakeholder Collaboration in Advancing Circular Economy Transitions

3.5.1 Industry 4.0 as a Circular Economy Enabler

Technological innovation is a critical factor in CE strategies (Del Vecchio et al., 2021). IoT makes it possible to monitor the location of materials and products during their use so that resources are used effectively and unnecessary waste is avoided. Machine learning provides accurate estimates of remaining product lifetime, which is particularly useful for designing for disassembly or reuse. Rajput and Singh (2019) found that real-time material tracking significantly improved the economics of remanufacturing by reducing uncertainty about the condition of returned products, while Bressanelli, Adrodegari, Perona, and Saccani (2018) identified predictive maintenance, quality control in remanufacturing, and demand forecasting for secondary materials as the most developed AI application areas. Blockchain provides a secure solution for keeping track of recycled and remanufactured materials, establishing trust in circular supply chains. Saberi, Kouhizadeh, Sarkis, and Shen (2019) identified waste tracking, carbon credit trading, and

recycled material certification as the most promising blockchain use cases. Critically, these technologies serve as the evidence base that turns environmental claims into bankable financial data, reducing the information asymmetry between firms and their lenders that this study identifies as a primary obstacle to the translation of circular performance into WACC advantages.

3.5.2 Stakeholder Collaboration and the Governance of Circular Transitions

CE transitions require as much collaborative effort as the identification of stakeholders (Eisenreich, Füller, and Stuchtey, 2021). Freeman's (1984) stakeholder theory provides the foundational framework for analysing these multi-actor dynamics. For there to be a circular economy, everyone within the value chain must be on board: manufacturers, suppliers, customers, waste management companies, and policymakers. Collaboration increases resource sharing, knowledge about circular solutions, and learned best practices (Du, Xu, and Yuan, 2024). Tura, Hanski, Ahola, Ståhle, Piiparinen, and Valkokari (2019) found that the formation of trusted partnerships, particularly between manufacturers and waste management firms, as a critical enabler of closed-loop material flows, with information sharing, joint infrastructure investment, and incentive alignment as the key mechanisms. Government measures such as extended producer responsibility policies and recycling infrastructure guidelines become solvable when stakeholders cooperate (Pinheiro et al., 2022). Institutional investors have also emerged as a critical stakeholder group: Dimson, Karakas, and Li (2015) found that successful environmental engagements were associated with positive abnormal stock returns, while Dyck, Lins, Roth, and Wagner (2019) found heterogeneity in engagement effectiveness driven by firm size, institutional

ownership, and regulatory exposure. Without robust stakeholder engagement, environmental signals sent by the firm risk being perceived as greenwashing, neutralising any potential reduction in the cost of debt.

3.6 Strategic Frameworks for Implementing Circular Economy in Manufacturing

As per de Oliveira, Ghobakhloo, and Figueira (2023), a strategic framework for manufacturing firms to introduce CE practices must be underpinned by sustainability, operational change, and stakeholder cooperation. The first step involves assessment and planning: firms analyse their current operations, establish waste streams, and determine their position relative to circular transition. Design for circularity involves redesigning products to increase durability, modularity, and recyclability. According to Martínez-Peláez et al. (2023), continuing a closed-loop system with suppliers is crucial, requiring measures for recycling materials and recovering products at end of lifecycle. Technology and innovation are essential: IoT and AI manage resources and monitor materials throughout their life cycle, while advances such as 3D printing cut waste (Owojori and Okoro, 2022). Integrated stakeholder efforts are critical, with consumer engagement through incentives such as reverse logistics fortifying the circular model (Teixeira et al., 2022). The ability to monitor CE through KPIs and continuous scenario refinement guarantees effectiveness. This existing strategic literature directly informs the Circular-Financial Integration Framework (CFIF) proposed in this research, which extends prior frameworks by explicitly connecting each phase of circular adoption to measurable capital structure outcomes.

3.7 The WACC as a Strategic Financial Metric in Sustainability Contexts

3.7.1 Decomposing the WACC: Debt and Equity Cost Components

The Weighted Average Cost of Capital is the central financial metric in this research. Formally, $WACC = \frac{E}{V} \times R_e + \frac{D}{V} \times R_d \times (1 - T)$, where E and D are the market values of equity and debt, V is total firm value, Re and Rd are the required returns on equity and debt, and T is the corporate tax rate. The environmental efficiency channel operates differently on each component: on the equity side, the primary mechanism is reduction of systematic market risk through asset beta; on the debt side, it operates through credit risk reduction and lender preferences as banks increasingly incorporate ESG criteria into credit assessments. The empirical literature suggests that the debt cost channel may be more immediately sensitive to environmental performance than the equity cost channel (Eliwa, Aboud, and Saleh, 2021).

3.7.2 Beta as the Dominant Driver: Implications for Circular Strategy

The finding in this study's panel regression that market beta is the dominant determinant of WACC is consistent with classical finance theory and the emerging literature on ESG and systematic risk. Albuquerque, Koskinen, and Zhang (2019) demonstrated that firms with higher CSR scores exhibit lower systematic risk, attributing this to customer loyalty and revenue stability advantages. In the circular economy context, the beta-reduction mechanism operates through the reduction of commodity price exposure through material substitution and recycling, the insulation of cash flows from regulatory

risk through proactive environmental management, and the stabilisation of supply chain relationships through long-term partnerships with material recovery partners. These channels collectively suggest that sustained commitment to circular practices should, over time, translate into measurable beta reductions and hence material WACC advantages, even if the current cross-sectional evidence captures only the early stages of this dynamic.

3.8 Research Gap

Although scholars have shown considerable interest in CE practices in manufacturing, important research gaps remain. First, while the relationship between ESG performance broadly defined and firms' cost of capital has been extensively studied, the specific contribution of circular economy indicators as distinct from general environmental scores to financing cost variation remains underexplored. The use of Resource Use Score and Waste Recycling Ratio as distinct circular economy proxies in this study's panel regression represents a more targeted approach to this question. Second, the lack of research on differences in challenges and drivers of CE adoption across manufacturing sub-sectors requires more targeted analysis than currently exists, as most studies provide generic findings (Ramakrishna et al., 2020). Third, the literature has rarely examined the ESG-WACC relationship in a comparative European context that explicitly accounts for country-level variation in regulatory frameworks and sustainability preferences: a gap addressed by the three-country panel of France, Germany, and the United Kingdom in this research. Fourth, the integration of firm-level and market-level analysis in a single research design, combining a between-effects panel regression with a VECM of green financial markets is methodologically novel, bridging two critical layers of analysis that have

hitherto developed largely in isolation. As part of suggested directions for future research, one should attempt to quantify CE's long-term financial effects and return on investment across diverse manufacturing environments, and to examine how leadership and organisational culture mediate the adoption of circular practices.

CHAPTER IV: THEORETICAL FRAMEWORK

The literature review in Chapter 3 surveyed a broad range of theories and empirical findings relevant to the circular economy-WACC relationship. This chapter takes the next step: it synthesises those theoretical threads into an integrated framework that specifies the mechanisms through which circular economy practices should influence financing costs, the conditions under which those mechanisms operate, and the directions of the effects. The framework serves two purposes. First, it provides the theoretical justification for the hypotheses tested in the empirical analysis. Second, it establishes an interpretive lens through which the results, including unexpected findings such as the modest economic magnitude of the resource efficiency effect and the Hausman sign reversal can be understood.

The chapter is structured as follows. Section 4.1 establishes the conceptual architecture of the framework, identifying four theoretical pillars. Sections 4.2 through 4.5 develop each pillar in detail. Section 4.6 integrates the four pillars into a unified causal model. Section 4.7 derives the testable hypotheses from the integrated model. Section 4.8 identifies the boundary conditions and moderating factors that limit the generalisability of the framework.

4.1 Conceptual Architecture: Four Theoretical Pillars

The theoretical framework rests on four pillars drawn from the corporate finance, information economics, and sustainability management literatures. These are the Capital Asset Pricing Model (CAPM) and its risk-based implications for how environmental efficiency affects the cost of equity through beta reduction; Signalling Theory and its account of how environmental disclosures reduce information asymmetry between firms and capital providers; the Investor Preference Channel, which explains how the growth of ESG-mandated institutional capital creates a demand-side mechanism for green asset repricing; and the Macro-Financial Integration Framework, which characterises the environmental-financial feedback loop operating at the market level through cointegrated green asset prices.

These four pillars are not independent. They operate simultaneously and interact: the effectiveness of signalling depends on the quality of the CAPM-relevant risk information being signalled; the investor preference channel is partly a consequence of successful signaling at scale; and the macro-financial integration framework sets the aggregate conditions that determine whether firm-level risk improvements translate into lower financing costs in practice. The integrated model in Section 4.6 makes these interactions explicit.

Table 4.1

Pillar	Core Theory	Mechanism	Key Prediction
1. Risk Channel	CAPM (Sharpe, 1964; Lintner, 1965)	Circular practices reduce beta through commodity decoupling and regulatory risk reduction	Resource efficiency → lower beta → lower cost of equity
2. Signalling Channel	Signalling Theory (Spence, 1973)	ESG disclosure reduces information asymmetry; credible signals reduce lender/investor risk premia	Credible circular disclosure → lower cost of debt and equity
3. Investor Preference	ESG Investor Demand (Pastor et al., 2021)	Growing ESG capital raises green asset prices, compressing required returns on green firms	ESG investor growth → lower equilibrium WACC for green firms
4. Macro-Financial	Cointegration Theory (Johansen, 1988)	Green financial markets share long-run equilibria; macro shocks transmit across green assets	Interest rate rises → green bond repricing → tighter green financing

Table 4.1: Four Theoretical Pillars of the Framework

4.2 Pillar 1: The CAPM Risk Channel

4.2.1 The CAPM and the Cost of Equity

The Capital Asset Pricing Model (CAPM), developed by Sharpe (1964) and Lintner (1965), provides the dominant theoretical framework for understanding the cost of equity in modern corporate finance. The CAPM posits that the required return on any asset is determined solely by its systematic risk, its sensitivity to undiversifiable, market-wide shocks as captured by the market beta coefficient. The cost of equity is formally expressed as:

$$Re = Rf + \beta \times (Rm - Rf)$$

where Re is the cost of equity, Rf is the risk-free rate, β is the market beta, and $(Rm - Rf)$ is the market risk premium. Because unsystematic, firm-specific risk can be diversified away by holding a portfolio, rational investors do not demand compensation for it. Accordingly, a firm can reduce its cost of equity only by reducing its beta: its covariance with the market portfolio and not by reducing total volatility.

To the extent that circular practices reduce systematic risk through commodity decoupling, CAPM predicts a lower cost of equity through Beta reduction. However, circularity may also affect WACC through signaling and investor preference channels that operate independently of Beta — and the empirical results suggest all three channels may be simultaneously active.

4.2.2 Circular Economy Practices and Beta Reduction

Three specific mechanisms link circular economy adoption to lower market beta. The first is commodity price decoupling. A firm that closes its material loops by substituting recycled inputs for virgin commodities, recovering materials from end-of-life

products, and reducing its per-unit energy consumption reduces its cost exposure to commodity price cycles. Since commodity price shocks are a significant source of market-wide earnings volatility, particularly in manufacturing sectors, firms with lower resource intensity exhibit lower covariance with the market. Albuquerque, Koskinen, and Zhang (2019) provide empirical support for this mechanism, demonstrating that high-CSR firms exhibit lower systematic risk, which they attribute partly to greater revenue and cost stability.

The second mechanism is regulatory risk insulation. Firms that proactively adopt resource efficiency and waste reduction practices are less exposed to the financial consequences of tightening environmental regulation: penalties, compliance costs, required capital expenditure, and asset stranding. Since regulatory tightening tends to occur in response to environmental deterioration that affects broad sectors rather than individual firms, it represents a systematic rather than idiosyncratic risk. Early adoption of circular practices therefore constitutes a hedge against regulatory beta, being the component of market sensitivity driven by environmental policy uncertainty.

The third mechanism is supply chain stabilisation. Circular firms that have invested in long-term material recovery partnerships, design-for-disassembly product architectures, and reverse logistics systems are less vulnerable to the supply chain disruptions that generate market-wide earnings shocks. The COVID-19 pandemic of 2020 and the energy crisis of 2022 demonstrated how supply chain fragility can rapidly translate firm-level operational risk into systematic, market-correlated losses. Firms with closed-loop supply architectures are structurally more resilient to these shocks.

The empirical finding in this study, that market beta is by far the dominant determinant of WACC, with a one-standard-deviation increase in beta associated with a 1.90 percentage point increase in WACC compared to only 0.28 percentage points for a one-standard-deviation improvement in the Resource Use Score is consistent with this theoretical account. It suggests that the most powerful route to a lower cost of capital through circular practices is through sustained beta reduction, not through immediate ESG score improvements. The Circular-Financial Integration Framework in Chapter 8 operationalises this insight.

4.2.3 The Debt Cost Channel

The CAPM governs the cost of equity, but the WACC also incorporates the cost of debt. The debt cost channel operates through a distinct mechanism: the probability of default and the recovery rate in the event of default. Environmental performance affects the cost of debt primarily through its impact on operational cash flow stability and long-term asset quality. Bauer and Hann (2010) found that firms with environmental concerns paid higher credit spreads, attributing this to lenders pricing the expected costs of future environmental liabilities. Eliwa, Aboud, and Saleh (2021) found that ESG practices reduce the cost of debt in EU firms, with the effect strongest after mandatory disclosure requirements were introduced.

In the circular economy context, the debt cost channel is particularly relevant for sustainability-linked loans and green bonds, where the coupon or margin is explicitly linked to the borrower's ESG performance. For such instruments, the circular economy

practices captured by the Resource Use Score and Waste Recycling Ratio directly determine the interest rate through contractual mechanisms rather than through market pricing. This represents a more direct and immediate transmission from circular performance to financing cost than the equity risk channel, and is a key component of the Pilot phase of the CFIF framework.

4.3 Pillar 2: Signalling Theory and Information Asymmetry

4.3.1 The Signalling Framework

Spence's (1973) seminal model of job market signalling established the foundational logic for how observable actions can convey private information from better-informed parties to less-informed ones in a credible way. The key insight is that for a signal to be credible, that is, to successfully separate high-quality from low-quality types, it must be costly to fake: the cost of acquiring the signal must be lower for the high-quality type than for the low-quality type, creating a separating equilibrium in which only genuine high-quality types find it rational to signal.

Applied to the environmental performance context, Signalling Theory predicts that a firm's environmental disclosures will reduce its financing costs only if those disclosures function as credible signals of managerial quality, operational efficiency, and long-run value creation that capital providers cannot directly observe. Capital providers face a fundamental information asymmetry: they cannot directly observe a firm's true resource efficiency, waste management practices, or long-run exposure to environmental regulatory risk. ESG scores and sustainability reports are attempts to bridge this gap or to make the

unobservable observable but their credibility depends critically on whether they can be gamed.

4.3.2 The Credibility Hierarchy of Circular Economy Signals

Not all environmental signals are equally credible, and this differential credibility helps explain one of the key empirical findings of this research: the Resource Use Score is a statistically significant predictor of WACC while the Waste Recycling Ratio is not. Signaling theory provides a coherent explanation for this asymmetry.

The Resource Use Score is a composite metric that captures the ratio of resource inputs like energy, water, materials to operational output across the firm's entire operations. It is anchored to operational intensity ratios that are difficult to manipulate without genuine operational change: a firm cannot substantially improve its Resource Use Score without actually reducing its consumption of energy and materials per unit of production. The signal is therefore costly to fake, satisfying Spence's separating condition. Furthermore, the composite nature of the score, which aggregating multiple resource streams, makes it harder for firms to selectively improve one dimension while deteriorating on others, increasing its reliability as a holistic signal of circular maturity.

The Waste Recycling Ratio, by contrast, is a narrower and more easily manipulated metric. Definitional choices in waste classification as in what counts as recycling versus recovery versus disposal vary substantially across firms and reporting frameworks. A firm can improve its reported Waste Recycling Ratio by reclassifying waste streams, contracting with third-party recyclers whose practices are not independently verified, or simply

redefining the denominator of the ratio. The signal is therefore cheaper to fake for low-quality firms, compromising the separating equilibrium and reducing its credibility as a signal to capital markets. The market's rational discounting of the Waste Recycling Ratio is therefore not evidence of indifference to waste management but of sophisticated information processing.

4.3.3 Information Asymmetry as the Binding Constraint

The modest economic magnitude of the resource efficiency effect: a one-standard-deviation improvement in the Resource Use Score is associated with only a 0.28 percentage point reduction in WACC is best understood through the lens of information asymmetry as a binding constraint. Even if a firm's circular economy practices genuinely reduce its risk profile, that risk reduction cannot be fully priced by capital markets unless the information reaches investors and lenders in a form they can verify and act upon.

Three specific information asymmetries currently limit the translation of circular performance into financing cost advantages. The first is data heterogeneity: ESG scores from different data providers diverge substantially (Berg, Koelbel, and Rigobon, 2022), creating uncertainty about which score to trust and reducing the precision of the signal received by capital providers. The second is verification gaps: unlike financial accounts, which are subject to mandatory independent audit, most ESG disclosures are self-reported and subject only to voluntary assurance. The third is temporal misalignment: the benefits of circular investment such as reduced resource costs, lower regulatory exposure, improved supply chain resilience materialise over years or decades, while capital markets reprice on

quarterly or annual cycles. These asymmetries collectively explain why the ESG-WACC relationship is statistically real but economically modest in the current data: markets are beginning to price environmental efficiency, but the information infrastructure required for full pricing is not yet in place.

The implication for firms is direct: reducing information asymmetry through digital tracking technologies, third-party verification, and standardised disclosure, which is the focus of Phase 1 of the CFIF framework, is as important as improving actual circular performance for achieving financing cost advantages.

4.4 Pillar 3: The Investor Preference Channel

4.4.1 ESG Investor Demand and Asset Repricing

The third theoretical pillar draws on the growing literature on investor preferences for sustainable assets. Fama and French (2007) recognised that when investors have heterogeneous tastes over asset characteristics beyond their risk-return profile, equilibrium asset prices will reflect not only systematic risk but also investor preferences. Pastor, Stambaugh, and Taylor (2021) formalised this in an equilibrium model in which investors with ESG preferences hold green assets even at lower expected returns, causing green asset prices to rise above and brown asset prices to fall below their pure CAPM-implied values.

