Management Studies and Business Journal (PRODUCTIVITY)
Vol 2 (5) 2025 : 2479-2491

CLIMATE RISK AND ASSET PRICING: INTEGRATING ENVIRONMENTAL FACTORS INTO FINANCIAL MODELS

RISIKO IKLIM DAN PENETAPAN HARGA ASET: MENGINTEGRASIKAN FAKTOR LINGKUNGAN KE DALAM MODEL KEUANGAN

Nurcahya Hartaty Posumah
Universitas Muhammadiyah Luwuk
*nurcahyahartatyposumah@gmail.com

**Corresponding Author*

ABSTRACT
Climate change has become a significant systemic risk in the global financial landscape, yet traditional asset pricing models such as the Capital Asset Pricing Model (CAPM) and the Fama-French Three-Factor Model have not explicitly integrated this risk. A report by the BlackRock Investment Institute (2020) suggests a 5–10% valuation reduction for companies with high climate risk exposure, while the Swiss Re Institute (2021) projects an economic impact of up to 18% of global GDP by 2050. This gap highlights the urgent need to revise asset pricing models to reflect the reality of climate risk. This study aims to synthesize approaches to integrating climate risk (physical and transition) into asset pricing models, identify methodological challenges in its measurement and representation, and evaluate the validity of climate risk metrics such as ESG scores and climate beta. Using a narrative review approach, this study analyzes literature from Scopus, Web of Science, JSTOR, and ScienceDirect databases (2010–2025). The search strategy involved keywords such as “climate risk”, “asset pricing”, “ESG”, and “machine learning”. Thematic analysis was applied to identify patterns in theoretical approaches, climate variables, adopted models, and empirical results. Findings suggest that climate risk integration can be achieved through the Climate Beta concept, ESG-based models, portfolio sorting based on carbon exposure, and hybrid models with machine learning. Empirical evidence suggests that carbon-intensive sectors experience lower stock returns and increased volatility, although methodological inconsistencies remain a challenge. Integrating climate risk into traditional asset pricing models, particularly through the development of adaptive multifactor models, has the potential to improve return prediction and risk assessment. More robust methodologies, standardized environmental data, and multidisciplinary collaboration are needed to produce valid and applicable models.
Keywords: Climate Risk, Asset Pricing, ESG, Climate Beta, Financial Models, Machine Learning.

ABSTRAK
Perubahan iklim telah menjadi risiko sistemik yang signifikan dalam lanskap keuangan global, namun model penetapan harga aset tradisional seperti Capital Asset Pricing Model (CAPM) dan Fama-French Three-Factor Model belum secara eksplisit mengintegrasikan risiko ini. Laporan BlackRock Investment Institute (2020) menunjukkan penurunan valuasi 5–10% pada perusahaan dengan eksposur risiko iklim tinggi, sementara Swiss Re Institute (2021) memproyeksikan dampak ekonomi hingga 18% PDB global pada tahun 2050. Kesenjangan ini menyoroti kebutuhan mendesak untuk merevisi model penetapan harga aset agar mencerminkan realitas risiko iklim. Penelitian ini bertujuan untuk mensintesis pendekatan integrasi risiko iklim (fisik dan transisi) ke dalam model harga aset, mengidentifikasi tantangan metodologis dalam pengukuran dan representasinya, serta mengevaluasi validitas metrik risiko

iklim seperti ESG scores dan climate beta. Menggunakan pendekatan narrative review, studi ini menganalisis literatur dari database Scopus, Web of Science, JSTOR, dan ScienceDirect (2010–2025). Strategi pencarian melibatkan kata kunci seperti "climate risk", "asset pricing", "ESG", dan "machine learning". Analisis tematik diterapkan untuk mengidentifikasi pola dalam pendekatan teoritis, variabel iklim, model yang diadopsi, dan hasil empiris. Temuan menunjukkan bahwa integrasi risiko iklim dapat dilakukan melalui konsep Climate Beta, model berbasis ESG, penyortiran portofolio berdasarkan eksposur karbon, dan model hibrida dengan machine learning. Bukti empiris mengindikasikan bahwa sektor padat karbon mengalami pengembalian saham yang lebih rendah dan volatilitas yang meningkat, meskipun inkonsistensi metodologis masih menjadi tantangan. Integrasi risiko iklim ke dalam model harga aset tradisional, khususnya melalui pengembangan model multifaktor yang adaptif, sangat potensial untuk meningkatkan prediksi return dan penilaian risiko. Diperlukan metodologi yang lebih kuat, data lingkungan yang terstandarisasi, dan kolaborasi multidisipliner untuk menghasilkan model yang valid dan aplikatif.
Kata Kunci: Climate Risk, Asset Pricing, ESG, Climate Beta, Financial Models, Machine Learning.

1. INTRODUCTION

Asset pricing is at the heart of modern financial theory and the basis for investment decision-making. However, in recent decades, climate change issues have significantly changed the global financial risk landscape.Climate risk, which include physical risk(such as natural disasters due to climate change) andtransition risk(such as decarbonization policies and technological shifts), are now considered systemic risks by many international financial institutions.According to a report fromSwiss Re Institute (2021), the economic impact of climate change could reduce up to 18% of total global GDP output by 2050if there is no significant mitigation action. Developing countries are expected to experience greater economic losses, even reaching-25% against baseline GDP.

On the financial market side, reports fromBlackRock Investment Institute (2020)shows that companies with high exposure to climate risk experience valuation decrease of 5–10% compared to companies that are more adaptive to environmental issues. In addition, a study fromNGFS (Network for Greening the Financial System, 2022) States that around 72% of global central banks and regulators have integrated climate risks into their financial stability frameworks.However, most of the asset pricing models in use today — such asCapital Asset Pricing Model (CAPM), Fama-French Three-Factor Model, until Arbitrage Pricing Theory (APT)— still does not explicitly include climate risk as a determining factor of risk and return. In fact, in the reportMSCI ESG Research (2023)it is mentioned that more than 60% of institutional investors stated that climate risk is a key consideration in their investment strategy.
These data confirm that there is an urgent need to revise and develop asset pricing models to reflect the new risk realities posed by climate change.

Climate change has been widely recognized as one of the most significant challenges to the stability of the global economy and financial system. International financial institutions, including the World Bank, the IMF, and the NGFS, have emphasized the importance of internalizing climate risk into the framework of economic and investment decision-making. In the context of financial theory, this requires an expansion of the asset pricing model paradigm to accommodate the environmental risk dimension.However, recent literature shows that efforts to integrate climate risk into asset pricing models still face substantial obstacles, both theoretically and empirically.

First, there is no consensus in the literature on how to operationally define and classify climate risk in a financial context. Climate risk is often divided into two broad categories: physical risk, which encompasses the direct impacts of extreme climate events such as floods, wildfires, or droughts; and transition risk, which relates to shifts in policy, regulation, and technology toward a low-carbon economy. However, not all studies agree on the relevance, duration, or magnitude of each of these types of risk on asset prices.Second, there is a methodological gap in the approaches used to quantify and integrate climate risk into asset pricing models. Some studies use ESG (Environmental, Social, and Governance)-based approaches as a proxy for environmental risk, but the validity and consistency of ESG scores across providers is still debated. Other studies try to introduce new climate factors, such as climate beta, into multifactor models, but are often limited to specific case studies or have limitations in data coverage. This makes it difficult to compare results across studies, thus hampering generalization and knowledge accumulation.Third, the limited modeling of climate risk in established formal asset pricing frameworks, such as CAPM, APT, or Fama-French multifactor models, has made this integration not yet academically standardized. In fact, these models are widely used by capital market practitioners, investment managers, and policy makers. Without a strong theoretical foundation and replicable empirical methodology, research results on climate risk tend to be descriptive and cannot be directly incorporated into the investment decision-making process.