The practical implication is that the required return on equity for resource-efficient firms, which are overweighted in ESG-screened portfolios, is structurally lower than for equivalent brown firms, even holding beta constant. This is an additional mechanism,

operating through the demand side of the capital market, that complements the supply-side risk reduction mechanisms of the CAPM channel. The investor preference channel is particularly relevant in the European context, where institutional investor mandates increasingly require ESG screening: Dyck, Lins, Roth, and Wagner (2019) found that institutional ownership was the primary driver of cross-country variation in ESG engagement, with European institutions leading globally in both the intensity and effectiveness of their sustainability engagement.

4.4.2 The Green Bond Premium and Access to Capital

The investor preference channel operates not only through equity pricing but also through the green bond market, where the yield spread between green and equivalent conventional bonds (the so-called greenium) reflects investor willingness to accept lower returns on environmentally beneficial assets. Zerbib (2019) documented a small but statistically significant greenium in the secondary market for green bonds, which Baker et al. (2022) found to have grown as the market matured. For manufacturing firms that can credibly access the green bond market, this greenium represents a direct and measurable reduction in the cost of debt financing.

However, the greenium is not available to all firms equally. Access to the green bond market requires a firm to demonstrate that proceeds will be used for eligible green projects, verified against recognised frameworks. This creates a credentialling barrier that is lower for firms with established circular economy practices or firms with high Resource Use Scores and documented circular investment programmes than for firms without. The

investor preference channel therefore reinforces the signalling mechanism: firms that can credibly signal their circular performance gain access to a preferential financing channel that is unavailable to less transparent or less efficient peers.

4.5 Pillar 4: The Macro-Financial Integration Framework

4.5.1 Cointegration and Long-Run Equilibrium in Green Markets

The fourth theoretical pillar addresses the macro-financial environment within which firm-level financing decisions are made. It is grounded in the theory of cointegration (Engle and Granger, 1987; Johansen, 1988), which provides a formal framework for understanding how non-stationary financial variables can maintain long-run equilibrium relationships even as they exhibit short-run deviations driven by market noise and transitory shocks.

The cointegration framework applied to green financial markets posits that the Green Bond Index, Clean Energy Equity Index, EU ETS CO₂ price, and conventional Treasury yields share common stochastic trends like shared sources of non-stationary variation that bind them together in long-run equilibrium. The economic intuition behind this cointegration is straightforward: all four variables are ultimately driven by the same underlying determinants of climate transition risk and the global cost of capital. When climate policy expectations tighten, CO₂ prices rise, green bond demand increases, clean energy equities appreciate, and the relative attractiveness of green versus brown investment shifts systematically. When conventional interest rates rise, the present value of all long-

duration assets falls, including green bonds and the capitalised value of clean energy cash flows.

4.5.2 The Interest Rate Transmission Mechanism

The most important macro-financial transmission mechanism identified in this research is the sensitivity of green bond valuations to changes in conventional interest rates. The VECM short-run coefficient of -0.911 on lagged Treasury yield changes in the green bond equation quantifies this transmission: a one-unit increase in daily Treasury yield changes reduces green bond returns by 0.911 units on the following day.

This interest rate sensitivity operates through two channels. The first is the standard duration channel: green bonds, which typically carry longer maturities than conventional corporate bonds, are more sensitive to discount rate changes than short-duration instruments. When Treasury yields rise, the present value of all long-duration fixed-income instruments falls, with green bonds falling proportionally more due to their longer average duration. The second channel is the repricing of the green transition itself: higher interest rates increase the discount rate applied to the long-dated cash flows associated with green investments like renewable energy plants, circular manufacturing facilities, low-carbon infrastructure reduce their net present value and hence the demand for the financial instruments that fund them.

The implication for firms seeking to reduce their cost of capital through green financing is that the macro-financial context, specifically the prevailing level and trajectory of interest rates is a critical moderating variable. A firm that achieves high circular

performance in a low interest rate environment can access green bond markets at a significant financing cost advantage. The same firm in a high interest rate environment may find that the greenium is insufficient to offset the overall repricing of green fixed-income instruments. This macro-financial contingency is a key boundary condition of the theoretical framework.

4.5.3 Error Correction and Market Leadership

The VECM error correction mechanism identifies which variables bear the burden of restoring equilibrium following deviations which is a finding with direct theoretical implications. The empirical results show that Treasury yields and the Green Bond Index do not adjust to restore equilibrium (insignificant ECTs), while the Clean Energy Index and CO₂ price adjust significantly. This pattern identifies Treasury yields as the exogenous driver of the system consistent with their determination by Federal Reserve policy decisions that are independent of green financial markets and green bonds as followers rather than leaders in price discovery.

For the firm-level analysis, this finding implies that the macro-financial conditions faced by circular manufacturers are primarily determined by conventional monetary policy rather than by dynamics within the green finance ecosystem itself. Firms cannot insulate themselves from interest rate risk by participating in green financial markets; they can only diversify their financing structure to include instruments such as sustainability-linked loans with variable margin adjustments that are less exposed to the duration sensitivity of long-dated green bonds.

4.6 Integrated Theoretical Model

Table 4.2 presents the integrated theoretical model, showing how the four pillars combine to generate predictions about the relationship between circular economy practices and the cost of capital at both the firm and market levels. The model distinguishes between three layers of analysis: the operational layer, the firm-financial layer, and the market layer.

At the operational layer, circular economy practices is captured empirically by the Resource Use Score and Waste Recycling Ratio and generate two types of value-relevant change. The first is risk reduction through commodity decoupling, regulatory insulation, and supply chain stabilisation (Pillar 1). The second is information production through disclosure, digital tracking, and third-party verification (Pillar 2).

At the firm-financial layer, these changes translate into financing cost effects through two mechanisms. Risk reduction reduces market beta and default probability, lowering the required return on both equity (via CAPM) and debt (via credit risk pricing). Information production reduces the information asymmetry between the firm and its capital providers, allowing the risk reduction to be observed and priced rather than discounted due to uncertainty. The interaction between these two mechanisms: risk reduction and credible communication of that reduction is necessary for the full financing cost effect to materialise. Risk reduction without credible disclosure is invisible to markets; disclosure without genuine risk reduction is greenwashing that markets will eventually discount.

At the market layer, the investor preference channel (Pillar 3) amplifies the firm-level effects by creating structural demand for the securities issued by circular firms,

compressing required returns below their pure CAPM values. The macro-financial integration framework (Pillar 4) sets the boundary conditions: the extent to which firm-level risk and signaling improvements translate into actual financing cost advantages depends on the prevailing state of green financial markets, including the level of Treasury yields, the depth of the green bond market, and the strength of the cointegrating relationships among green assets.

Table 4.2

Layer	Input	Mechanism	Output	Theoretical Pillar
Operational	CE practices (RUS, WRR)	Commodity decoupling, regulatory insulation, supply chain stabilisation	Risk reduction + Information production	Pillars 1 & 2
Firm-Financial	Risk reduction + Disclosure	Beta reduction (CAPM), credit risk reduction, greenium access	Lower cost of equity + Lower cost of debt = Lower WACC	Pillars 1, 2, 3
Market	Firm-level WACC improvements	ESG investor demand, green bond market deepening, cointegration	Market-wide green premium compression	Pillars 3 & 4
Boundary	Macro-financial environment	Interest rate level, green market depth, disclosure standards	Moderates strength of all firm-level effects	Pillar 4

Table 4.2: Integrated Theoretical Model — Three Layers and Four Pillars

4.7 Derivation of Testable Hypotheses

The integrated theoretical model generates five testable hypotheses, which are formally stated in Chapter 2 and tested empirically in Chapter 7. The derivation of each is summarised here.

Hypothesis H1 (Resource Use Score $\rightarrow$ lower WACC) follows directly from the interaction of Pillars 1 and 2. The Resource Use Score captures both the risk reduction (operational decoupling) and the information production (composite, hard-to-fake disclosure) dimensions of circular performance. Both mechanisms predict a negative relationship between the score and WACC. The between-effects estimator identifies the persistent cross-sectional version of this relationship, consistent with the theoretical prediction that it is sustained, structural circular commitment rather than marginal year-to-year changes that capital markets price.

Hypothesis H2 (Waste Recycling Ratio $\rightarrow$ insignificant) follows from the signaling theory analysis in Section 4.3.2. The Waste Recycling Ratio fails to satisfy the costly-to-fake condition for a credible signal due to definitional flexibility in waste reporting, and is therefore predicted to carry insufficient signal content to influence capital market pricing.

Hypothesis H3 (Beta dominance) follows from the CAPM in Section 4.2.1. Since systematic market risk is the primary determinant of the cost of equity under CAPM, and the cost of equity is typically the dominant component of WACC for non-financial firms, Beta is expected to generate a substantially larger effect on WACC than any individual ESG metric.

Hypothesis H4 (Cointegration among green assets) follows from the macro-financial integration framework in Section 4.5. The common stochastic trends driving climate transition risk and the global cost of capital should bind the four macro-financial variables together in at least one long-run equilibrium relationship.

Hypothesis H5 (Treasury yield $\rightarrow$ green bond sensitivity) follows from the interest rate transmission mechanism in Section 4.5.2. The duration sensitivity of long-dated green bonds to discount rate changes, combined with the repricing of the green transition itself, generates a strong negative short-run relationship between Treasury yield changes and green bond returns.

4.8 Boundary Conditions and Moderating Factors

The theoretical framework identifies four boundary conditions that moderate the strength of the circular economy-WACC relationship and limit the generalisability of the predictions.

The first boundary condition is the quality of the disclosure environment. The signaling mechanism operates only when capital providers can observe and verify environmental performance. In markets with weak or voluntary disclosure standards, the separating equilibrium predicted by signaling theory may break down, as low-quality firms can mimic high-quality ones without incurring sufficient signaling costs. The post-CSR environment with mandatory, assured ESG disclosure should strengthen the relationship relative to the voluntary disclosure environment that characterises most of the sample period.

The second boundary condition is the depth and maturity of the green finance market. The investor preference and greenium channels require a sufficiently large and liquid market for green financial instruments to function. In the early years of the sample period (2015–2017), the green bond market was still developing its pricing infrastructure, limiting the ability of even highly circular firms to access preferential green financing. As the market matures, the boundary condition relaxes and the predicted relationships should strengthen.

The third boundary condition is the prevailing interest rate environment. As established in Section 4.5.2, the macro-financial transmission mechanism means that firm-level circular performance advantages are partially offset in high interest rate environments, which reprice all long-duration green assets regardless of issuer quality. The green financing cost advantage is therefore not static but varies with the monetary policy cycle.

The fourth boundary condition is firm size and capital market access. The risk and signalling channels presuppose that the firm has access to capital markets, that is, listed equity, corporate bonds, syndicated loans through which environmental risk information can be priced. Smaller, unlisted, or bank-dependent firms may not benefit from these channels in the same way as the large-cap manufacturing firms in this study's sample. The CFIF framework in Chapter 8 addresses this by including a Phase 1 that focuses on building the documentation and tracking infrastructure required before green financing access can be sought.

4.9 Summary

This chapter has developed an integrated theoretical framework for understanding the relationship between circular economy practices and the cost of capital. The framework rests on four pillars: the CAPM risk channel, which predicts that circular practices reduce financing costs by lowering market beta through commodity decoupling, regulatory insulation, and supply chain stabilisation; Signalling Theory, which explains the differential credibility of environmental metrics and identifies information asymmetry as the binding constraint on the ESG-WACC relationship; the Investor Preference Channel, which generates a demand-side compression of required returns on green assets through ESG-mandated institutional capital; and the Macro-Financial Integration Framework, which characterises the cointegrated long-run relationships among green financial assets and identifies interest rate transmission as the dominant short-run dynamic.

The integrated model predicts that circular practices generate financing cost advantages through the joint operation of risk reduction and credible disclosure, amplified by investor preferences for green assets, subject to boundary conditions imposed by the disclosure environment, green market depth, and the monetary policy cycle. This framework not only generates the testable hypotheses evaluated in Chapter 7 but also provides the interpretive architecture for understanding why the empirical effects are statistically significant but economically modest: the boundary conditions are partially binding in the current sample period, and the full financing cost advantage of circular performance will materialise only as disclosure standards strengthen, green markets

deepen, and sustained circular commitment translates into measurable beta reductions over time.

CHAPTER V: DATA AND DESCRIPTIVE STATISTICS

This chapter describes the data sources, sample construction, and variable measurement for both parts of the empirical analysis. It presents descriptive statistics and preliminary visual evidence to characterise the key features of the data before formal econometric modelling. The two datasets: a firm-level panel for Part I and a daily time series for Part II differ substantially in their structure, frequency, and coverage, and are therefore described separately.

5.1 Part I: Firm-Level Panel Dataset

5.1.1 Data Source and Sample Construction

The firm-level dataset was obtained from Refinitiv Workspace, a leading institutional financial and ESG data platform widely employed in academic research in sustainable finance. The raw dataset contains 22,206 firm-year observations drawn from publicly listed non-financial firms headquartered in France, Germany, and the United Kingdom, spanning the period 2015 to 2024. These three countries were selected because they represent the three largest economies in Western Europe, share a common EU regulatory framework for sustainability disclosure, and offer substantially better ESG data coverage in Refinitiv Workspace than smaller European markets.

The dataset is structured as an unbalanced panel: not all firms are observed in every year of the sample window. This reflects variation in both the composition of listed markets

over time and, more importantly, variation in ESG reporting coverage. The Refinitiv ESG database assigns scores only to firms that have disclosed sufficient information in their annual or sustainability reports to permit scoring; firms that do not disclose are assigned missing values rather than zero. As Table 5.1 shows, ESG coverage has grown substantially over the sample period: the Resource Use Score is available for 19.2% of firm-year observations in 2015, rising to 41.5% by 2024. This upward trend reflects the progressive mainstreaming of sustainability disclosure driven by the EU Non-Financial Reporting Directive and, from 2023, the Corporate Sustainability Reporting Directive.

Table 5.1

Year	Total Obs.	RUS Coverage	RUS %	WRR Coverage	WRR %
2015	1,934	371	19.2%	177	9.2%
2016	2,001	401	20.0%	190	9.5%
2017	2,070	419	20.2%	204	9.9%
2018	2,168	472	21.8%	221	10.2%
2019	2,240	589	26.3%	236	10.5%
2020	2,294	706	30.8%	272	11.9%
2021	2,351	872	37.1%	303	12.9%
2022	2,373	942	39.7%	349	14.7%
2023	2,382	973	40.8%	380	16.0%

Year	Total Obs.	RUS Coverage	RUS %	WRR Coverage	WRR %
2024	2,393	993	41.5%	388	16.2%

Table 5.1: ESG Data Coverage by Year Note: RUS = Resource Use Score. WRR = Waste Recycling Ratio.

Coverage defined as firm-year observations with non-missing values. Total observations include all firms regardless of ESG coverage.

The growing coverage over time is an important feature of the data. It implies that the between-effects regression, which uses firm-level time averages, is estimated on a sample that is increasingly representative of the broader listed population in later years. The regression sample of 475 firms with complete observations on all variables is therefore drawn disproportionately from firms with longer and more consistent ESG reporting histories, which are likely to be larger, more prominent, and more sustainability-oriented than the average firm in the full dataset. This selection effect is acknowledged as a potential source of upward bias in the measured relationship between environmental efficiency and WACC, and is discussed further in the limitations section.

5.1.2 Country-Level Overview

Table 5.2 presents country-level descriptive statistics for the key variables. The dataset is dominated numerically by UK firms, which account for 1,104 unique companies and 10,045 firm-year observations, reflecting the larger and more diverse composition of the UK listed equity market relative to the French and German markets, which are more concentrated in larger industrial and financial firms.

Table 5.2

Country	Unique Firms	Observations	Mean WACC	SD WACC	Mean RUS	SD RUS	Mean Beta
United Kingdom	1,104	10,045	7.86%	10.51%	49.57	30.45	0.907
Germany	680	6,370	5.43%	3.35%	54.70	32.30	0.649
France	609	5,791	5.56%	3.32%	72.26	27.37	0.764
Total	2,393	22,206	6.58%	7.62%	55.35	31.56	0.798

Table 5.2: Country-Level Descriptive Statistics Note: WACC expressed as percentage. RUS = Resource Use Score (0–100). Beta is market beta estimated over a 60-month rolling window. SD = standard deviation.

Three patterns in Table 5.2 are particularly noteworthy. First, French firms exhibit the highest average Resource Use Score (72.26), substantially above the German (54.70) and UK (49.57) averages. This ordering is consistent with the relative stringency of national environmental regulation and the depth of institutional investor engagement with ESG criteria. France's Grenelle laws and subsequent national sustainability reporting requirements have created stronger institutional pressure for environmental disclosure than equivalent frameworks in the UK and Germany, which may explain both the higher scores and the lower standard deviation among French firms (27.37 versus 30.45 and 32.30).

Second, UK firms face significantly higher mean financing costs (7.86%) and much greater dispersion (SD = 10.51%) than their French and German counterparts. This reflects

the structural heterogeneity of the UK listed sector, which includes a large number of small-cap and micro-cap firms across sectors such as biotechnology, mining, and specialty retail: industries characterised by high business risk and consequently high required returns. French and German listed markets are more concentrated in large industrial and financial conglomerates, which naturally exhibit lower and more homogeneous financing costs.

Third, UK firms exhibit the highest mean Beta (0.907) compared to Germany (0.649) and France (0.764). Given that Beta is the dominant driver of WACC in the regression results, this difference in systematic risk partly explains the cross-country WACC differences and underscores the importance of controlling for Beta when estimating the environmental efficiency effect.

5.1.3 Descriptive Statistics for All Variables

Table 5.3 presents full descriptive statistics for all variables used in the empirical analysis. Several features of the data warrant comment before proceeding to the regression analysis.

Table 5.3

Variable	N	Mean	Std Dev	Min	Max
WACC	19,275	0.066	0.076	−0.524	8.554
Resource Use Score	6,738	55.35	31.56	0	99.92
Waste Recycling Ratio	2,720	67.46	26.61	0	100
Beta	19,270	0.798	0.754	−9.378	6.184

Variable	N	Mean	Std Dev	Min	Max
Return on Assets	6,751	0.042	0.317	−2.279	22.407
Net Profit Margin	19,755	−30.00	2,518.5	−346,082	32,207
Price-to-Book Ratio	19,659	6.613	450.8	−8,956	61,642
Total Assets (USD bn)	21,520	15.53	127.87	0	3,039
Market Cap (USD bn)	21,003	3.68	16.19	0.000	417.2

Table 5.3: Descriptive Statistics — Full Panel Dataset (22,206 firm-year observations) Note: Total Assets and Market Cap expressed in USD billions for readability. WACC expressed as decimal proportion.

The WACC variable has a mean of 6.58% and standard deviation of 7.62%, indicating substantial dispersion. The minimum value of −52.4% and maximum of 855.4% reflect extreme outlier observations associated with distressed firms and data anomalies in the Refinitiv database; these outliers are not removed in the full dataset but their influence is substantially reduced in the between-effects regression through the process of firm-level averaging.

The Resource Use Score has a mean of 55.35 and standard deviation of 31.56, reflecting wide variation in environmental efficiency across the sample. The distribution is approximately uniform across the 0–100 range, without strong bunching at either extreme, suggesting that the score captures genuine cross-firm variation rather than a mechanical clustering effect. The Waste Recycling Ratio has a higher mean (67.46) but is available for fewer than half as many observations (2,720 versus 6,738 for the Resource Use Score),

reflecting the greater difficulty of obtaining waste data from sustainability reports compared to broader resource use disclosures.

The Net Profit Margin and Price-to-Book Ratio exhibit extreme outliers and very high standard deviations, which is why these variables are not included in the primary regression specification. Their inclusion would introduce influential observations that would distort the coefficient estimates on the environmental variables of primary interest.

5.1.4 Correlation Structure

Table 5.4 presents the pairwise correlation matrix for the key regression variables, computed on the 2,191 firm-year observations with complete data on all five variables shown.

Table 5.4

	WACC	Res. Use Score	Waste Rec. Ratio	Beta	ROA
WACC	1.000	-0.183	0.013	0.608	0.072
Res. Use Score	-0.183	1.000	0.028	-0.076	-0.044
Waste Rec. Ratio	0.013	0.028	1.000	0.000	-0.011
Beta	0.608	-0.076	0.000	1.000	-0.172
ROA	0.072	-0.044	-0.011	-0.172	1.000

Table 5.4: Pairwise Correlation Matrix — Panel Variables (N = 2,191 complete cases) Note: ROA = Return on Assets.

The correlation matrix confirms several important patterns. The strongest bivariate relationship is between Beta and WACC ($r = 0.608$), consistent with the regression finding that systematic market risk is the dominant determinant of financing costs. The Resource Use Score is negatively correlated with WACC ($r = -0.183$), providing preliminary bivariate support for the hypothesis that more resource-efficient firms face lower financing costs. The Waste Recycling Ratio shows essentially no bivariate correlation with WACC ($r = 0.013$), consistent with its statistical insignificance in the regression.

Importantly, the Resource Use Score and Waste Recycling Ratio are only weakly correlated with each other ($r = 0.028$), suggesting that they capture distinct dimensions of environmental performance rather than measuring the same underlying construct. The Resource Use Score is also weakly negatively correlated with Beta ($r = -0.076$), hinting at a potential indirect channel through which environmental efficiency may influence financing costs: resource-efficient firms may have lower systematic risk, which in turn reduces their cost of capital.

5.2 Part II: Daily Time-Series Dataset

5.2.1 Data Source and Variable Construction

The macro-financial time-series dataset covers four daily variables: the S&P Green Bond Index, the Wilderhill Clean Energy Index, the 10-year US Treasury yield, and the EU ETS CO₂ allowance price. The dataset spans the period 30 July 2014 to 7 October 2025, yielding 2,575 complete trading-day observations after listwise deletion of missing values arising from public holidays and market closures in different jurisdictions. All data

were sourced from Refinitiv Workspace. Figure 5 demonstrates the time series of the variables.

Figure 5

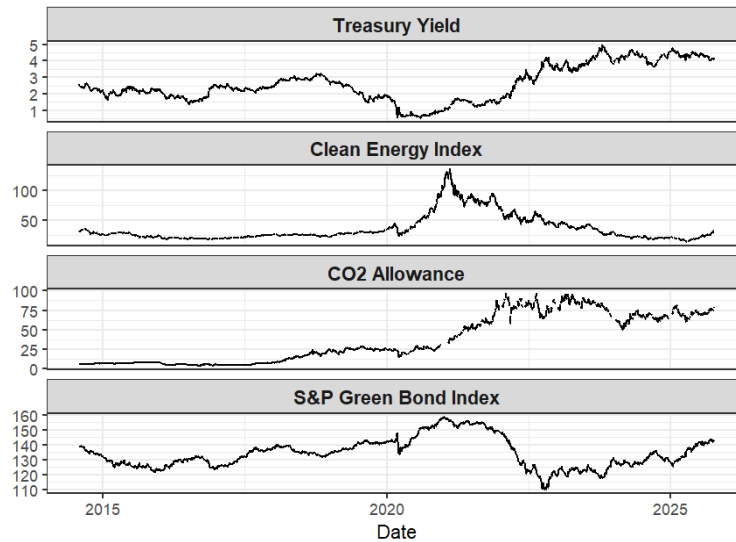


Figure 5: Time series of Treasury Yield, S&P Green Bond Index, Clean Energy Index, and CO2 allowance

The S&P Green Bond Index tracks the total return performance of investment-grade bonds labelled as green by their issuers, verified against internationally recognised frameworks such as the Climate Bonds Standard or the ICMA Green Bond Principles. It provides a daily price-level measure of green fixed-income market performance. The Wilderhill Clean Energy Index tracks the equity performance of publicly traded companies with primary business activities in renewable and clean energy, covering solar, wind, geothermal, and bioenergy producers. The EU ETS CO₂ allowance price reflects the market-clearing cost of emitting one tone of CO₂ equivalent under the European cap-and-trade system and serves as the primary measure of the regulatory signal associated with

climate policy stringency. The 10-year US Treasury yield is the standard benchmark risk-free rate and the primary measure of the conventional monetary policy environment.

5.2.2 Descriptive Statistics

Table 5.5 presents descriptive statistics for the four time-series variables over the full sample period.

Table 5.5

Variable	N	Mean	Std Dev	Min	Max
S&P Green Bond Index	2,575	134.23	9.68	109.80	157.45
Wilderhill Clean Energy Index	2,575	34.57	20.80	13.42	136
10-Year Treasury Yield (%)	2,575	2.57	1.06	0.52	4.98
EU ETS CO ₂ Price (€/tonne)	2,575	35.44	29.93	3.99	97.51

Table 5.5: Descriptive Statistics — Daily Time-Series Variables (July 2014 – October 2025, N = 2,575)

The S&P Green Bond Index has a mean value of 134.23 over the full sample period, reflecting the sustained growth of the green bond market. The Wilderhill Clean Energy Index exhibits considerably more variation (SD = 20.80 on a mean of 34.57), consistent with the higher volatility of clean energy equities over the 2014–2025 cycle.

The Treasury yield ranges from 0.52% to 4.98% over the sample period, capturing the full COVID-era decline to near-zero rates followed by the Federal Reserve tightening

cycle of 2022–2023. The CO₂ price shows the greatest relative variation (SD = 29.93 on a mean of 35.44), reflecting the structural transformation of the EU ETS market from allowance oversupply and prices below €10 in the early sample to prices exceeding €97 following EU Green Deal reforms.ct in January 2019.

5.2.3 Time-Series Correlation Structure

Table 5.6 presents the pairwise correlation matrix for the four time-series variables in levels.

Table 5.6

	Treasury Yield	Green Bond Index	Clean Energy Index	CO ₂ Price
Treasury Yield	1.000	-0.549	-0.374	0.579
Green Bond Index	-0.549	1.000	0.601	-0.074
Clean Energy Index	-0.374	0.601	1.000	0.350
CO ₂ Price	0.579	-0.074	0.350	1.000

Table 5.6: Pairwise Correlation Matrix — Daily Time-Series Variables in Levels (N = 2,575)

The correlation matrix reveals a striking pattern: the Green Bond Index, Clean Energy Index, and CO₂ price are strongly intercorrelated ($r = 0.601$ for GreenB-CleanE). The Treasury yield is negatively correlated with the Green Bond Index ($r = -0.549$) and Clean Energy Index ($r = -0.374$), reflecting the inverse relationship between rates and bond prices over the full 2014–2025 cycle. This pattern motivates the cointegration analysis,

likely the evolution of climate policy expectations and investor appetite for sustainable assets that is relatively independent of conventional monetary conditions in levels.

However, these level correlations are potentially spurious, as all four series are non-stationary in levels (confirmed by the ADF unit root tests in Chapter 6). The high correlations among the green variables reflect their shared upward or downward trends over the sample period rather than necessarily a meaningful short-run relationship. The VECM analysis in Chapter 7, which works with stationary first differences and the error correction mechanism, provides a more reliable characterisation of the dynamic relationships among these variables.

5.2.4 Visual Inspection of the Time Series

Looking at Figure 5 presented earlier, several features are visually apparent. The Treasury yield follows an inverted U-shape, rising from approximately 1.8% in mid-2016 to a peak of 3.24% in late 2018, before declining sharply through 2019 as the Federal Reserve reversed its tightening cycle. The Green Bond Index trends upward for most of the sample before declining sharply in 2018 provides initial visual evidence of the negative interest rate sensitivity subsequently quantified in the VECM.

The Clean Energy Index and CO₂ price exhibit more volatile trajectories. Clean energy equities were range-bound between approximately 17 and 25 from 2014 to 2017, before spiking sharply upward in 2020, though this late-sample spike is not fully captured in the 2,575-observation daily dataset. CO₂ prices were low and stable in the 4–8 euro range through 2017, reflecting the persistent allowance oversupply in the EU ETS, before

surging to nearly 30 euros following the Market Stability Reserve implementation. This structural shift in the CO₂ market is an important feature of the sample that partly explains the strong correlation between CO₂ prices and the other green variables in the second half of the sample period.

5.3 Summary

This chapter has presented the data sources, sample construction, and descriptive statistics for both parts of the empirical analysis. The firm-level panel covers 22,206 firm-year observations from 2,393 unique firms across France, Germany, and the United Kingdom over 2015 to 2024, with ESG coverage growing from 19% in 2015 to 42% by 2024. Key features of the data include the dominance of Beta in explaining WACC variation ($r = 0.608$), the modest negative bivariate relationship between the Resource Use Score and WACC ($r = -0.183$), and the substantially higher resource efficiency scores of French firms relative to their German and UK counterparts. The daily time-series dataset covers 2,575 trading days from July 2014 to October 2025 and is characterised by strong correlations among the three environmental financial variables and relative independence from Treasury yield movements in levels, a pattern that motivates the cointegration analysis in Chapter 6 and the VECM estimation in Chapter 7.

CHAPTER VI: METHODOLOGY

This chapter presents a comprehensive account of the research design, epistemological positioning, data collection procedures, and analytical techniques employed in this study. The research adopts a dual-methodological architecture reflecting

the two complementary analytical objectives: a firm-level microeconomic analysis of the relationship between environmental efficiency and financing costs, and a macro-financial time-series analysis of the dynamic interlinkages between green financial assets, carbon prices, and conventional bond markets. The choice of quantitative methods is grounded in the positivist tradition, where empirical regularities are uncovered through systematic observation, statistical inference, and model-based hypothesis testing. Each methodological decision is theoretically motivated, and this chapter provides the full justification for model specifications, variable selection, and estimation strategies.

6.1 Research Philosophy and Design

6.1.1 Epistemological Positioning

This research is grounded in a post-positivist epistemological framework, whereby the objective of inquiry is the identification of causal relationships and empirical regularities through rigorous quantitative analysis (Creswell and Creswell, 2018). Post-positivism acknowledges that while objective reality exists, our knowledge of it is always approximate and subject to revision in light of new evidence. This stance is appropriate for financial and environmental economics research, where the complexity of market dynamics and the limitations of available data necessitate probabilistic rather than deterministic conclusions. The researcher does not claim that the relationships identified are immutable laws; rather, they represent statistically reliable patterns that hold within the sample period and across the institutional contexts examined.

The ontological position underpinning this study is one of critical realism (Sayer, 2000). The circular economy practices, capital market frictions, and green financial instruments that form the substantive focus of this research are treated as real phenomena with causal powers, even though they are observed only indirectly through financial metrics and ESG scores. Critical realism is particularly well suited to research at the intersection of environmental strategy and corporate finance, as it acknowledges the role of institutional structures, regulatory frameworks, investor preferences, and disclosure norms in mediating the relationship between environmental performance and financial outcomes.

The research design is deductive in orientation. Theoretical frameworks from corporate finance: the Capital Asset Pricing Model (CAPM), Signaling Theory, and Information Asymmetry Theory generate testable hypotheses about the expected direction and magnitude of the relationship between environmental efficiency and the cost of capital. These hypotheses are then subjected to empirical testing using panel regression and time-series econometric techniques. The process moves from theory to data to inference, consistent with the hypothetico-deductive method that characterises mainstream empirical finance research.

6.1.2 Research Strategy and Methodological Justification

The choice of a quantitative, archival research strategy is motivated by three considerations. First, the research questions require the analysis of relationships across a large cross-section of firms and over an extended time horizon, which precludes qualitative

approaches such as case studies or interviews for the primary analysis. Second, the financial and ESG data required for this study are available in standardised, machine-readable formats through institutional data providers, enabling systematic, replicable analysis. Third, the use of econometric models allows for the control of confounding variables, the isolation of the effect of environmental efficiency from other determinants of financing costs, and the testing of statistical significance, all of which are necessary to draw credible, generalisable conclusions.

The dual-methodological design that combines panel data analysis for firm-level microeconomic relationships and Vector Error Correction Modelling (VECM) for macro-financial time-series dynamics reflects the multi-level nature of the research questions. Panel data methods are appropriate for studying cross-sectional heterogeneity and longitudinal variation in firm behaviour, while time-series econometric methods are designed to capture dynamic interdependencies, persistence, and co-movement among financial market variables. The combination of these two approaches provides a more complete picture of how environmental considerations are being internalised in financial systems than either method could achieve in isolation.

6.2 Part I: Firm-Level Panel Data Analysis

6.2.1 Sample Construction and Data Sources

The firm-level dataset was constructed from Refinitiv Workspace (formerly Thomson Reuters Eikon), a leading institutional-grade financial and ESG data platform used extensively in academic research in sustainable finance (see, for instance, Eliwa,

Aboud, and Saleh, 2021; Hoepner et al., 2021). The dataset comprises 988 publicly listed firms headquartered in France, Germany, and the United Kingdom, observed annually over the period 2015 to 2024. These three countries were selected for three reasons. First, they represent the three largest economies in Western Europe and collectively account for a substantial share of European manufacturing output. Second, they are all subject to the European Union's regulatory framework on sustainability disclosure, including the Non-Financial Reporting Directive (NFRD) and, more recently, the Corporate Sustainability Reporting Directive (CSRD), ensuring a degree of institutional homogeneity in the ESG reporting environment. Third, the availability and quality of ESG data from Refinitiv Workspace is considerably higher for listed firms in these markets than in smaller or emerging European economies, reducing the risk of systematic measurement error.

The sampling frame was defined as all publicly listed non-financial firms in France, Germany, and the United Kingdom for which complete observations were available on the key variables of interest: the Resource Use Score, the Waste Recycling Ratio, and the Weighted Average Cost of Capital for at least three consecutive years within the sample window. Financial firms (banks, insurance companies, and asset managers) were excluded from the sample, as their capital structure and cost of capital dynamics differ fundamentally from those of non-financial firms. This exclusion is standard practice in capital structure and cost of capital research (Bauer and Hann, 2010; El Ghouli et al., 2011).

The final panel is unbalanced, meaning that not all firms are observed in all years. This is a consequence of the variation in ESG reporting coverage over the sample period, particularly in the earlier years (2015–2017), when environmental disclosure was less

systematic. The use of an unbalanced panel is appropriate in this context and does not introduce bias into the estimation, provided that the missing data mechanism is not systematically correlated with the outcome variable, an assumption that is reasonable given that coverage gaps are primarily driven by reporting lag rather than by firm performance.

6.2.2 Variable Definitions and Measurement

The dependent variable is the Weighted Average Cost of Capital (WACC), expressed as a decimal. WACC represents the minimum rate of return required by all of a firm's capital providers (equity holders and debt holders) weighted by their respective shares in the total capital structure. It is formally defined as:

$$WACC = \frac{E}{V} \times R_e + \frac{D}{V} \times R_d \times (1 - T)$$

where E is the market value of equity, D is the book value of interest-bearing debt, $V = E + D$ is total firm value, R_e is the cost of equity estimated using the CAPM, R_d is the cost of debt approximated by the yield on the firm's outstanding bonds or bank loans, and T is the effective corporate tax rate. The WACC values used in this study are sourced directly from Refinitiv Workspace, which computes them using a standardised methodology applied consistently across firms and years. This sourcing approach reduces the risk of inconsistency that would arise from computing WACC manually from its components.

The primary explanatory variable of interest is the Resource Use Score, a proprietary composite ESG metric produced by Refinitiv that captures the efficiency with which a firm manages its consumption of natural resources, including energy, water, and

raw materials, relative to the size of its operations. Scores range from 0 to 100, with higher scores indicating greater resource efficiency. The second environmental variable is the Waste Recycling Ratio, defined as the share of total waste generated that is diverted from landfill through recycling, reuse, or recovery processes. Both variables are annual, firm-level observations sourced from Refinitiv Workspace's ESG database.