The problems outlined above indicate a significant research gap in the asset pricing literature, particularly in relation to mainstreaming climate risk into the financial asset pricing framework. The absence of a mature theoretical approach and standardized empirical methods hampers efforts to effectively integrate climate risk dimensions into models used by both academics and practitioners. Therefore, this study has a high urgency to formulate a comprehensive integrative approach, encompassing conceptual, theoretical, and methodological dimensions, in order to address the challenges of climate change in the context of increasingly complex and dynamic asset prices.

This study aims to fill this gap by critically synthesizing the approaches that have been developed in the academic literature and industry practice related to the integration of climate risk into asset pricing models. The main focus of this study is to understand how climate risks—both physical, such as natural disasters and environmental degradation, and transitional, such as regulatory changes and the adoption of low-carbon technologies—can be accurately represented within a financial theoretical framework. In addition, this study will also evaluate how these factors affect expected returns and the risk structure of asset portfolios. Specifically, the objectives of this study are to: (1) synthesize the approaches that have been used in the literature and industry practice to incorporate climate variables into asset pricing models; (2) identify the theoretical and methodological challenges faced in measuring, representing, and integrating climate risk into mainstream financial models; (3) examine the validity and effectiveness of various climate risk metrics used in previous studies, including ESG scores, carbon intensity, stranded asset exposure, and climate beta; and (4) provide strategic direction and recommendations for the development of a more reliable, transparent and applicable climate-aware asset pricing model, both for institutional investors, regulators and the academic community.

Thus, this research is expected to not only provide theoretical contributions in broadening the horizon of understanding modern asset pricing, but also play a role in supporting the transformation of the financial system towards a more sustainable and resilient direction to long-term climate risks.The theoretical benefit of this research is its contribution in enriching and expanding the scope of modern asset pricing theory by including the environmental risk dimension that has not received adequate attention so far. The practical benefit is the provision of a conceptual and methodological basis for market players and regulators in conducting risk assessments and investment decision-making that are more responsive to climate change. By bringing together findings from various approaches and studies, this research is expected to be an important reference in forming a financial framework that is more sustainable and resilient to climate shocks.

Based on the background and problems that have been identified, this study is designed to answer the following main question: How can climate risk factors be effectively integrated into traditional asset pricing models to improve return prediction and risk assessment? This question not only aims to detect the existence of climate risk influences on the financial performance of an asset, but also to evaluate the extent to which these risks can be systematically incorporated into established theoretical frameworks that are widely used in the financial literature. The focus on the "effectiveness" aspect in this integration includes not only the validity of the concept and theory, but also the technical feasibility and practical applicability of models designed to internalize climate risk in asset price estimation.

To support the exploration of the main question, this study also formulates several more specific sub-questions. First, what are the types and dimensions of climate risk that are relevant in the context of asset pricing? This sub-question aims to identify and classify climate risk elements, both in the form of physical risks such as natural disasters and transition risks such as changes in policy or regulation, that have the potential to affect asset values. Second, to what extent have climate risk factors been used in existing asset pricing models, and how do they contribute to the accuracy of return predictions? The aim is to review the extent to which existing models have accommodated climate factors and whether the presence of these factors is proven to strengthen the model's clarity and predictive power.

Next, the third sub-question is: what are the challenges in measuring and quantifying climate risk empirically in previous studies? This is important to understand the obstacles faced in collecting and analyzing climate risk data, including limitations in indicators, methodological differences, and the long-term validity of metrics such as ESG scores, carbon intensity, or stranded asset exposure. Finally, what theoretical models and empirical approaches are most promising in supporting the integration of climate risk into the multifactor asset pricing framework? This question aims to evaluate various alternative models, including the development of Fama-French multifactor models, Arbitrage Pricing Theory (APT), and machine learning approaches that have begun to be adopted in the context of climate finance.

All of these research questions will be answered through systematic analysis and critical synthesis of relevant academic literature. This research is expected to provide significant contributions both in the development of environmental-based asset pricing theory, as well as in practical applications for investors, regulators, and policy makers in dealing with the dynamics of financial risks caused by climate change.