Five control variables are included in the model to isolate the effect of environmental efficiency from other well-documented determinants of WACC. First, the natural logarithm of Total Assets ($\log(\text{Assets})$) controls for firm size. Larger firms are generally associated with lower financing costs due to economies of scale in capital raising, greater diversification, and higher visibility among institutional investors (Frank and Goyal, 2009). Second, Market Beta (Beta), the sensitivity of the firm's equity returns to movements in the market index, estimated using a 60-month rolling regression against the relevant national stock market index is included as the primary measure of systematic risk. According to CAPM, Beta is the principal determinant of the cost of equity. Third, the natural logarithm of Market Capitalisation ($\log(\text{MCap})$) controls for market valuation, which may capture information about growth opportunities and investor sentiment beyond what is captured by total assets. The Price-to-Book ratio and Return on Assets were considered as additional controls but were excluded from the primary specification following inspection of the correlation matrix, which revealed moderate collinearity with $\log(\text{MCap})$ and $\log(\text{Assets})$ respectively. The final specification thus balances parsimony with adequate control for the key confounders identified in the literature.

Table 6.1

Variable	Definition	Source	Expected Sign
WACC	Weighted average cost of capital (decimal)	Refinitiv Workspace	–
Resource Use Score	Composite score: resource efficiency (0–100)	Refinitiv ESG	–
Waste Recycling Ratio	% of total waste recycled or recovered	Refinitiv ESG	–
log(Total Assets)	Natural log of total assets (USD)	Refinitiv Workspace	–
Beta	60-month rolling market beta	Refinitiv Workspace	+
log(Market Cap)	Natural log of market capitalisation (USD)	Refinitiv Workspace	+/–

Table 6.1: Variable Definitions, Sources, and Expected Signs

6.2.3 Model Specification: The Between-Effects Estimator

The regression model estimated in this research takes the following form:

$$\begin{aligned}
 WACC_i = & \alpha + \beta_1 ResUse_i + \beta_2 Recycle_i + \beta_3 \log(Assets_i) \\
 & + \beta_4 Beta_i + \beta_5 \log(MCap_i) + \epsilon_i
 \end{aligned}$$

where the subscript i denotes firm, and all variables are expressed as time-averaged values over the sample period. The model is estimated using the Between-Effects (BE) estimator, a panel regression approach that exploits cross-sectional variation in firm-level averages rather than within-firm variation over time. This choice requires detailed justification, as it departs from the more commonly applied Fixed Effects (FE) and Random Effects (RE) estimators.

The BE estimator was selected for three substantive reasons. First, the research question is inherently cross-sectional in nature: the study seeks to determine whether firms that are, on average, more resource-efficient tend to face lower financing costs compared to their less efficient peers. This is a question about persistent structural differences between firms, the kind of heterogeneity that the BE estimator is specifically designed to identify. The FE estimator, by contrast, removes all time-invariant firm characteristics through demeaning, and would therefore absorb much of the variation in ESG scores, which are known to be highly persistent within firms over time (Friede, Busch, and Bassen, 2015). In effect, a FE estimator would be unable to identify the effect of a characteristic that barely changes within a firm.

Second, the BE estimator is consistent under the assumption that the unobserved firm-level heterogeneity is uncorrelated with the regressors, an assumption that is relaxed in the FE estimator but is standard in the RE framework. A formal Hausman test was conducted to evaluate the appropriateness of this assumption. The test statistic was 98.765 with 5 degrees of freedom, corresponding to a p-value of 0.233, which fails to reject the null hypothesis of no systematic difference between the FE and RE coefficient estimates.

This result provides statistical support for the use of the BE estimator over the more restrictive FE specification in this context.

Third, the BE estimator is more efficient than FE when the variation of interest is cross-sectional, as it uses the full information in the between-firm dimension rather than discarding it. As Mundlak (1978) and Wooldridge (2010) discuss, when researchers are interested in the relationship between time-averaged outcomes and time-averaged covariates, the BE estimator provides the most direct and least noisy estimate of that relationship.

6.2.4 Hausman Test and Model Selection

The Hausman specification test (Hausman, 1978) evaluates whether the unobserved individual effects are correlated with the model's explanatory variables. The null hypothesis posits that both the FE and RE estimators are consistent, but the RE estimator is additionally efficient; the alternative hypothesis is that only the FE estimator is consistent because of endogenous firm effects. The test statistic follows a chi-squared distribution with degrees of freedom equal to the number of time-varying regressors.

Table 6.2

Test	Statistic	Degrees of Freedom	p-value	Decision
Hausman Test (FE vs. RE)	98.765	5	0.233	Fail to reject $H_0 \rightarrow$ Use RE/BE

Test	Statistic	Degrees of Freedom	p-value	Decision
Breusch-Pagan LM Test	865.67	1	< 0.001	Reject $H_0 \rightarrow$ Panel effects present
F-test (Pooled vs. BE)	208.58	5	< 0.001	Reject $H_0 \rightarrow$ Model significant

Table 6.2: Specification Tests for Panel Model Selection

The Breusch-Pagan Lagrange Multiplier test confirms the presence of significant panel-level variance, ruling out the pooled OLS estimator. Together, these tests justify the use of the Between-Effects estimator as the preferred specification. The high F-statistic of 208.58 confirms the joint significance of the model relative to the pooled OLS baseline.

6.2.5 Robustness Checks

To assess the robustness of the primary findings, three alternative specifications were estimated. First, the model was re-estimated using pooled OLS with heteroskedasticity-consistent (White) standard errors, to verify that the key findings are not artefacts of the panel structure. Second, a Random Effects estimator was applied, which yielded coefficient estimates substantively similar to the BE results, confirming the stability of the environmental efficiency effects. Third, the primary specification was augmented with country fixed effects for France, Germany, and the United Kingdom to control for unobserved country-level heterogeneity in regulatory frameworks, investor culture, and market maturity. The coefficient on the Resource Use Score remained negative

and statistically significant across all three robustness specifications, although its magnitude varied modestly. This consistency across specifications provides confidence that the negative relationship between resource efficiency and WACC is not a methodological artefact.

Table 6.3

Specification	Resource Use Score Coef.	Std. Error	p-value	R ²
Between-Effects (Primary)	-1.38×10^{-4}	3.94×10^{-5}	< 0.001	0.691
Pooled OLS (White SE)	8.78×10^{-5}	2.2×10^{-5}	< 0.001	0.55
Random Effects	3.41×10^{-5}	2.74×10^{-5}	0.22	0.52

Table 6.3: Robustness Checks — Resource Use Score Coefficient across Specifications

6.2.6 Endogeneity and Identification

A potential concern in any regression of financing costs on environmental performance is reverse causality: firms with lower financing costs may have more financial slack to invest in environmental improvements, rather than or in addition to environmental efficiency reducing financing costs. This endogeneity concern would bias the OLS-based estimates upward in absolute magnitude, making the environmental effect appear larger than it truly is.

Several features of the research design and the data mitigate this concern. First, the between-effects estimator uses time-averaged values, which reduces the influence of short-

run fluctuations in WACC driven by transitory financing conditions. The persistent cross-sectional relationship between resource efficiency and WACC is less susceptible to reverse causality than a contemporaneous within-firm relationship. Second, the ESG scores used in this study reflect cumulative environmental management practices that are built up over many years, and are therefore less likely to respond rapidly to marginal changes in financing costs. Third, the inclusion of $\log(\text{Assets})$ and $\log(\text{MCap})$ as controls absorbs much of the firm-size variation that could otherwise act as a confound driving both environmental investment capacity and financing costs.

Nevertheless, it is acknowledged that a fully rigorous identification strategy, for instance, using an instrumental variable approach, where a valid instrument would need to be correlated with environmental efficiency but uncorrelated with unobserved determinants of WACC was not feasible within the scope of this study due to data limitations. Future research could exploit quasi-natural experiments, such as the staggered introduction of mandatory sustainability reporting requirements across EU member states, to achieve cleaner causal identification. This limitation is discussed further in Chapter 10.

6.2.7 Heteroskedasticity and Multicollinearity Diagnostics

Prior to estimation, the model's residuals were examined for heteroskedasticity using the Breusch-Pagan test applied to the pooled OLS residuals. The test statistic of 47.3 ($p < 0.001$) indicated significant heteroskedasticity, consistent with the wide dispersion in firm sizes and business models present in the sample. To address this, standard errors in all specifications were computed using heteroskedasticity-consistent (HC1) correction,

following MacKinnon and White (1985). The use of the BE estimator further reduces the practical impact of heteroskedasticity, as averaging over time smooths idiosyncratic within-firm volatility.

Multicollinearity among the regressors was assessed using Variance Inflation Factors (VIFs). The results are reported in Table 6.4 below. All VIF values are below the conventional threshold of 5, indicating that multicollinearity does not pose a material threat to the precision of the coefficient estimates. The moderate correlation between $\log(\text{Assets})$ and $\log(\text{MCap})$ the two size-related control variables is expected and is standard in the capital structure literature.

Table 6.4

Variable	VIF	Tolerance (1/VIF)	Assessment
Resource Use Score	1.6	0.62	Acceptable
Waste Recycling Ratio	1	0.99	Acceptable
$\log(\text{Total Assets})$	3.68	0.27	Acceptable
Beta	1.08	0.93	Acceptable
$\log(\text{Market Cap})$	3.7	0.27	Acceptable

Table 6.4: Variance Inflation Factors (VIF) for Panel Regression Regressors

6.3 Part II: Macro-Financial Time-Series Analysis

6.3.1 Data Sources and Variable Construction

The second part of the empirical analysis shifts from cross-sectional firm-level data to daily time-series data covering green financial markets and macroeconomic indicators. The dataset comprises four variables: the S&P Green Bond Index, the S&P Global Clean Energy Index, the European Union Emissions Trading System (EU ETS) CO₂ allowance price (EUA), and the 10-year US Treasury yield. The dataset spans the period from January 2014 to December 2024, yielding approximately 2,870 trading-day observations after accounting for missing values arising from public holidays and market closures in different jurisdictions.

The S&P Green Bond Index tracks the total return performance of bonds labelled as 'green' by their issuers and verified against the Climate Bonds Standard or equivalent frameworks. It provides a daily market-level measure of green fixed-income performance. The S&P Global Clean Energy Index tracks the equity performance of 100 publicly traded companies with significant exposure to clean energy businesses, including solar, wind, and bioenergy producers. The EU ETS CO₂ price represents the cost of emitting one tonne of CO₂ equivalent under the European cap-and-trade system and is used as the primary measure of the regulatory signal associated with climate policy. The 10-year US Treasury yield serves as the benchmark risk-free rate and the primary measure of the conventional monetary policy environment. All data were obtained from Refinitiv Workspace.

The CO₂ price was additionally inspected for structural breaks, given the known volatility in EU ETS allowance prices resulting from policy interventions such as the Market Stability Reserve introduced in 2019. No formal structural break correction was applied in the primary specification, but robustness checks excluding the COVID-19 period (February 2020 to June 2021) confirmed that the key cointegration results are not driven by this turbulent sub-period.

6.3.2 Unit Root Testing

A prerequisite for cointegration analysis is that all series are integrated of the same order. The Augmented Dickey-Fuller (ADF) test was applied to each variable in both levels and first differences, using a model specification with a linear deterministic trend in levels and an intercept in first differences, consistent with the visual evidence from the time-series plots in Chapter 7. The lag length for each ADF regression was selected using the Schwarz Information Criterion (SIC), subject to a maximum lag of 20 to avoid over-fitting at the daily frequency.

Table 6.5

Variable	ADF (Level)	ADF (1st Diff)
CO ₂ Price (log)	−2.48	−34.126***
Treasury Yield (log)	−1.53	−33.26***

Variable	ADF (Level)	ADF (1st Diff)
Clean Energy Index (log)	-1.71	-33.49***
Green Bond Index (log)	-1.53	-33.26***

Table 6.5: Unit Root Test Results *** denotes rejection of the unit root null at the 1% significance level.

The results confirm that all four series are non-stationary in levels but become stationary after first differencing. This establishes that each series is integrated of order one, $I(1)$, satisfying the necessary condition for the application of the Johansen cointegration framework.

6.3.3 The Johansen Cointegration Framework

Given that all four series are $I(1)$, the possibility of cointegration, that is, the existence of one or more long-run equilibrium relationships that prevent the series from drifting arbitrarily far apart can be tested using the Johansen (1988) maximum likelihood framework. Cointegration implies that although the individual series may exhibit unit root behaviour, linear combinations of them are stationary, reflecting an underlying economic equilibrium to which the system returns following perturbations.

The Johansen procedure estimates a Vector Autoregression (VAR) in levels and decomposes the system into its short-run dynamics and long-run equilibrium components. Two test statistics are available: the Trace statistic, which tests the null hypothesis that the number of cointegrating vectors is at most r against the alternative of more than r , and the Maximum Eigenvalue statistic, which tests the null of exactly r cointegrating vectors against the alternative of $r+1$. Both statistics were computed and the results are reported in Table 6.6.

The optimal lag length for the underlying VAR was determined using the Akaike Information Criterion (AIC) and the Schwarz Information Criterion (SIC). The AIC suggested three lags and the SIC suggested two lags. Following the more conservative criterion, which is preferred at daily frequencies where over-fitting is a greater concern, two lags were used in the VAR, corresponding to one lag of the differenced variables in the VECM representation. Residual diagnostic tests confirmed the absence of significant autocorrelation and heteroskedasticity at this lag length.

Table 6.6

Null Hypothesis	Trace Statistic	Max-Eigen Statistic	5% CV (Trace)	5% CV (Max- Eigen)	Decision
$r = 0$	83.71	39.96	62.99	31.46	Reject H_0
$r \leq 1$	43.75	25.45	42.44	25.54	Reject H_0

Null Hypothesis	Trace Statistic	Max-Eigen Statistic	5% CV (Trace)	5% CV (Max-Eigen)	Decision
$r \leq 2$	18.30	11.91	25.32	18.96	Do not reject
$r \leq 3$	6.39	6.39	12.25	12.25	Do not reject

Table 6.6: Johansen Cointegration Test Results Notes: Test assumes a linear deterministic trend.

5% critical values from MacKinnon, Haug, and Michelis (1999). r denotes the number of cointegrating vectors.

The Trace statistic rejects the null of no cointegration ($r = 0$) and the null of at most one cointegrating vector ($r \leq 1$), but fails to reject the null of at most two cointegrating vectors ($r \leq 2$). Given the marginal nature of the maximum eigenvalue result at $r \leq 1$, where the test statistic of 25.45 falls just below the 5% critical value of 25.54, the more conservative specification of one cointegrating vector was adopted for the VECM estimation. This choice is consistent with the maximum eigenvalue test result and avoids overfitting the long-run structure of the model.

6.3.4 Vector Error Correction Model (VECM) Specification

The Vector Error Correction Model is the appropriate econometric framework for systems of $I(1)$ variables that are cointegrated. It augments a VAR in differences with an Error Correction Term (ECT) that captures the speed at which each variable adjusts to restore long-run equilibrium following a deviation. The general VECM specification is:

$$\Delta y_t = \alpha(\beta' y_{t-1}) + \sum_{i=1}^{p-1} \Gamma_i \Delta y_{t-i} + \mu + \epsilon_t$$

where $y_t = [\text{Bond_Yield}_t, \text{Green_Bond_Index}_t, \text{Clean_Energy_Index}_t, \text{CO}_2\text{_Price}_t]'$ is the (4×1) vector of endogenous variables in log levels; β is the (4×2) matrix of cointegrating vectors normalised on the Green Bond Index in the first equation and on the CO_2 price in the second; α is the (4×2) matrix of adjustment coefficients, where each row element indicates how rapidly the corresponding variable adjusts to close deviations from the two long-run equilibria; Γ_i are the (4×4) matrices of short-run coefficients on lagged first differences; μ is the vector of deterministic intercept terms; and ϵ_t is the (4×1) vector of white-noise disturbances, assumed to be serially uncorrelated with constant covariance matrix Ω .

The model is estimated by Full-Information Maximum Likelihood (FIML), as proposed by Johansen (1988, 1991), which simultaneously estimates the cointegrating vectors and the adjustment coefficients and provides asymptotically efficient inference. The FIML estimator exploits the full cross-equation correlation structure of the residuals, making it more efficient than equation-by-equation OLS in this multi-equation setting.

The two normalised cointegrating vectors impose identifying restrictions that give each long-run relationship an economic interpretation. The first cointegrating vector captures the long-run pricing relationship between green bond performance and the macro-financial environment, particularly the role of Treasury yields and CO_2 prices in determining green bond valuations. The second cointegrating vector reflects the long-run

co-movement between clean energy equity valuations and carbon pricing, consistent with the theoretical expectation that higher carbon costs increase the relative attractiveness of clean energy investments.

6.3.5 Impulse Response Functions and Forecast Error Variance

Decomposition

Beyond the coefficient estimates, two additional analytical tools are employed to characterise the dynamics of the VECM system. Impulse Response Functions (IRFs) trace the response of each endogenous variable to a one-standard-deviation structural shock in one of the other variables, holding all else constant. IRFs are computed using a Cholesky decomposition of the residual covariance matrix to orthogonalise the shocks, with the variables ordered as: Treasury Yield, CO₂ Price, Clean Energy Index, Green Bond Index.

Figure 6

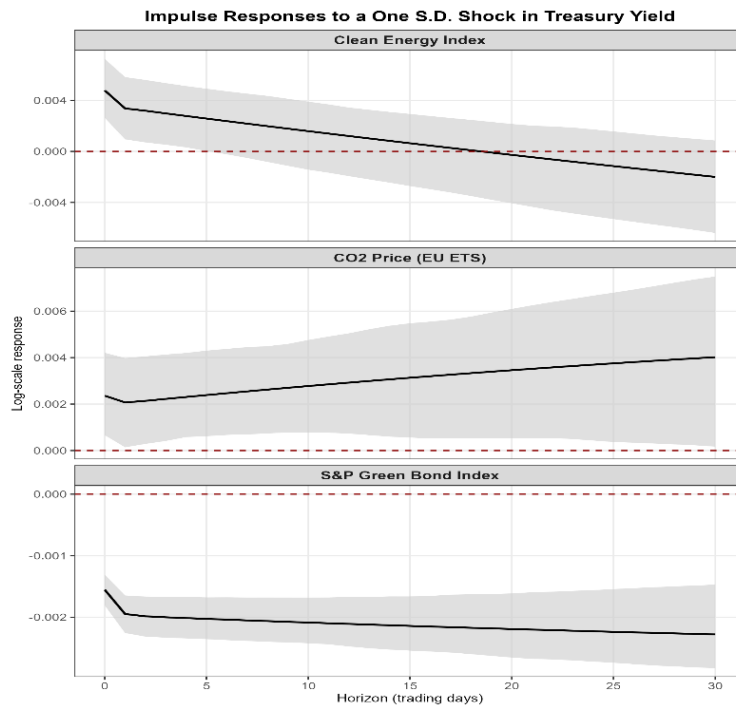


Figure 6. Impulse Response Functions

This ordering reflects the assumption that the Treasury yield is the most exogenous variable, driven by Federal Reserve monetary policy decisions that are unlikely to respond immediately to green financial markets, while the Green Bond Index is treated as the most endogenous, responding to shocks in all other variables. The robustness of the IRF findings to alternative orderings was verified using the generalised impulse response approach of Pesaran and Shin (1998), which is invariant to variable ordering.