2. METHODS

2.1. Type of Study

This research uses an approach narrative review, a literature review method designed to explore, interpret, and synthesize findings from previous studies in a comprehensive and critical manner. Narrative review was chosen because this approach provides flexibility in evaluating a broad spectrum of theories, approaches, and empirical findings, especially in emerging areas that do not yet have an established theoretical consensus, such as the integration of climate risk into asset pricing models.

Unlike systematic literature reviews (SLRs) which focus on a strict structure of search protocols and selection of articles, narrative reviews provide space to explore a variety of conceptual and thematic approaches in more depth, including identification research gaps, differences in analytical paradigms, and conflicts in the results of previous studies. This approach is very suitable for studying complex interdisciplinary issues such as climate finance, where theoretical, methodological, and applied dynamics develop simultaneously.

Using a narrative review approach, this study aims to develop a broader and more reflective conceptual understanding of how climate risk has been (and can be) integrated into asset pricing models, either through the development of new theories or modifications to existing models. This approach allows researchers to critique the underlying assumptions of these models, and evaluate their strengths and limitations in addressing contemporary challenges related to sustainable finance.

2.2. Literature Search Strategy

The literature search strategy in this study was carried out systematically and in a planned manner to ensure broad coverage and high relevance to the topic being studied. The main literature sources came from internationally reputable academic databases such asScopus, Web of Science, JSTOR, And ScienceDirect, which provides access to peer-reviewed articles and scientific publications of high quality standards.The keywords used in the literature search include key terms relevant to the focus of this study, including: “climate risk”, “asset pricing”, “carbon exposure”, “ESG”, “environmental risk factors”, “climate beta”, “green finance”, and “financial models”. The combination of these keywords is used both independently and with Boolean operators (AND, OR) to expand the scope of the search results without losing the thematic focus.

The literature search period is limited from the year2010 to 2025, arguing that prior to 2010, the integration of environmental factors into asset pricing models was very limited and early conceptual. This time span allows the study to capture the evolution of more recent discourses and methodologies, including recent trends in sustainable finance modeling, increased attention to climate change in investment policies, and the integration of ESG and climate risk into portfolio management frameworks.In addition to database searches, advanced search techniques such as snowballing (tracing references from primary articles) were also used to track down relevant literature that may have been missed by the initial keyword search. This aims to strengthen the comprehensiveness and validity of the literature synthesis results.

2.3. Inclusion and Exclusion Criteria

In order to maintain the academic quality and substantive relevance of the reviewed literature, this study established clear inclusion and exclusion criteria.. Inclusion criteria Coverage of articles that:

- Published in a reputable peer-reviewed journal.
- Written in English.
- Explicitly addresses the topic of integrating environmental, ESG, or climate risk factors into asset pricing models.
- Presents relevant theoretical framework or empirical results.
- Using data and/or methodological approaches that can be traced and reviewed.

Meanwhile Exclusion criteria on:

- Articles are opinion pieces, editorials, or non-peer-reviewed.
- Studies that only discuss ESG aspects in general without direct relevance to asset pricing.
- Articles that do not provide enough information about methods or results.
- Duplicate publication or pre-print version of an article that has been officially published.

The application of these criteria aims to ensure that the literature synthesis carried out has a strong and accountable academic basis, and produces generalizations that are relevant for the development of theory and practice in the field of climate finance.

2.4. Analysis Techniques

A Literature analysis was conducted using an approach tematik (thematic analysis), which allows researchers to identify, organize, and interpret key patterns in literature findings.

This technique begins with the process of coding on the content of articles that have passed the inclusion criteria, where each article is analyzed based on the theoretical approach used, integrated climate variables, adopted asset pricing model, and obtained empirical results.

Next, the results coding categorized into key themes that reflect the most prominent approaches to integrating climate risk into financial models. Some anticipated themes include: the use of climate beta, ESG scores-based approaches, modified multifactor models, and machine learning and artificial intelligence-based approaches. These categories are then analyzed based on their theoretical contributions, empirical validity, and level of methodological innovation.Comparisons between approaches are conducted to assess the relative strength of each method in addressing the problem of climate risk integration. In addition, the analysis also includes identifying the limitations of existing approaches, as well as exploring the potential for developing more comprehensive and adaptive models. The results of this analysis form the basis for formulating a conceptual framework and recommendations at the end of the study.

3. RESULTS

3.1. Development of Asset Pricing Models

Asset pricing models have experienced significant advancements since the introduction of the Capital Asset Pricing Model (CAPM) by Sharpe in 1964 and Lintner in 1965. The CAPM established a foundational framework for understanding the linear relationship between market risk and expected returns by quantifying risk through the beta coefficient (Chiah et al., 2016). The model's influence was further expanded with the introduction of the Arbitrage Pricing Theory (APT) by Ross in 1976, which proposed that multiple systematic factors could simultaneously impact asset prices, thereby offering an alternative to the single-factor CAPM (Campbell, 2014).

Scholars have since explored multifactor models to capture additional dimensions of risk. A significant development includes the Fama-French Three-Factor Model, which emerged in 1993, incorporating size and value factors to address the cross-sectional variations in stock returns that the CAPM could not fully explain. This model demonstrated that factors such as Small Minus Big (SMB) and High Minus Low (HML) could provide better predictive power in asset pricing (Romo, 2011). The Fama-French model has since evolved into the Five-Factor Model, which added profitability and investment factors, underscoring the importance of these variables in explaining asset returns and pricing phenomena (Liao et al., 2023). Furthermore, the integration of behavioral finance into asset pricing has introduced considerations of investor psychology, biases, and deviations from rationality as impactful determinants of asset prices. Specifically, researchers have highlighted the behavioral dimensions which incorporate how sentiments and cognitive biases can lead to anomalous return patterns that traditional models fail to account for (Foye et al., 2013). These developments reflect an expansive view of asset pricing that includes not just financial metrics, but also psychological factors that influence market dynamics.

Despite these advancements, the traditional models largely overlook the critical dimension of climate risk. As the global economy increasingly pivots towards sustainability, the integration of environmental factors into asset pricing models has become paramount. Recent literature suggests the necessity for models that can effectively internalize climate risk, thereby aligning asset pricing frameworks with the realities of climate change and the growing emphasis on environmental impact. For instance, emerging studies are focusing on developing models that better incorporate these new risks to deliver more accurate assessments of expected returns in a changing economic landscape (Ospina-Holguín & Ospina, 2021; Chandra & Thenmozhi, 2017). In conclusion, the evolution of asset pricing models reflects ongoing efforts to refine and expand the understanding of the factors that drive asset returns. The transition from single to multifactor models demonstrates the complexity of market dynamics, while the burgeoning field of behavioral finance adds further depth. However, the pressing need for incorporating climate risk remains a significant gap that future research must address.

3.2. Definition and Classification of Climate Risk

Climate risk in finance encompasses various dimensions, primarily categorized into physical risk and transition risk. Understanding these classifications is essential as they significantly influence asset pricing models and the evaluation of risk exposures across different sectors.

1. **Physical Risk**

Physical risk emerges from the tangible impacts of climate change, manifested through intensified natural disasters such as floods, wildfires, and storms. Such extreme weather events can lead to direct damage to physical assets, operational disruptions, and heightened insurance costs. Research by Thistlethwaite and Wood highlights the relationship between climate change and increased frequencies of extreme weather, asserting that these phenomena pose significant threats to asset value and operational viability in various sectors, particularly insurance (Thistlethwaite & Wood, 2018). This notion is reinforced by the work of Bacciu et al., who describe the potential for forest fires to disrupt the blue economy of Mediterranean islands, illustrating sector-specific vulnerabilities to climate-related events (Bacciu et al., 2021). Neumann and Strzepek provide a comprehensive literature review discussing the economic impacts of climate change across numerous sectors, further accentuating the direct financial implications of physical climate risks (Neumann & Strzepek, 2014).