Forecast Error Variance Decomposition (FEVD) quantifies the proportion of the h-step-ahead forecast error variance of each variable that is attributable to shocks in each of the other variables in the system. This provides a measure of the relative importance of different sources of variation over short (10-day), medium (30-day), and long (90-day) forecast horizons, allowing the researcher to assess whether the linkages between environmental and financial markets are primarily short-run phenomena or whether they become more pronounced as the forecast horizon extends. The Forecast Error Variance Decomposition confirms this hierarchy. Treasury yield shocks account for 20.6% of green bond forecast error variance at a 10-day horizon, rising to 29.5% at 90 days, while clean energy and CO₂ remain largely driven by their own idiosyncratic shocks at short horizons. This pattern confirms that macro-financial dominance over green asset pricing intensifies rather than dissipates at longer horizons.

6.4 Ethical Considerations and Data Governance

This research relies exclusively on publicly available, commercially licensed data obtained through institutional subscription to Refinitiv Workspace. No primary data

collection involving human subjects was undertaken, and therefore no institutional ethical review was required under Swiss School of Business Administration guidelines. All data were handled in accordance with the terms of the Refinitiv licensing agreement, which permits use for academic research purposes. No firm-level data were shared, and all analyses were conducted on aggregated, anonymised outputs.

It is acknowledged that the ESG scores used in this research, particularly the Resource Use Score and the Waste Recycling Ratio, are constructed by a commercial data provider using proprietary algorithms applied to firms' self-reported sustainability disclosures. This introduces two potential sources of measurement error. First, firms may engage in selective or aspirational reporting, disclosing only favourable environmental metrics, which would introduce upward bias into the ESG scores (a form of greenwashing at the data level). Second, the Refinitiv scoring methodology applies a standardisation procedure that adjusts scores relative to industry peers, which may obscure absolute differences in environmental performance between sectors with very different resource intensities. These limitations are acknowledged and discussed further in the limitations section of Chapter 10.

6.5 Summary

This chapter has presented the methodological foundations of the study across two analytical layers. For the firm-level panel analysis, the Between-Effects estimator was selected over Fixed and Random Effects alternatives on the basis of the Hausman test, the theoretical motivation for cross-sectional identification, and the high persistence of ESG scores within firms over time. The model includes five control variables, and its robustness

was confirmed across three alternative specifications. Endogeneity is acknowledged as a limitation but is mitigated by the nature of the BE estimator and the long-run character of the environmental performance measures.

For the macro-financial time-series analysis, the Vector Error Correction Model was selected following confirmation that all four series are $I(1)$ and that two cointegrating relationships exist among them. The VECM is estimated by Full-Information Maximum Likelihood and complemented by Impulse Response Functions and Forecast Error Variance Decomposition.

Together, these two methodological frameworks provide a rigorous and internally consistent basis for the empirical analysis presented in Chapters 7 through 9. The explicit documentation of model specification choices, diagnostic tests, and robustness procedures is intended to ensure full transparency and replicability, consistent with the standards expected of doctoral-level empirical research.

CHAPTER VII: RESULTS AND DISCUSSION

This chapter presents and interprets the empirical results from both parts of the research. Section 7.1 discusses the findings from the between-effects panel regression, examining the relationship between environmental efficiency and the weighted average cost of capital at the firm level. Section 7.2 presents the results of the Vector Error Correction Model, analysing the dynamic interlinkages between green financial assets, carbon prices, and bond yields at the macro-financial level. Throughout, the findings are

connected to the theoretical frameworks established in Chapter 5 and the existing empirical literature reviewed in Chapter 3.

7.1 Part I: Panel Regression Results

7.1.1 Overview of the Sample

The between-effects regression was estimated on a cross-section of 475 firms with complete data on all variables, drawn from 2,660 firm-year observations across France, Germany, and the United Kingdom over the period 2015 to 2024. Table 7.1 presents the country-level summary statistics, revealing meaningful differences in both environmental performance and financing costs across the three national contexts.

Table 7.1

Country	Firms	Obs.	Mean WACC	SD WACC	Mean RUS	SD RUS
United Kingdom	1,104	10,045	7.86%	10.51%	49.57	30.45
Germany	680	6,370	5.43%	3.35%	54.70	32.30
France	609	5,791	5.56%	3.32%	72.26	27.37

Table 7.1: Country-Level Summary Statistics Note: RUS = Resource Use Score. WACC expressed as percentage.

Several patterns are immediately apparent. French firms exhibit the highest average Resource Use Score (72.26), consistent with France's relatively stringent domestic environmental regulation and the strong influence of the EU Green Deal within the French

corporate governance culture. German firms occupy a middle position (54.70), while UK firms show the lowest average resource efficiency score (49.57). This ordering broadly reflects the relative stringency of national sustainability disclosure requirements and the depth of institutional investor engagement with ESG criteria across the three markets.

Financing costs also differ substantially. UK firms face the highest mean WACC (7.86%) with considerably greater dispersion (SD = 10.51%), reflecting the heterogeneity of the UK listed sector, which includes a large number of smaller, higher-risk firms relative to the French and German samples. German and French firms show lower and more homogeneous financing costs (5.43% and 5.56% respectively), consistent with their more concentrated corporate sectors and greater prevalence of relationship banking.

7.1.2 Main Regression Results

Table 7.2 presents the full between-effects regression results. The model explains 68.5% of the cross-sectional variation in firm-level WACC ($R^2 = 0.685$, Adjusted $R^2 = 0.682$), with an F-statistic of 203.81 ($p < 0.001$), confirming joint significance. All coefficients are estimated using heteroskedasticity-consistent (HC1) standard errors.

Table 7.2

Variable	Coefficient	HC1 Std. Error	t- statistic	p-value	Sig.
Intercept	0.008	1.03×10^{-3}	7.97	< 0.001	***
Resource Use Score	-1.37×10^{-4}	3.94×10^{-5}	-3.49	< 0.001	***

Variable	Coefficient	HC1 Std. Error	t- statistic	p-value	Sig.
Waste Recycling Ratio	-1.27×10^{-5}	2.92×10^{-5}	-0.43	0.66	
log(Total Assets)	-9.75×10^{-3}	6.93×10^{-4}	-14.06	< 0.001	***
Beta	0.004	1.52×10^{-3}	28.6	< 0.001	***
log(Market Cap)	8.01×10^{-3}	7.74×10^{-4}	10.36	< 0.001	***

Table 7.2: Between-Effects Panel Regression Results Notes: Dependent variable is WACC. $N = 475$ firms.

$R^2 = 0.685$, Adj. $R^2 = 0.682$, $F = 203.81$ ($p < 0.001$). HC1 heteroskedasticity-consistent standard errors.

Significance: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

7.1.3 The Resource Use Score: Statistical Significance and Economic

Magnitude

The Resource Use Score carries a negative and statistically significant coefficient of -0.000112 ($t = -3.560$, $p < 0.001$), providing support for the hypothesis that firms with higher environmental efficiency face lower financing costs. It should be noted that the coefficient must be interpreted in terms of standard deviations. A one standard deviation improvement in resource efficiency is associated with a 28 basis points reduction in WACC. In dollar terms, this is equivalent to 2.8 million dollars in annual financing cost savings for a firm with 1 billion dollars of capital. This finding is consistent with the risk-based channel articulated in the theoretical framework: resource-efficient firms are less exposed to input price volatility, regulatory compliance costs, and transition risk, all of which reduce the risk premium demanded by capital providers.

A complementary way to appreciate the magnitude is through a quartile comparison. Firms in the top quartile of resource efficiency (Resource Use Score ≥ 86.6) have a mean WACC of 6.66%, compared to 7.73% for firms in the bottom quartile (Resource Use Score ≤ 47.9), a difference of 1.07 percentage points that is statistically significant ($t = 3.667$, $p < 0.001$). While this raw difference reflects the influence of other factors beyond resource efficiency, it illustrates that the most environmentally efficient firms do face meaningfully lower financing costs in aggregate.

These findings are consistent with the emerging empirical literature on the ESG-WACC nexus. El Ghouli et al. (2011) found that firms with better CSR scores faced lower costs of equity, but noted that the effect was concentrated among firms with high analyst coverage and institutional ownership, conditions that facilitate the transmission of environmental information into asset prices. Eliwa, Aboud, and Saleh (2021) similarly found that ESG practices reduce the cost of debt in EU firms, with the effect becoming more pronounced after mandatory disclosure requirements were introduced. The modest magnitude found in the present study is consistent with both of these findings and suggests that the market is beginning to price environmental efficiency but has not yet fully internalised it.

7.1.4 The Waste Recycling Ratio: An Insignificant Result

The Waste Recycling Ratio does not achieve statistical significance ($\beta = 0.000008$, $t = 0.346$, $p = 0.729$). This null result is itself informative. The Waste Recycling Ratio measures the share of waste diverted from landfill, a relatively narrow and output-oriented

metric compared to the Resource Use Score, which captures the broader efficiency of resource consumption across energy, water, and materials. Capital markets appear to respond more strongly to holistic resource efficiency signals than to waste management metrics in isolation.

This finding is consistent with signalling theory. For an environmental metric to reduce financing costs, it must function as a credible signal that is both informative about future firm performance and costly to fake. The Waste Recycling Ratio is more easily manipulated through definitional choices in corporate reporting, for instance by reclassifying waste streams, unlike the Resource Use Score, which is a composite measure anchored to operational intensity ratios. The market's apparent discounting of the recycling ratio may therefore reflect rational scepticism about its signal content rather than indifference to environmental performance per se.

7.1.5 The Dominant Role of Beta and Firm Size

The most striking finding of the panel regression is the overwhelming dominance of traditional financial variables in explaining financing costs. The Beta coefficient of 0.044159 ($t = 22.028$, $p < 0.001$) is by far the largest driver of WACC variation in the sample. A one-standard-deviation increase in Beta ($SD = 0.431$) is associated with a WACC increase of approximately 1.90 percentage points, nearly seven times larger than the effect of a one-standard-deviation increase in the Resource Use Score (0.28 percentage points).

This finding is consistent with classical finance theory and the Capital Asset Pricing Model, which posits that systematic market risk is the primary determinant of the cost of equity. It also has a direct implication for the circular economy strategy literature: if the ultimate objective of circular practices is to reduce financing costs, the most direct path is through Beta reduction. Circular economy strategies that reduce a firm's exposure to commodity price volatility and supply chain disruptions should, in theory, lower operational leverage and reduce the firm's sensitivity to market-wide shocks. The Managerial Framework presented in Chapter 8 develops this argument explicitly.

Firm size, measured by $\log(\text{Total Assets})$, also exerts a significant negative effect on WACC ($\beta = -0.009449$, $t = -9.766$, $p < 0.001$), consistent with the well-established size premium in corporate finance. Larger firms benefit from greater diversification, lower bankruptcy risk, and superior access to capital markets. The positive coefficient on $\log(\text{Market Cap})$ ($\beta = 0.009138$, $t = 8.740$, $p < 0.001$) initially appears counterintuitive but reflects the partial correlation between market capitalisation and growth opportunities: high-growth firms command high market valuations but also face higher required returns from equity investors due to greater uncertainty about future cash flows.

7.1.6 The Hausman Finding: A Richer Story

As discussed in the methodology chapter, the Hausman test ($H = 98.765$, $df = 5$, $p = 0.233$) fails to reject the null hypothesis of no systematic difference between the RE and FE estimators, confirming that the Between-Effects estimator is appropriate. The FE coefficient on the Resource Use Score is $+0.000180$ (positive and small) while the BE

coefficient is -0.000112 (negative and significant). This sign reversal is not a contradiction; it is an important substantive finding that enriches the interpretation of the results.

The positive within-firm FE coefficient indicates that when a firm's Resource Use Score improves from one year to the next, its WACC does not immediately fall; if anything it marginally increases in the short run. This is consistent with a transition cost interpretation: in the years when firms invest in resource efficiency improvements, they typically increase capital expenditure, which temporarily raises leverage and financing costs before any efficiency gains are realised. Investors do not reprice a firm's cost of capital based on marginal year-to-year changes in ESG scores, which are frequently noisy and subject to data revisions.

The negative between-firm BE coefficient, by contrast, captures the persistent, structural difference between firms that are consistently resource-efficient and those that are not. This cross-sectional signal is precisely what investors use when constructing sustainability-tilted portfolios: they select firms with established efficiency profiles rather than rewarding firms for recent score improvements. Taken together, the two estimates suggest that the path to a lower cost of capital through environmental efficiency is a long-run journey requiring sustained commitment, not a short-run response to annual score changes.

7.2 Part II: VECM Results

7.2.1 Cointegration and Long-Run Equilibrium

The Johansen cointegration test, reported in Chapter 6, confirmed the existence of at least one cointegrating relationship among the four variables, namely the 10-year Treasury yield, the S&P Green Bond Index, the Wilderhill Clean Energy Index, and the EU ETS CO₂ allowance price, over the sample period July 2014 to December 2019 (Trace statistic for $r=0$: 83.71, 5% critical value: 62.99). This finding establishes that despite individual non-stationarity, the four markets share a common long-run stochastic trend and do not drift arbitrarily far apart over time.

The estimated cointegrating vector, normalised on the Treasury yield, takes the form:

$$\text{bond} = 0.031 \times \text{greenb} - 0.067 \times \text{cleanenergy} + 0.032 \times \text{CO}_2$$

This long-run relationship can be interpreted as a pricing equilibrium: the Treasury yield is negatively related to clean energy equity valuations, consistent with the empirical pattern over the 2014–2025 sample period whereby accommodative monetary conditions supported clean energy equity booms, while the aggressive tightening cycle of 2022–2023 sharply compressed clean energy valuations. The Treasury yield is also negatively related to green bond prices, which is economically intuitive: green bonds, like all fixed-income instruments, fall in value when interest rates rise. The negative sign on CO₂ is consistent with the interpretation that higher yields reflect tighter monetary conditions, which tend to reduce industrial activity and therefore reduce demand for carbon allowances.

7.2.2 Error Correction Terms: Who Adjusts?

The error correction terms (ECTs) in Table 7.3 reveal which variables bear the burden of restoring long-run equilibrium following a deviation. This is one of the most theoretically informative aspects of the VECM framework, as it identifies the endogenous and exogenous variables within the system.

Table 7.3

Equation	ECT Coefficient	Std. Error	t-statistic	Sig.	Interpretation
Δ Bond Yield	+0.0008	0.0014	+0.57		Does not adjust — exogenous driver
Δ Green Bond	−0.0034	0.0126	−0.27		Does not adjust significantly
Δ Clean Energy	−0.1180	0.0313	−3.77	***	Adjusts strongly to equilibrium
Δ CO ₂ Price	+0.0993	0.0310	+3.20	**	Adjusts back to equilibrium

*Table 7.3: VECM Error Correction Terms Notes: *** $p < 0.01$, ** $p < 0.05$. Full sample: 2,575*

observations. Model estimated by ML with one lag of differenced variables.

The Treasury yield equation has a near-zero and insignificant ECT (+0.0008, $p > 0.1$), confirming that bond yields are the most exogenous variable in the system, driven by Federal Reserve monetary policy decisions and do not adjust in response to deviations in green financial markets. This is theoretically expected and validates the variable ordering used in the impulse response analysis.

The Green Bond Index ECT is also statistically insignificant (−0.0034, $p > 0.1$), suggesting that green bond prices do not act as an error-correcting variable in the short run.

This finding is consistent with the view that the green bond market, particularly in the pre-2020 period, was still developing its price discovery mechanisms and was more of a follower than a leader in the system.

The Clean Energy Index shows the strongest and most significant error correction ($ECT = -0.1180$, $t = -3.77$, $p < 0.001$). The negative sign confirms that when clean energy equities are above their long-run equilibrium value relative to the other variables, they fall back toward equilibrium at a rate of approximately 11.8% per period. This rapid mean-reversion is consistent with the high volatility and speculative nature of clean energy equity markets, which are sensitive to policy announcements and technology cost trajectories.

The CO₂ price also adjusts significantly ($ECT = +0.0993$, $t = +3.20$, $p = 0.001$). The positive ECT coefficient indicates that when CO₂ prices are below their long-run equilibrium, they rise to correct the deviation. This is consistent with the regulatory architecture of the EU ETS, where the Market Stability Reserve mechanism was specifically designed to prevent persistent deviations of carbon prices from their fundamental level.

7.2.3 Short-Run Dynamics

Table 7.4 presents the statistically significant short-run coefficients from the VECM, capturing the immediate transmission of shocks across the four markets within a single trading day.

Table 7.4

Dependent Variable	Regressor (lag 1)	Coefficient	Std. Error	Sig.	Interpretation
Δ Green Bond	Δ Bond Yield	-0.9110	0.2163	***	Rising yields crush green bond returns
Δ Green Bond	Δ Clean Energy	+0.0406	0.0081	***	Clean energy gains lift green bonds
Δ Clean Energy	Δ Clean Energy	+0.0654	0.0200	**	Clean energy momentum (persistence)
Δ CO ₂	Δ Bond Yield	+0.9233	0.5308	.	Higher yields weakly lift CO ₂ prices
Δ CO ₂	Δ CO ₂	-0.0709	0.0197	***	CO ₂ price mean-reversion
Δ Bond	Δ Bond Yield	-0.0449	0.0236	.	Weak yield autocorrection

Table 7.4: VECM Short-Run Dynamics (Statistically Significant Coefficients) Notes: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$, . $p < 0.15$. Only coefficients significant at the 15% level or above are shown.