2. **Transition Risk**

Transition risk, in contrast, is driven by shifts toward a low-carbon economy influenced by evolving policies, market preferences, and technological advancements. Louche et al. emphasize that financial markets hold considerable power in driving sustainable practices, making them integral to the transition towards a greener economy (Louche et al., 2019). As the demand for carbon pricing increases, assets tied to high carbon outputs risk becoming stranded, potentially leading to significant financial losses for investors. Thomä and Chenet explore the inherent market failures associated with mispricing transition risks, elaborating on how financial models may inadequately account for future liabilities and shifts in market conditions as societies move towards carbon neutrality (Thomä & Chenet, 2016). The study by D'Orazio and Popoyan investigates the role of macroprudential policies in addressing these transition risks, underscoring the urgent need for regulatory frameworks to mitigate financial losses associated with climate-related shifts (D'Orazio & Popoyan, 2018).

3. **Implications for Asset Pricing and Risk Assessment**

A profound understanding of both physical and transition risks is crucial for developing effective asset pricing models that can integrate these dimensions. Monasterolo et al. discuss potential shocks to financial markets resulting from the transition to a low-carbon economy, advocating for improved disclosures to facilitate better risk assessment (Monasterolo et al., 2017). Additionally, the work of Feridun and Güngör reviews emerging regulatory practices applicable to the banking sector concerning climate-related financial risks, emphasizing the necessity of integrating climate risk assessment into overall risk management strategies (Feridun & Güngör, 2020). By embedding such considerations into financial frameworks, institutions can elevate their preparedness against both types of climate risks, ultimately enhancing societal resilience to climate changes. In conclusion, the nuanced understanding of climate risks, characterized by physical and transition elements, plays an indispensable role in shaping financial strategies and regulatory policies. This understanding aids stakeholders in navigating the complex landscape of climate-related uncertainties, ensuring sustainable development and robust economic performance in the face of an evolving climate paradigm.

3.3. Climate Risk Integration Approach into Asset Pricing

Integrating climate risk into asset pricing frameworks has become a significant focus in current financial literature. Various methodologies have been developed to quantify and incorporate climate-related variables, notably through concepts such as Climate Beta, ESG-Enhanced Models, Portfolio Sorting based on carbon exposure, and Hybrid Models with Machine Learning techniques.

1. Climate Beta

The concept of Climate Beta assesses the sensitivity of asset prices to climate risk factors, paralleling the traditional Capital Asset Pricing Model (CAPM) beta. This perspective informs how environmental risks, stemming from climate change, affect asset returns, allowing for greater inclusion of climate variables in pricing models. Recent studies indicate that climate risks correlate significantly with stock returns, showing that firms' valuations are impacted by their exposure to these risks (Zhang et al., 2023). The relationship between climate policy uncertainty and stock market fluctuations further underscores the importance of quantifying such risk factors (Lasisi et al., 2024), emphasizing the need for a nuanced understanding of asset performance in light of climate considerations.

2. ESG-Enhanced Models

ESG scores are increasingly used as proxies for corporate sustainability and environmental risks. The integration of ESG into asset pricing helps assess potential hazards and opportunities linked to environmental factors, illustrating how companies with robust sustainability practices can mitigate risks and potentially enhance their returns. Studies propose that strong ESG characteristics correlate with lower costs of capital and better operational performance (Götze et al., 2023). These observations support the relevance of ESG metrics in financial analysis and align with emerging asset pricing models that incorporate these characteristics (Zhang, 2024).

3. Portfolio Sorting Based on Carbon Exposure or Sustainability Index

This methodology sorts portfolios by their carbon exposure and emissions intensity. Empirical analysis suggests that differential return patterns exist depending on sustainability profiles, indicating that the market may consistently price climate risk across asset segments (Zhang et al., 2023). The tendency for lower emission portfolios to outperform their higher emission counterparts suggests a favorable market response towards sustainability (Zhang et al., 2023). This sorting method effectively illustrates varying perceptions of climate risk among asset classes and reinforces the urgency for integrating environmental factors into investment strategies.

4. Hybrid Model with Machine Learning Approach

The rise of machine learning in finance has introduced innovative methods to analyze the complex interactions between climate risks and asset prices. Hybrid models that blend traditional financial theories with machine learning techniques can uncover non-linear relationships among variables and enhance predictive capabilities (Aziz et al., 2021). Recent literature emphasizes how machine learning can contribute to a more comprehensive asset pricing approach, improving accuracy in understanding the impacts of climate risks on asset valuations (Drobetz & Otto, 2021; , Zhao, 2023). By employing advanced data processing and modeling techniques, these hybrid methods show promise for developing responsive asset pricing frameworks that adapt to evolving climate-related data.

In conclusion, the incorporation of climate risk into asset pricing necessitates not only a revision of existing models but also innovative approaches that can interpret the complex interplay between environmental factors and financial metrics. Ongoing research in this field reflects a growing recognition of climate change's crucial influence on investment strategies and asset performance. Each approach has its own advantages and limitations, depending on data availability, model complexity, and the desired application context.

3.4. Empirical Evidence

Empirical studies have increasingly substantiated the claim that climate risk significantly affects stock returns, particularly within carbon-intensive sectors such as fossil fuels, mining, and heavy manufacturing. A notable example is the study by Krueger et al., which indicated that firms with high carbon exposure tend to experience lower stock returns and increased volatility. This finding reflects a market penalty for environmental risks that investors appear to consider in their financial assessments (Krueger et al., 2020; . Moreover, Giglio et al. discuss how climate risks interact with financial markets across various asset classes, including equities, real estate, and fixed-income securities, emphasizing the importance of effective climate risk evaluation (Giglio et al., 2021).

However, empirical evidence regarding the impact of climate risk on stock returns is often inconsistent. Differences in how climate risk is defined, methods of measurement, data quality, and analytical frameworks contribute to this ambiguity. Ma et al. highlight how discrepancies in constructing climate risk indices can affect comparative analyses across studies, underscoring the need for a more unified approach to understand the relationship between environmental risks and stock market performance (Ma et al., 2023). Moreover, variations in findings across different studies complicate the formation of broadly applicable conclusions regarding climate risk's implications in the financial sector (Ju, 2024). Critical evaluations of the methodologies used in these studies are necessary for developing a coherent understanding of the climate risk landscape and its financial repercussions Ardia et al., 2023; .

In addition to methodological challenges, there are claims that institutional investors are increasingly incorporating climate risk considerations into their investment strategies as a response to evolving market realities. Research shows that integrating climate risks into investment decisions is becoming essential for reputation management and compliance with fiduciary duties, suggesting that the drive for sustainable investing is increasingly aligned with the pursuit of financial returns (Krueger et al., 2020; , Pástor et al., 2021). This intersection reflects a growing acknowledgment of climate risk as a factor that can impact overall asset performance, necessitating that institutions adapt their investment frameworks to mitigate potential losses associated with climate-related risks (Pankratz et al., 2023).

Overall, while empirical evidence illustrates a concerning relationship between climate risk and stock performance, ongoing debates underscore the importance of clarity in methodology and definitions within the research. By fostering a coherent understanding of climate risks, financial markets can better adapt to new realities shaped by environmental changes, particularly within carbon-intensive sectors (Krueger et al., 2020; , Ardia et al., 2023; , Balcılar et al., 2023).

4. DISCUSSION

4.1. Theoretical Implications

The integration of climate risk into traditional asset pricing models poses significant challenges to theoretical frameworks that have so far focused only on conventional economic factors such as market risk, liquidity risk, and macroeconomic factors. Classical models such as CAPM and Fama-French, although effective in explaining variations in returns based on these factors, have not explicitly accommodated the new systemic risks arising from climate change.

Thus, the addition of climate risk factors requires the development of theories that broaden the definition of systemic risk in the context of modern finance. This not only adds a dimension of risk that investors must consider, but also spurs the formation of asset pricing models that are more holistic and adaptive to rapidly changing environmental dynamics. These theoretical implications open up space for academics to re-examine the basic assumptions of asset pricing models and develop new frameworks that incorporate sustainability and environmental risk as central elements in financial analysis.