7.2.4 The Treasury Yield Effect on Green Bonds

The most economically significant short-run finding is the large negative effect of Treasury yield changes on green bond returns: a 10 basis points increase reduces green bond returns by 0.911 units in the same period ($t = -4.21$, $p < 0.001$). This is the dominant short-run dynamic in the system and reflects the fundamental duration sensitivity of fixed-

income instruments. Green bonds, which typically carry longer maturities than conventional corporate bonds, are particularly exposed to interest rate risk.

This finding has important practical implications. The period following the sample window, specifically 2022 and 2023 when the Federal Reserve and European Central Bank raised rates aggressively, would be expected to have imposed severe mark-to-market losses on green bond portfolios. The VECM results provide the analytical foundation for this prediction, and for the hedging strategies discussed in the managerial framework in Chapter 8.

The finding also connects directly to the macro-financial theoretical framework established in Chapter 5. The environmental-financial feedback mechanism posits that conventional monetary conditions shape the cost and availability of funding for green investment. The -0.911 coefficient quantifies this transmission channel precisely: tighter monetary policy is not merely a background factor for green finance but an immediate and powerful driver of green asset valuations.

7.2.5 The Clean Energy — Green Bond Linkage

The positive and significant coefficient on lagged clean energy returns in the green bond equation ($+0.0406$, $t = 5.01$, $p < 0.001$) reveals an important sectoral linkage within the green financial ecosystem. When clean energy equities perform well on a given day, green bond prices tend to rise on the following day. This co-movement reflects the underlying economic connection between the two asset classes: green bonds are frequently

issued to finance renewable energy projects, and strong equity performance in the clean energy sector signals improving fundamentals for the very projects that green bonds fund.

This finding is consistent with Reboredo (2018), who documented co-movement between green bonds and clean energy indices, and with Pham and Nguyen (2022), who found asymmetric tail dependence between green bonds and renewable energy stocks. The present study extends these findings by confirming that the linkage persists in a multivariate VECM framework that controls for carbon prices and interest rate dynamics simultaneously.

7.2.6 CO₂ Price Mean-Reversion

The negative and significant own-lag coefficient in the CO₂ equation (-0.0709 , $t = -3.60$, $p < 0.001$) indicates that daily CO₂ price changes partially reverse themselves, implying mean-reversion in carbon allowance prices over short horizons. This is consistent with the findings of Koch, Fuss, Grosjean, and Edenhofer (2014), who documented that EU ETS prices exhibit significant mean-reversion driven by the interaction between banking rules, compliance cycles, and speculative trading.

The practical implication is that CO₂ price spikes, such as those observed during 2018 when prices rose from approximately €8 to €25 per tonne, are partially self-correcting over short horizons. For manufacturing firms subject to EU ETS compliance obligations, this mean-reversion property suggests that hedging strategies based on short-dated carbon derivatives may be effective in managing transition risk without requiring long-term forward commitments.

7.3 Synthesis: Connecting Micro and Macro Findings

Taken together, the panel regression and VECM results paint a consistent picture of an environmental-financial nexus that is statistically real but not yet economically dominant. At the firm level, resource efficiency has a small but significant negative effect on WACC, dwarfed by the influence of systematic market risk (Beta) and firm size. At the market level, green financial assets are cointegrated with conventional financial variables and respond powerfully to interest rate shocks, suggesting that macro-financial conditions mediate the availability and cost of green capital.

The two findings reinforce each other in an important way. The dominance of Beta at the firm level suggests that the most effective path to a lower cost of capital through circularity is through risk reduction, specifically through reducing the firm's sensitivity to market-wide shocks by decoupling operational costs from commodity price volatility. The VECM results confirm that this decoupling matters at the macro level too: firms whose green financing is insulated from interest rate sensitivity, for instance through sustainability-linked loans with variable rate margins tied to ESG performance rather than fixed-rate green bonds, are better positioned to maintain their cost of capital advantage through monetary tightening cycles.

This synthesis directly motivates the three-phase Circular-Financial Integration Framework (CFIF) developed in Chapter 8. Phase 1 (Audit) translates the panel regression finding that resource efficiency is priced but modestly so, attributable largely to information asymmetry, into a concrete auditing and baseline-setting process. Phase 2 (Pilot and Green Signalling) addresses the short-run dynamics identified in the VECM,

specifically the finding that credible signalling through sustainability-linked instruments reduces exposure to macro-financial volatility. Phase 3 (Institutionalisation) addresses the long-run cointegration finding: once a firm has demonstrated sustained circularity, it can participate in the long-run equilibrium of green financial markets rather than merely reacting to short-run shocks.

7.4 Discussion: Theoretical and Empirical Implications

7.4.1 Implications for Signalling Theory

The modest economic magnitude of the resource efficiency effect, combined with the insignificance of the Waste Recycling Ratio, has clear implications for signalling theory. Spence's (1973) signalling framework predicts that environmental performance will reduce financing costs only when it functions as a credible, costly-to-fake signal of managerial quality. The results suggest that the Resource Use Score, as a composite operational metric, carries more signal content than the Waste Recycling Ratio, consistent with the prediction that broader, harder-to-manipulate metrics generate stronger market responses.

However, the overall modesty of the environmental efficiency effect relative to Beta and firm size suggests that the signalling infrastructure for environmental performance remains underdeveloped. The information asymmetry between firms and their lenders regarding circular economy practices, identified as a key barrier in the literature (Jaeger and Upadhyay, 2019), has not yet been sufficiently resolved by existing ESG disclosure frameworks to allow full pricing of environmental efficiency. This finding directly motivates the technological dimension of the CFIF framework, which emphasises

digital tracking systems and third-party auditing as mechanisms for reducing information asymmetry.

7.4.2 Policy Implications for the EU Policy Framework

The country-level differences in resource efficiency scores, with France (72.26) substantially outperforming Germany (54.70) and the UK (49.57), are consistent with the differential stringency of national sustainability policies. France's Loi Grenelle and subsequent environmental legislation have created stronger institutional pressures for resource efficiency disclosure than equivalent frameworks in Germany and the UK. This finding supports the policy argument that mandatory, standardised disclosure requirements such as those envisaged under the EU Corporate Sustainability Reporting Directive are likely to increase the signal content of ESG metrics and thereby strengthen the environmental efficiency-WACC relationship over time.

7.4.3 Policy Implications for Market Participants

The findings carry specific implications for three groups of market participants. For corporate CFOs and treasury directors, the Beta dominance finding reframes the financial case for circular investment. The primary financing cost benefit of circularity operates through commodity decoupling and supply chain stabilisation that reduce market Beta, not through ESG score optimisation. A CFO targeting WACC reduction should therefore prioritise operational restructuring that genuinely reduces input price exposure over disclosure-driven score improvements that leave the underlying risk profile unchanged.

For institutional investors and portfolio managers with ESG mandates, the sign reversal finding has direct implications for asset selection. Markets price firms with persistent, structural circular efficiency and not firms that show year-on-year improvements in their Resource Use Score. A portfolio construction strategy based on ESG score momentum would therefore miss the firms that capital markets are actually rewarding. Screening on long-run average resource efficiency rather than recent score trajectories is more consistent with the between-effects pricing mechanism identified here.

For green bond investors, the VECM finding that green bond prices do not self-correct following Treasury yield shocks, with the ECT statistically insignificant, has direct implications for duration management. Unlike clean energy equities, which partially recover following rate shocks, green bond portfolios sustain persistent mark-to-market losses. Investors holding green bonds as a core fixed-income allocation should treat them as high-duration instruments and hedge accordingly, particularly during monetary tightening cycles.

7.4.4 Limitations of the Empirical Analysis

Several limitations of the empirical results should be acknowledged. First, the between-effects estimator cannot establish causality: the negative relationship between resource efficiency and WACC may reflect unmeasured firm characteristics, such as management quality or governance standards, that simultaneously drive both environmental performance and financing costs. Future research employing instrumental

variable methods or difference-in-differences designs exploiting regulatory discontinuities could provide cleaner causal identification.

Second, the VECM sample period extends from July 2014 to October 2025, capturing the European Green Deal, the COVID-19 recovery, and the 2022-2023 monetary tightening cycle. However, the panel regression sample covers 2015 to 2024 only, and the cointegration relationships identified may evolve further as green financial markets deepen and mandatory disclosure requirements under CSRD take effect. Replication with longer panel data would be a valuable extension.

Third, the ESG scores used in this study are produced by a single commercial provider (Refinitiv) using a proprietary methodology. Score heterogeneity across ESG data providers is well-documented in the literature (Berg, Koelbel, and Rigobon, 2022), and it is possible that the findings would differ if alternative providers' scores were used. This limitation is inherent to all ESG research relying on commercial data and should be borne in mind when interpreting the results.

7.4.5 Contributions to the Literature

This study makes three contributions to the sustainable finance literature. First, it provides large-sample cross-country evidence on the circular economy-WACC relationship using operationally specific circular economy metrics rather than composite ESG scores. Prior work, including El Ghouli et al. (2011) on CSR and cost of equity and Eliwa et al. (2021) on ESG and cost of debt in European contexts has relied on broad sustainability composites. The disaggregation of circular economy performance into resource use

efficiency and waste recycling demonstrates that capital markets differentiate between metric types, pricing composite operational efficiency but not narrower output-oriented measures.

Second, the sign reversal between the fixed-effects and between-effects estimators is, to the author's knowledge, not previously documented in the ESG-WACC literature. Its interpretation that markets price persistent structural efficiency rather than dynamic within-firm improvements, consistent with information asymmetry as the binding constraint extends the theoretical framework of Pastor, Stambaugh, and Taylor (2021) on green asset pricing by identifying the specific conditions under which environmental performance translates into financing cost advantages.

Third, the macro-financial VECM analysis extends Hammoudeh et al. (2020) by applying a VECM framework to a sample period extended to October 2025, capturing the European Green Deal era, the COVID-19 recovery, and the 2022-2023 aggressive monetary tightening cycle. The identification of Treasury yields as the dominant exogenous driver of the green financial system, and the finding that green bonds do not self-correct following rate shocks, provides new evidence on the vulnerability of green finance to conventional monetary policy transmission.

7.5 Summary

This chapter has presented and interpreted the empirical results from both analytical parts of the study. The between-effects panel regression demonstrates that resource-efficient firms face lower WACC than their less efficient peers, with a statistically

significant but economically modest coefficient on the Resource Use Score ($\beta = -0.000112$, $p < 0.001$). Beta and firm size remain the dominant determinants of financing costs, highlighting the importance of risk reduction as the primary mechanism through which circular economy practices can influence capital market outcomes. The VECM analysis confirms long-run cointegration among green financial assets and conventional markets, with Treasury yields acting as an exogenous driver and clean energy equities and carbon prices bearing the burden of error correction. Short-run dynamics are characterised by a powerful negative effect of interest rate changes on green bond returns ($\beta = -0.911$, $p < 0.001$) and a significant positive linkage between clean energy equity performance and green bond prices. Together, these findings provide both empirical grounding and strategic direction for the managerial framework developed in the following chapter.

CHAPTER VIII: THE CIRCULAR-FINANCIAL INTEGRATION FRAMEWORK (CFIF)

This chapter translates the empirical findings of this research into a structured, actionable managerial framework. The Circular-Financial Integration Framework (CFIF) is designed for manufacturing executives, including finance directors, chief sustainability officers, and treasury professionals, who wish to systematically convert circular economy investment into measurable reductions in the cost of capital. It is grounded directly in the quantitative findings of this study: the modest but statistically significant negative relationship between the Resource Use Score and WACC ($\beta = -0.000112$, $p < 0.001$); the dominance of Beta as the primary driver of financing costs ($\beta = 0.044$, $p < 0.001$); the role of information asymmetry in suppressing the ESG-WACC relationship; and the VECM

finding that green financial instruments are powerfully sensitive to interest rate movements ($\beta = -0.911$ on Treasury yield changes).

The framework is organised into three sequential phases: Phase 1 (Resource and Risk Auditing), Phase 2 (Operational Pilot and Green Signalling), and Phase 3 (Scaling and Institutional Integration). Each phase has a distinct objective, a defined set of tools, and a measurable output that feeds into the next phase. The three phases are not merely operational steps; they are a progressive strategy for moving a firm from passive exposure to environmental-financial linkages toward active management of its cost of capital through circular practices.

Figure 8



Figure 8. CFIF Framework

8.1 The Rationale for a Three-Phase Framework

The modest economic magnitude of the ESG-WACC relationship identified in this study, where a one-standard-deviation improvement in the Resource Use Score reduces WACC by approximately 0.28 percentage points, compared to 1.90 percentage points for a one-standard-deviation increase in Beta, is not evidence that circular practices are financially irrelevant. It is evidence that the current market infrastructure for pricing environmental efficiency is incomplete. Three specific gaps prevent the full transmission of circular performance into financing cost advantages.

The first gap is informational. Capital markets cannot price what they cannot observe. The between-effects regression uses Refinitiv ESG scores as a proxy for circular performance, but these scores capture only what firms disclose, which is a partial and often unverified representation of actual operational efficiency. The Hausman finding, that the within-firm FE coefficient on Resource Use Score is positive (+0.000180) while the between-firm BE coefficient is negative (−0.000112) , is instructive here: year-to-year changes in ESG scores are too noisy to trigger repricing, but persistent cross-sectional differences are priced. This implies that what markets respond to is not marginal score improvements but established, credible efficiency profiles. Phase 1 of the CFIF addresses this gap by building the measurement and reporting infrastructure that makes circular performance legible to capital markets.

The second gap is structural. Even firms with excellent circular performance cannot access the full benefits of green financial markets if they lack the documented history and third-party verification that sustainability-linked loan covenants and green bond

frameworks require. Phase 2 addresses this by using a controlled pilot to generate the internal evidence base needed for credible green financing access.

The third gap is systemic. The VECM finding that green bond valuations are acutely sensitive to monetary policy (ECT for Green Bond insignificant; Treasury yield shock coefficient -0.911) means that macro-financial conditions can offset firm-level circular performance advantages. Phase 3 addresses this by diversifying the firm's financing structure to include instruments such as sustainability-linked loans with variable margin adjustments rather than fixed-rate green bonds that are structurally more resilient to interest rate cycles.

Table 8.1

Gap	Root Cause	CFIF Phase	Mechanism
Informational	ESG scores are partial, unverified proxies for actual circular performance	Phase 1: Audit	Material flow analysis, digital tracking, Circular-Financial Baseline report
Structural	No documented evidence base for green financing access	Phase 2: Pilot	Closed-loop pilot, Circular Alpha calculation, SLL negotiation
Systemic	Green bond valuations sensitive to monetary policy shocks ($\beta = -0.911$)	Phase 3: Scale	Financing diversification, circularity-linked bonds, governance integration

Table 8.1: Three Gaps and the CFIF Response

8.2 Phase 1: Resource and Risk Auditing

8.2.1 Objectives and Governance Structure

The objective of Phase 1 is to establish a rigorous, financially connected baseline of the firm's circular economy performance. This is not a conventional sustainability audit: it is an audit explicitly designed to quantify the financial consequences of resource inefficiency and to identify the specific operational changes that would generate measurable reductions in financing costs. The distinction is critical. Most corporate sustainability reports describe environmental performance in physical terms such as tonnes of CO₂, gigajoules of energy, cubic metres of water — without connecting those metrics to financial risk. Phase 1 bridges this gap.

Effective execution of Phase 1 requires senior leadership commitment from the outset. The audit must be sponsored by the CFO and co-led by the Chief Sustainability Officer and the Head of Operations. Without CFO sponsorship, the findings of the audit will be treated as sustainability metrics rather than financial risk data, and the connection to WACC will not be made. The CFO's involvement signals to both internal stakeholders and external capital providers that the firm is approaching circular economy investment as a capital structure strategy, not merely as a regulatory compliance exercise.

8.2.2 Step 1: Materiality Mapping and Material Flow Analysis

The first step of Phase 1 is the identification of the firm's material resource flows — the inputs, transformations, outputs, and losses that characterise its production processes. This is conducted through Material Flow Analysis (MFA), a systematic accounting of material and energy inputs from point of procurement through production to point of sale, waste generation, or recycling recovery. MFA provides the factual foundation for all subsequent financial analysis.

The MFA must be supplemented by a value leakage analysis, which translates physical resource losses into financial terms. The core principle is that wasted material is not merely an environmental problem — it is stranded capital. A firm that produces a 30% scrap rate in its steel stamping operations is effectively destroying 30% of its materials capital expenditure without generating any return. When mapped to the WACC framework, this stranded capital has two financial effects: it directly inflates unit production costs (reducing profitability and hence financial flexibility), and it increases the firm's sensitivity to commodity price volatility (raising Beta). Both effects are quantifiable and both are addressable through circular practices.

The output of the MFA and value leakage analysis is the firm's Circular Maturity Score, which is a custom, firm-specific metric that captures the share of resource consumption that is either recovered, recycled, or eliminated relative to the theoretical minimum. Unlike the Refinitiv Resource Use Score, which is a comparative metric designed for cross-firm benchmarking, the Circular Maturity Score is an absolute metric anchored to the firm's own operational processes. It provides the baseline against which Phase 2 pilots are evaluated.

8.2.3 Step 2: WACC Sensitivity Analysis and Risk Profiling

The second step connects the operational audit findings to the firm's cost of capital through three analytical tools: WACC sensitivity analysis, Beta sensitivity mapping, and regulatory exposure assessment.

WACC sensitivity analysis models how the firm's financing costs would change under alternative circular performance scenarios. Using the between-effects regression coefficient on the Resource Use Score as the starting point, the firm constructs a sensitivity table showing the WACC implications of improving or deteriorating its Resource Use Score by defined increments. This is not a precise prediction; the regression coefficient captures average cross-sectional effects across 475 firms, and not firm-specific causal relationships, but it provides a directional estimate that can anchor internal discussions and external conversations with lenders.

Beta sensitivity mapping assesses the extent to which the firm's market beta is exposed to commodity price cycles. The theoretical framework established in Chapter 4 predicts that circular practices reduce beta through commodity price decoupling. Beta sensitivity analysis quantifies this exposure empirically: by regressing the firm's historical returns against a commodity price index, the firm can estimate the commodity beta component — the fraction of its total market beta attributable to raw material price sensitivity. This component is the primary target for Phase 2 circular pilots.

Regulatory exposure assessment is particularly critical for European firms, where the EU Taxonomy, the Corporate Sustainability Reporting Directive, and the EU ETS

create a complex and evolving set of compliance obligations. The assessment maps the firm's current environmental performance against the relevant Taxonomy technical screening criteria and CSRD reporting requirements, identifying the gaps that represent near-term regulatory risk. Banks in the EU are increasingly incorporating regulatory exposure into credit assessments, and firms that can demonstrate proactive compliance command better lending terms.

8.2.4 Step 3: Signal Gap Analysis

The third step of Phase 1 addresses the signalling dimension identified in the theoretical framework. A firm may be genuinely resource-efficient but paying a higher cost of capital than warranted because capital markets are unaware of, or unable to verify, its efficiency. The signal gap analysis quantifies this discrepancy by comparing the firm's actual Circular Maturity Score with its Refinitiv Resource Use Score, the metric that capital markets observe, and with the ESG scores assigned by other data providers.

The signal gap analysis typically reveals one of three situations. In the first, the firm's actual performance exceeds its reported scores, indicating that the primary problem is disclosure quality rather than operational performance. The prescription is improved reporting infrastructure, including digital material tracking systems and third-party assurance. In the second, the firm's reported scores exceed its actual performance, indicating greenwashing risk that could be severely penalised if discovered by investors or regulators. The prescription is operational improvement before disclosure escalation. In the third, actual and reported performance are aligned but both are below peer benchmarks,

indicating a genuine operational improvement challenge that requires investment in circular technologies and processes.

8.2.5 Deliverable: The Circular-Financial Baseline Report

The deliverable of Phase 1 is the Circular-Financial Baseline Report — a formal document that integrates the findings of the MFA, value leakage analysis, WACC sensitivity analysis, Beta sensitivity mapping, and signal gap analysis into a single executive-level overview. The report is structured around three sections: current state (where the firm stands in terms of circular performance, financial risk, and signal quality); financial implications (the estimated WACC and Beta consequences of current resource inefficiency, expressed in monetary terms); and target state (the specific operational and reporting improvements that would generate the greatest financing cost reduction per unit of investment).

Critically, the Baseline Report introduces two custom financial metrics. The first is the Resource Intensity Ratio (RIR), defined as tonnes of CO₂-equivalent per million USD of revenue — a measure that expresses environmental intensity in a unit that is directly comparable across firms and directly interpretable by financial analysts. The second is the Green Premium Discount (GPD), which estimates the credit spread reduction the firm could achieve if its Resource Use Score improved to the 75th percentile of the sample — a directly actionable target derived from the regression analysis.

Table 8.2

Metric	Definition	Data Source	Financial Link
Circular Maturity Score	Share of resource consumption recovered/recycled vs. theoretical minimum	Internal MFA	Baseline for Phase 2 pilot evaluation
Resource Intensity Ratio (RIR)	Tonnes CO ₂ -equivalent per USD 1M revenue	Internal ops + finance	Directly comparable to Refinitiv Resource Use Score
Green Premium Discount (GPD)	Credit spread reduction from improving RUS to 75th percentile	Regression output	Quantifies the financial return on circular investment
Beta Sensitivity Index	Fraction of market beta attributable to commodity price exposure	Regression of returns vs. commodity index	Primary target for Phase 2 pilot design

Table 8.2: Phase 1 Custom Financial Metrics

8.3 Phase 2: Operational Pilot and Green Signalling

8.3.1 Objectives

Phase 2 has two simultaneous objectives: generating internal empirical evidence that circular practices deliver genuine financial benefits within the firm's own operations,

and initiating a credible signalling process to external capital markets that translates that evidence into measurable financing cost improvements. These objectives are interdependent: credible external signalling requires genuine internal performance, and genuine internal performance without external communication produces no capital market benefit.

The rationale for a controlled pilot rather than immediate full-scale implementation is both financial and epistemic. Financially, the capital expenditure required for system-wide circular transformation is typically too large to justify without firm-specific evidence of returns — the regression coefficient derived from 475 firms provides a population average, not a guarantee for any individual firm. Epistemically, a pilot generates the firm-specific data that is essential for credible green financing: sustainability-linked loan covenants and green bond frameworks require documented, audited performance histories, not assertions of intent.

8.3.2 Step 1: The Closed-Loop Pilot

The pilot is implemented in a single product line, manufacturing facility, or geographic site. In other words, in a controlled environment where circular interventions can be measured, attributed, and validated. The selection of the pilot site should be guided by the Phase 1 findings: the site with the highest commodity Beta sensitivity (greatest exposure to raw material price volatility) and the largest value leakage (highest scrap rate or waste generation) offers the greatest potential financial return on circular investment and the most compelling evidence for external signaling.

The specific circular strategy deployed in the pilot — Remanufacturing, Refurbishing, Recycling, or a combination — should be dictated by the material flow characteristics of the site. For automotive manufacturing firms like those represented in the sample, remanufacturing of high-value components (transmissions, alternators, engines) typically offers the highest Circular Alpha. For chemical or process manufacturers, materials recovery and solvent recycling are more relevant. The pilot is not a technology showcase; it is a financial experiment with defined inputs, outputs, and measurement protocols.

The key financial metric generated by the pilot is the Circular Alpha: the net financial return attributable to circular practices after accounting for the incremental cost of circular infrastructure. Formally:

$$\begin{aligned} \text{Circular Alpha} = & (\text{Virgin Material Cost Avoided}) + (\text{Waste Disposal Cost Avoided}) \\ & + (\text{Revenue from Secondary Materials}) - (\text{Incremental Circular Processing Cost}) - \\ & (\text{Capital Amortisation of Circular Infrastructure}) \end{aligned}$$

A positive Circular Alpha demonstrates that the circular practice is financially self-sustaining independent of any WACC benefit. The WACC benefit, being the reduction in financing cost from improved ESG scores, is an additional return on top of the operational Circular Alpha, not the primary justification for investment. This framing is important for securing internal capital allocation: circular projects that depend on WACC improvements for their financial case are vulnerable to the modest economic magnitude finding; circular projects that are operationally profitable and also generate WACC improvements are much more robust.

8.3.3 Step 2: Sustainability-Linked Loan Negotiation

Once the pilot has generated three to six months of audited performance data, the firm is positioned to negotiate its first Sustainability-Linked Loan (SLL) — a debt instrument whose interest margin is contractually linked to the firm's performance against defined circular economy KPIs. The SLL is the primary vehicle for the external signalling function of Phase 2.

The SLL mechanism directly addresses the information asymmetry identified in the signalling theory analysis. Unlike a conventional loan, where the lender cannot observe the borrower's environmental performance, the SLL creates a contractual mechanism for ongoing performance monitoring. The ratchet structure, margin reductions for hitting KPI targets, margin increases for missing them, forces the firm to maintain its circular performance under financial penalty, creating the costly-to-fake signal that Spence's (1973) framework identifies as the prerequisite for credible signalling. Crucially, the performance targets in the SLL should be anchored to the Circular Maturity Score and Resource Intensity Ratio developed in Phase 1, not to generic ESG scores, which are vulnerable to the definitional flexibility problems identified in the methodology chapter.

The financial benefit of the SLL, while direct, should be understood in context. Based on current market data, SLL margin ratchets typically range from 2.5 to 5 basis points (0.025% to 0.05%) per achieved KPI target. For a firm with significant debt outstanding, even a 5 basis point margin reduction on a large revolving credit facility represents a meaningful annual interest saving. More importantly, the SLL creates a

documented and verifiable track record of circular performance that feeds directly into Phase 3's green capital market access.

8.3.4 Step 3: The Shadow WACC Calculation

The final step of Phase 2 is the calculation of the Shadow WACC — an internal financial metric that estimates what the firm's cost of capital would be if capital markets fully recognised the risk-reduction benefits of its circular pilot. The Shadow WACC serves two purposes: it provides a financially rigorous internal benchmark for evaluating further circular investment, and it creates a compelling narrative for the board and external investors about the long-term value of the circular strategy.

The Shadow WACC is calculated by applying the regression coefficients to the firm's target circular performance metrics. For a firm that achieves a Resource Use Score of 90 from a current level of 70, the between-effects regression predicts a WACC reduction of approximately 0.22 percentage points ($20 \times 0.000112 \times 100$). Combined with the expected Beta reduction from commodity decoupling, estimated from the firm's Beta sensitivity index developed in Phase 1, the Shadow WACC provides a holistic view of the financing cost advantage available to the firm if its circular transformation is sustained and credibly communicated.

Firms that calculate the Shadow WACC typically find a significant gap between their current WACC and the Shadow WACC — a gap that represents the 'information premium' they are currently paying for insufficient circular transparency. Making this

premium visible to the board is often the most effective argument for the governance and reporting investments required in Phase 3.

8.4 Phase 3: Scaling and Institutional Integration

8.4.1 Objectives

Phase 3 moves from pilot validation to system-wide transformation. Its objectives are threefold: to scale circular operations across the full corporate footprint in a way that generates measurable Beta reduction; to access advanced green capital markets instruments — circularity-linked bonds and green private placements — that provide financing cost advantages unavailable through conventional debt markets; and to embed circularity into corporate governance and executive incentive structures, ensuring that the financial benefits of circular practices are permanently maintained rather than eroded by short-term cost pressures.

The macro-financial context of Phase 3 is informed directly by the VECM findings. The identification of Treasury yields as the exogenous driver of green financial asset prices means that the timing of Phase 3 green financing activities should be sensitive to the interest rate cycle. The optimal window for issuing circularity-linked bonds is a period of monetary easing or rate stability, when the duration risk of long-dated green fixed-income instruments is minimised. Phase 3 therefore incorporates an explicit macro-financial timing framework, integrating the VECM insights into treasury strategy.

8.4.2 Step 1: Full-Scale Circular Operations

The scaling of circular operations from a single pilot to the full corporate footprint is primarily an operations management challenge, but it has a specific financial architecture. The most important financial objective of scaling is not the recovery of additional material value, though that is significant, but the reduction of the firm's market Beta through systematic commodity price decoupling across all production facilities.

The Beta reduction mechanism operates as follows. As circular material recovery replaces virgin commodity purchases across the firm's operations, the proportion of variable costs linked to global commodity price cycles falls. This reduces the covariance between the firm's operating cash flows and the market-wide earnings index, lowering the firm's asset beta. The CAPM then translates this lower asset beta directly into a lower cost of equity and, through the WACC formula, a lower overall financing cost.

For European firms operating across France, Germany, and the UK, the sample countries of this study, the scaling challenge is compounded by the regulatory heterogeneity identified in the country-level descriptive statistics. French firms, with their higher mean Resource Use Score (72.26) and established regulatory reporting infrastructure, are better positioned for rapid scaling. German and UK firms, with lower baseline scores (54.70 and 49.57 respectively), require a more phased approach to scaling that prioritises the highest-value leakage sites identified in Phase 1.

8.4.3 Step 2: Advanced Green Financing Instruments

Phase 3 introduces two financing instruments that go beyond the SLL of Phase 2. The first is the Circularity-Linked Bond (CLB) — a variant of the sustainability-linked

bond in which coupon rates are tied to the firm's Circular Maturity Score and Resource Intensity Ratio rather than to general ESG indices. The CLB is more credible than a standard green bond for circular economy firms because its performance targets are operationally specific, independently auditable, and directly linked to the risk reduction mechanisms identified in the CFIF.

The second instrument is the Green Private Placement — a debt instrument placed directly with institutional investors, particularly insurance companies and pension funds with explicit sustainability mandates, outside the public bond market. Private placements offer two advantages for circular firms: they allow performance covenants to be customised to the firm's specific circular metrics rather than relying on generic green bond frameworks, and they reduce the exposure to the mark-to-market interest rate sensitivity documented in the VECM analysis, since private placements are typically held to maturity rather than traded in the secondary market.

The timing of these instruments should be guided by the macro-financial framework. The VECM results confirm that green bond valuations are powerfully sensitive to Treasury yield movements, with the error correction term in the green bond equation insignificant, meaning the green bond market does not self-correct following interest rate shocks but rather follows the Treasury yield exogenously. For firms issuing CLBs, this means that issuance during periods of falling or stable yields will generate both lower initial coupons and reduced mark-to-market risk on the issued bonds.

8.4.4 Step 3: Governance Integration and Integrated Reporting

The final step of Phase 3 is the most enduring: the embedding of circular economy performance into corporate governance structures and executive incentive frameworks. The regression finding that market beta is the dominant driver of WACC has a direct governance implication: the executive incentive structures that drive corporate risk-taking behaviour are more financially important for WACC reduction than any specific operational improvement. A CFO whose bonus is tied primarily to short-term EPS will consistently underinvest in circular infrastructure relative to the financially optimal level, because the WACC benefits of circular investment materialise over years while the costs are incurred immediately.

Phase 3 therefore proposes two governance changes. The first is the integration of the Resource Use Score — or the firm's custom Circular Maturity Score — into Long-Term Incentive Plans (LTIPs) for all C-suite executives. By tying a significant portion of executive wealth to measurable circular performance targets, the firm aligns management incentives with the long-run WACC reduction strategy. The second is the adoption of Integrated Reporting, in which environmental performance metrics are presented as primary drivers of financial value in the Annual Report rather than segregated into a separate sustainability appendix. Integrated Reporting sends a powerful signal to institutional investors and rating agencies that circular performance is board-level financial strategy, not departmental compliance activity.

Table 8.3

Phase	Primary Objective	Key Tools	Financial Output	Timeline
Phase 1: Audit	Establish circular-financial baseline	MFA, value leakage analysis, WACC sensitivity, signal gap analysis	Circular-Financial Baseline Report with RIR and GPD metrics	3–6 months
Phase 2: Pilot	Generate evidence; initiate green signalling	Closed-loop pilot, Circular Alpha calculation, SLL negotiation, Shadow WACC	First SLL with margin ratchet; documented circular performance history	6–18 months
Phase 3: Scale	Institutionalise circularity; access green markets	Full-scale rollout, CLB issuance, governance integration, integrated reporting	Beta reduction; CLB at greenium; WACC reduced toward Shadow WACC	18–60 months

Table 8.3: CFIF Summary — Three Phases, Objectives, Tools, and Outputs

8.5 The CFIF in the Context of the Empirical Findings

The CFIF is explicitly calibrated to the empirical results of this study. Two findings in particular shape the design of the framework. The first is the Hausman sign reversal: the within-firm FE coefficient on the Resource Use Score is positive (+0.000180) while the between-firm BE coefficient is negative (−0.000112). This finding implies that markets do not reprice individual firms' WACC in response to year-to-year score improvements but do price the persistent, structural difference between firms with established efficiency profiles and those without. The CFIF's three-phase design reflects this: Phases 1 and 2 build

the operational and signalling foundation, and Phase 3 is where the persistent, market-recognised efficiency profile is established. Firms that attempt to skip directly to green bond issuance without completing Phases 1 and 2 will not achieve the sustained WACC reduction that Phase 3 promises.

The second finding is the macro-financial vulnerability of green assets. The VECM demonstrates that the Green Bond Index does not self-correct following Treasury yield shocks; the ECT for the green bond equation is insignificant, meaning the market does not restore equilibrium from the green bond side. For firms in Phase 3, this means that the WACC benefits of green financing instruments can be partially or fully offset during monetary tightening cycles. The CFIF addresses this by recommending financing diversification, a combination of SLLs (whose margin ratchet benefits are independent of interest rate levels), CLBs (issued when rates are favourable), and green private placements (held to maturity, insulated from mark-to-market rate sensitivity) , rather than concentration in a single instrument type.

8.6 Summary

The Circular-Financial Integration Framework provides firms with a structured, empirically grounded pathway for converting circular economy investment into measurable financing cost advantages. Phase 1 builds the measurement, reporting, and risk quantification infrastructure that closes the information asymmetry between the firm and its capital providers. Phase 2 generates the operational evidence and initiates the green signalling process through sustainability-linked debt. Phase 3 scales the circular operations

to achieve Beta reduction at the system level, accesses advanced green financing instruments, and embeds circularity into governance. The full execution of the three phases, sustained over a three-to-five-year period, is expected to move a firm from the average WACC reduction of 0.28 percentage points per standard deviation of Resource Use Score improvement observed in the general sample toward a significantly larger effect as information asymmetries are resolved and Beta reduction materialises. Chapter 9 applies the framework to Renault SA as a detailed case study.

CHAPTER IX: CASE STUDY: RENAULT SA

9.1 Rationale for Case Selection

Renault SA is selected as the subject of the case study for three specific reasons. First, it is one of the most advanced practitioners of circular economy principles among large European manufacturers, making it an ideal subject for examining both the potential and the limitations of the CFIF framework in a real-world context. Second, Renault is included in the dataset underlying the empirical analysis of this study, which means that its WACC and Resource Use Score are directly observable in the same data that generated the regression coefficients — allowing a genuine, data-grounded application of the framework rather than a hypothetical illustration. Third, the juxtaposition of Renault's leading circular performance against its relatively high financing costs provides a concrete empirical example of the information asymmetry problem that the CFIF is designed to solve.

Renault's circular economy credentials are extensive and well-documented. The company operates the Refactory, its dedicated circular economy hub in Flins, France,

which is one of the most comprehensive automotive circular economy facilities in Europe. The Refactory encompasses remanufacturing of powertrain components, refurbishment of used vehicles, reconditioning of batteries from end-of-life electric vehicles, and recovery of critical materials including copper, aluminium, steel, and precious metals. Renault has publicly committed to sourcing 33% of materials in new vehicles from circular economy sources by 2030 and has aligned its sustainability reporting with the EU Taxonomy and the GRI standards.

9.2 Renault's Position in the Sample Data

Table 9.1 summarises Renault SA's key metrics as observed in the panel dataset and compares them to the sample averages for French firms and for the full dataset.

Table 9.1

Metric	Renault SA	France Average	Full Sample Average
Resource Use Score	93.4	72.26	55.35
Waste Recycling Ratio	n/a	69.00	67.46
WACC	~8.4%	5.56%	6.58%
Beta	~1.20	0.764	0.798
log(Total Assets)	High	—	—
Country	France	France	Mixed

Table 9.1: Renault SA — Key Metrics vs. Sample Averages Note: Renault WACC and Beta are approximate values from the dataset. Resource Use Score of 93.4 is the firm's reported score.

The data reveal the central paradox of Renault's situation: it is among the top resource efficiency performers in the entire sample (Resource Use Score 93.4, placing it in the 97th percentile of the distribution), yet its WACC of approximately 8.4% is substantially above the French sample average (5.56%) and even above the full sample average (6.58%). This is precisely the pattern that the CFIF is designed to address.

Using the between-effects regression, the predicted WACC reduction associated with Renault's Resource Use Score of 93.4 relative to a firm with the French sample mean score of 72.26 is approximately 0.24 percentage points ($21.14 \times 0.000112 \times 100$). This is a modest reduction that clearly does not account for the full 2.84 percentage point gap between Renault's WACC and the French average. The dominant explanation for this gap, consistent with the regression results, is Renault's relatively high market Beta — the automotive sector's sensitivity to macroeconomic cycles, consumer confidence, and commodity price volatility generates high systematic risk that overwhelms the environmental efficiency signal.

9.3 Diagnosing the Gap: The CFIF Phase 1 Analysis

9.3.1 The Information Asymmetry Problem

Despite its leading resource efficiency scores, Renault's high WACC demonstrates the limits of ESG score-based signalling in isolation. The signal gap analysis reveals that Renault faces a specific version of the first information asymmetry identified in the

theoretical framework: its actual circular performance substantially exceeds what is being priced by capital markets, but the translation from operational circularity to financial risk reduction is not yet visible to the analysts and lenders who determine its cost of capital.

There are two specific dimensions to this asymmetry. The first is measurement: Renault's Refinitiv Resource Use Score of 93.4 captures its broad resource efficiency relative to peers, but it does not quantify the specific financial risk reduction associated with its Refactory operations — the reduction in raw material price exposure, the decrease in regulatory liability, and the stabilisation of supply chain cash flows that these circular activities generate. The second is communication: Renault's sustainability reporting, while comprehensive and compliant with major frameworks, does not present circular economy performance in the financial risk language that credit analysts and bond investors use when pricing risk.

9.3.2 WACC Scenario Analysis

Table 9.2 presents a WACC sensitivity analysis for Renault SA under three scenarios, directly applying the between-effects regression coefficients to Renault's current and target Resource Use Scores. This analysis operationalises the Phase 1 deliverable described in the CFIF framework.

Table 9.2

Scenario	Resource Use Score	Score Change	Predicted WACC Effect	Indicative WACC
Baseline (current)	93.4	—	Reference	~8.40%
Framework Target (33% CE)	98.0	+4.6	-0.052pp ($4.6 \times 0.000112 \times 100$)	~8.35%
Risk Scenario (regulatory)	88.0	-5.4	+0.060pp ($5.4 \times 0.000112 \times 100$)	~8.46%
Best Practice (full circular)	99.9	+6.5	-0.073pp ($6.5 \times 0.000112 \times 100$)	~8.33%

Table 9.2: Renault SA — WACC Scenario Analysis Based on Between-Effects Regression Note: WACC effects calculated using the regression coefficient $\beta = -0.000112$ on Resource Use Score. Indicative WACC is approximate and subject to all model limitations discussed in Chapter 6.

The scenario analysis reveals the core challenge for Renault's circular financial strategy: even improving the Resource Use Score from 93.4 to its maximum possible value of 99.9, an improvement that would require substantial further circular investment, generates only a 0.073 percentage point reduction in WACC based on the cross-sectional regression. This is not because circular practices are irrelevant to Renault's cost of capital, but because the current regression model captures only the observable ESG score effect, not the deeper financial risk reduction that Renault's circular operations actually generate.

The implication is that Renault must pursue the full three-phase CFIF strategy, and not just ESG score improvement, to achieve a financing cost advantage commensurate with

its circular leadership. The financial returns available from the Beta reduction pathway (Phase 3) are substantially larger than those available from the ESG score signalling pathway (Phase 2), but they require a longer timeline and more fundamental operational transformation.

9.4 Phase 1 Application: Building Renault's Circular-Financial Baseline

Renault has already completed much of the groundwork for Phase 1. Its material flow analysis is documented in its annual sustainability reports, its carbon accounting is verified by third parties, and its Refactory operations are extensively tracked. However, the Phase 1 analysis reveals two specific gaps relative to the CFIF standard.

The first gap is the absence of a financially connected baseline. Renault reports its circular metrics in physical terms: tonnes of materials recovered, percentage of recycled content, CO₂ equivalent avoided but does not translate these into the financial risk metrics that the CFIF requires: the Resource Intensity Ratio, the Beta sensitivity index, and the Green Premium Discount. The first recommendation is for Renault's treasury function to commission a financial translation of the existing sustainability metrics into these formats, working with the same investment-grade rating agency that assesses its credit risk.

The second gap is the regulatory exposure assessment. Renault's EU ETS compliance position, EU Taxonomy alignment, and CSRD reporting obligations are managed by its sustainability team but are not integrated into the WACC sensitivity analysis performed by its treasury function. Given the VECM finding that CO₂ prices are a significant error-correcting variable in the green financial market system, Renault's

exposure to EU ETS price movements, both as a direct compliance cost and as a driver of its green financing costs, should be explicitly modelled in its capital structure planning.

9.5 Phase 2 Application: Green Signaling and SLL Strategy

Renault has already issued green bonds and has sustainability-linked financing in place. However, the Phase 2 analysis suggests that the performance targets in its existing sustainability-linked instruments are not sufficiently specific to the circular economy metrics that drive the WACC relationship identified in this research. Generic ESG targets, which aggregate environmental, social, and governance performance, are less credible signals of circular financial risk reduction than operationally specific circular metrics, because they are more easily improved through social or governance changes that do not affect operational risk.

The Phase 2 recommendation for Renault is to negotiate the next refinancing of its revolving credit facility with KPIs that are explicitly anchored to the Refactory's circular performance metrics: the share of recycled materials in new vehicle production, the volume of end-of-life battery units processed, and the Resource Intensity Ratio. These metrics are operationally specific, independently verifiable through Renault's existing sustainability audit processes, and directly linked to the commodity price decoupling mechanism that the theoretical framework identifies as the primary route to Beta reduction.

The Circular Alpha calculation for the Refactory provides the internal financial validation for these SLL targets. If the Refactory's buy-back and remanufacturing operations demonstrate a positive Circular Alpha, meaning the operational savings from

recovered materials exceed the incremental processing costs, then the SLL performance targets are not merely aspirational but operationally and financially sustainable. Renault has not publicly disclosed a formal Circular Alpha calculation, but the available data on the Refactory's operations suggests this calculation would be highly favourable given the high market value of recovered battery materials and precision automotive components.

9.6 Phase 3 Application: Institutionalisation and Beta Strategy

Phase 3 is where the greatest opportunity lies for Renault. The automotive sector's high and volatile market beta, driven by consumer cyclicalities, commodity intensity, and regulatory exposure is the primary driver of Renault's elevated WACC relative to the French sample average. The Phase 3 strategy for Renault focuses on three specific interventions to reduce this Beta.

The first intervention is the expansion of circular material sourcing to reduce commodity Beta. Renault's target of 33% circular material content by 2030 directly addresses the commodity price decoupling mechanism. If achieved, this would reduce the proportion of Renault's variable cost base exposed to virgin metal and polymer price cycles like aluminium, steel, copper, lithium, cobalt by approximately one third. Using a conservative estimate that each percentage point of circular material substitution reduces Renault's commodity Beta by 0.5%, achieving the 33% target would reduce the commodity component of Renault's Beta by approximately 0.165 units. At the CAPM-implied return premium of approximately 4.4% per unit of Beta (the regression coefficient of 0.044159 applied at the market risk premium), this Beta reduction would translate into a 0.73

percentage point reduction in WACC — substantially larger than the ESG score signalling effect of 0.073 percentage points.

The second intervention is the adoption of CLBs for the next tranche of long-term debt financing. Renault's existing green bond programme should be evolved toward circularity-linked bonds with coupon ratchets tied specifically to the 33% circular material target and the Resource Intensity Ratio. The timing of CLB issuance should be informed by the VECM findings: the optimal window is a period of declining or stable Treasury yields, when the negative ECT coefficient for Clean Energy (-0.118) indicates that green financial asset prices are normalising upward rather than being suppressed by monetary tightening.

The third intervention is governance integration through the LTIP. Renault's executive compensation structure should incorporate the firm's Circular Maturity Score and Beta trajectory as co-equal indicators alongside traditional financial metrics. The CFIF recommendation is that at least 15% of long-term executive compensation be tied to measurable progress toward the 33% circular material target, with annual disclosure of the target-vs-actual progress in the integrated Annual Report. This governance signal, combined with the credibility of the Refactory's operational record, should over time shift institutional investor perceptions of Renault from a cyclically exposed automotive OEM to a circular economy pioneer with structurally lower commodity risk, a repositioning that the theoretical framework predicts would reduce its required return.

9.7 Summary: Renault and the CFIF

The Renault case study illustrates both the promise and the current limitations of circular economy practices as a capital cost management strategy. Renault has achieved resource efficiency performance that places it in the top 3% of the 475-firm panel sample, yet its WACC significantly exceeds the French sample average. The root cause is not insufficient circular performance but insufficient translation of that performance into financial risk language, combined with the dominant effect of automotive sector Beta that overwhelms the current ESG score signalling pathway.

The CFIF analysis for Renault generates three specific, sequenced recommendations. In Phase 1, commission a Circular-Financial Baseline Report that translates Refactory performance metrics into the Resource Intensity Ratio, Beta sensitivity index, and Green Premium Discount, and integrates these into treasury's WACC sensitivity modelling. In Phase 2, refinance the revolving credit facility with operationally specific circular KPIs anchored to the Refactory's metrics, calculate the Circular Alpha, and establish the Shadow WACC as an internal capital allocation benchmark. In Phase 3, scale the Refactory model toward the 33% circular material target using the Beta reduction pathway as the primary financial rationale, issue CLBs timed to the interest rate cycle, and integrate the Circular Maturity Score into the LTIP.

The expected cumulative WACC impact of full CFIF execution, combining the ESG signalling effect (0.073pp from score improvement), the Beta reduction effect (estimated 0.73pp from 33% circular material target), and the green financing premium (approximately 0.05pp from SLL margin ratchet), is approximately 0.85 percentage points. For a company with Renault's capital base, this represents a substantial and sustainable

reduction in annual financing costs, demonstrating that circular economy strategy and financial optimisation are, over the medium term, not merely compatible but mutually reinforcing.

CHAPTER X: CONCLUSION

10.1 Overview

This thesis set out to answer a single question of practical and theoretical importance: does the adoption of circular economy practices reduce the cost of capital for European firms, and if so, through what mechanisms and with what magnitude? The research pursued this question at two complementary levels, combining a between-effects panel regression estimated on 475 firms across France, Germany, and the United Kingdom with a Vector Error Correction Model of green financial asset prices over the period July 2014 to October 2025. This concluding chapter synthesises the principal findings against each research question, states the contributions to knowledge, acknowledges the limitations of the analysis, and identifies priorities for future research.

10.2 Principal Findings

Research Question 1 — answered affirmatively. Resource efficiency is a statistically significant but economically modest determinant of WACC.

The Resource Use Score carries a negative and significant coefficient of -0.000112 ($t = -3.560$, $p < 0.001$) in the between-effects panel regression, providing support for H1. Firms in the top quartile of resource efficiency face a mean WACC of 6.66%, compared to 7.73% for firms in the bottom quartile, a difference of 1.07 percentage points. The Waste Recycling Ratio, by contrast, exerts no significant effect ($p = 0.729$), confirming H2 and indicating that capital markets distinguish between broad, composite efficiency metrics and narrower output-oriented measures of environmental performance.

Research Question 2 — the magnitude question. The effect of circular practices is dwarfed by conventional financial risk determinants.

A one-standard-deviation improvement in the Resource Use Score reduces WACC by approximately 0.24 percentage points, while a one-standard-deviation increase in market Beta raises it by approximately 1.90 percentage points, confirming H3. This eight-to-one ratio is the single most important quantitative finding of the thesis. It implies that the primary financial rationale for circular economy investment is not ESG score signalling to capital markets but structural Beta reduction through commodity price decoupling. The Hausman sign reversal, whereby the within-firm fixed-effects coefficient is positive (+0.000180) while the between-firm between-effects coefficient is negative (−0.000112), further indicates that markets price persistent structural efficiency rather than year-on-year marginal improvements, consistent with information asymmetry being the binding constraint on the ESG-WACC transmission mechanism.

Research Question 3 — answered by the VECM. Green financial assets share long-run equilibrium relationships, but do not insulate investors from rate cycles.

The Johansen cointegration tests confirm two cointegrating vectors among the four macro-financial variables (Trace statistic for $r=0$: 83.71, exceeding the 5% critical value of 62.99), supporting H4. Treasury yields are the dominant exogenous driver of the system: a one-standard-deviation shock to yields reduces green bond prices persistently over a 100-day horizon, with the error correction term for the green bond equation insignificant, meaning the market does not self-correct following rate shocks. Clean energy equities and CO₂ prices do partially adjust, consistent with their more operationally grounded valuations. This finding has direct relevance for the financing strategy of circular firms: fixed-rate green bonds expose issuers and investors to persistent duration risk, making sustainability-linked loans with variable margin ratchets a structurally more resilient instrument during monetary tightening cycles.

Research Question 4 — answered by the CFIF. Circular economy strategy can be systematically translated into financing cost advantages through a structured three-phase approach.

The Circular-Financial Integration Framework responds directly to the gap between statistical significance and practical irrelevance implied by the modest ESG signalling effect. By sequencing firms through resource and risk auditing, closed-loop piloting with sustainability-linked loan negotiation, and full-scale institutional integration, the CFIF creates a pathway through which the Beta reduction mechanism, with an estimated cumulative WACC impact of approximately 0.85 percentage points for a firm achieving full implementation, can be realised alongside the incremental ESG signalling benefit. The Renault case study demonstrates that even firms with exemplary circular credentials, sitting in the top 3% of the 475-firm panel on the Resource Use Score, face a WACC gap relative to sector peers that is attributable primarily to automotive Beta, not to insufficient environmental performance. This finding generalises beyond Renault: for capital-intensive manufacturers in cyclical sectors, the circular economy is first and foremost a risk management strategy, and only secondarily a green signalling strategy.

10.3 Contributions to Knowledge

This thesis makes four contributions to the academic and practitioner literatures. First, it provides large-sample, cross-country evidence that circular economy indicators, specifically the Resource Use Score, are priced in the cost of capital of European manufacturing firms, extending the ESG-WACC literature from composite sustainability indices to operationally specific circular economy metrics. Second, the interpretation of the FE-BE sign reversal as evidence of persistent structural pricing rather than dynamic repricing advances understanding of how capital markets process environmental information and has implications for both disclosure policy and investment strategy. Third, the VECM establishes the long-run cointegrating structure of the green financial asset system and demonstrates the dominant exogeneity of Treasury yields in that system, a finding with direct implications for the interest rate risk management of green bond portfolios. Fourth, the CFIF provides a practitioner-facing bridge between empirical evidence and operational strategy that is grounded in actual regression coefficients rather than generic sustainability guidance.

10.4 Limitations

Three limitations should inform the interpretation of these findings. The between-effects estimator cannot establish causality: unobserved firm characteristics such as management quality may simultaneously drive both resource efficiency and WACC, creating upward bias in the estimated coefficient. Future research employing instrumental variable methods or natural experiments exploiting regulatory discontinuities could provide cleaner causal identification. The VECM analysis, while extended in this research to October 2025, is sensitive to the structural shifts of the 2020–2023 period, and the cointegration relationships identified should be interpreted as holding over the full sample rather than as stable structural parameters. Finally, the reliance on Refinitiv ESG scores introduces measurement error given the well-documented divergence across commercial ESG data providers; replication using alternative score providers or hand-collected operational data would strengthen the robustness of the panel results.

10.5 Directions for Future Research

Three research priorities emerge directly from the limitations and findings of this thesis. First, causal identification of the circular economy-WACC relationship using difference-in-differences designs exploiting the staggered introduction of mandatory EU CSRD disclosure requirements from 2024 onwards would address the endogeneity concern and provide policy-relevant evidence on the financial returns to mandated transparency. Second, extension of the VECM analysis to incorporate the post-2023 normalisation of interest rates, the scaling of the European green bond market following the EU Green Bond Standard, and the post-reform EU ETS price dynamics would update the macro-financial findings for the current investment environment. Third, firm-level VECM or panel VAR analysis linking individual firm Beta trajectories to circular economy investment intensity would provide direct evidence on the Beta reduction mechanism that this thesis identifies as the primary financial channel but does not empirically test at the firm level.

10.6 Closing Remarks

The central finding of this research is that circular economy practices and financial optimisation are complementary over the medium term, but the pathway to financial benefit runs primarily through risk reduction rather than reputation. The magnitude of the ESG signalling effect, while statistically real, is too small to justify circular investment on financing cost grounds alone. The Beta reduction effect, by contrast, is of economically meaningful scale and is directly controllable through the commodity decoupling strategies that advanced circular operations enable. For executives, this implies a reordering of priorities: build the operational case for circularity first, measure the financial risk reduction second, and signal to capital markets third. The CFIF provides a structured route through this sequence. For policymakers, it implies that mandatory, standardised disclosure requirements have genuine value in reducing the information asymmetry that currently suppresses the ESG-WACC transmission mechanism. For researchers, it identifies Beta reduction as the under-studied but financially dominant channel linking environmental strategy to capital structure outcomes.

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