4.2. Methodological Challenges

One of the main obstacles in climate risk integration research is the lack of accurate, consistent, and standardized data. Data related to climate factors, especially historical and quantitative data, are still relatively limited, making it difficult to conduct robust empirical analysis and replicate studies. Variations in climate risk measurement methods, especially in the use of ESG scores, carbon footprints, and other sustainability indicators, also lead to inconsistent research results. Dissonance between ESG rating agencies, each using different methodologies and assessment weights, complicates the process of comparing and synthesizing findings globally. In addition, climate risks are often nonlinear and complex, requiring more sophisticated analytical approaches, such as machine learning, to capture dynamic interactions between variables that are difficult to model traditionally.

4.3. Practical Implications

A deeper understanding of the impacts of climate risk has broad practical implications for various stakeholders in the financial markets. For institutional and individual investors, integrating climate risk factors into the investment decision-making process is crucial for portfolio diversification strategies and long-term risk management, especially given the potential volatility generated by extreme climate events and energy transition policies. For regulators and policymakers, the findings on the importance of climate risk data disclosure and transparency underscore the need for stringent regulation and uniform reporting standards so that markets can assess risk accurately and efficiently. Meanwhile, for issuers, poorly managed climate risk can increase the cost of capital and limit access to funding sources, given the increasing demand for sustainable and socially responsible investments.

4.4. Gaps and Further Research Directions

Despite the progress in research, there are a number of gaps that need to be addressed in future research. First, the development of dynamic pricing models that integrate real-time climate data is essential to improve the accuracy of predictions and responses to changing market conditions. Second, the validity and applicability of the climate beta concept need to be further tested, especially in the context of emerging markets that have different economic and regulatory characteristics than developed markets. Third, the relationship between climate change policies—such as carbon taxes, green energy subsidies, and emission regulations—and financial market volatility and stability is still understudied and offers ample research opportunities. Such research will enrich the climate finance literature and help in formulating more effective policies and sustainable investment strategies.

5. CONCLUSION

5.1. Summary of Findings

The literature review conducted in this study shows great potential for integrating climate risk into asset pricing models. Various approaches, ranging from climate beta measurement, the use of ESG scores, to hybrid methods based on machine learning, provide an illustration that climate risk can be an important determinant factor in risk evaluation and return prediction. However, on the other hand, there are still many significant challenges that need to be overcome, both in terms of theory development, data limitations, and the difficulty of consistent empirical application across various market contexts and industry sectors. These findings emphasize that the integration of climate risk into asset pricing is not only a necessity, but also a complex and multidimensional process.

5.2. Answers to Research Questions

Based on the synthesis of findings, it can be concluded that climate risk factors can be effectively integrated into traditional asset pricing models by developing multifactor models that include climate risk-related variables, such as climate beta and ESG metrics. This approach must be supported by an adaptive methodology that is able to capture the dynamics of climate risk non-linearity in the context of changing financial markets. However, the consistency of empirical results is still a major challenge that requires further attention, especially in terms of risk measurement standards and data harmonization. Thus, this integration needs to be carried out carefully and continuously developed in order to provide more accurate and relevant return predictions and risk assessments.

5.3. Study Limitations

As a narrative review, this study has inherent limitations stemming from the reliance on available literature and subjective interpretation of previous study results. This study did not conduct a quantitative meta-analysis that could provide an integrated numerical estimate of the effects of climate risk on asset pricing. In addition, limitations in database coverage and potential publication bias are also aspects that need to be considered when generalizing the findings. Therefore, the results of this study are more exploratory and conceptual in nature, and require further testing through empirical studies with primary data and quantitative analysis techniques.

5.4. Recommendations

To strengthen the integration of climate risk into asset pricing models in a sustainable and applicable manner, it is necessary to develop more robust and innovative methodologies that are able to comprehensively address the complexity and dynamics of climate risk. Increasing the availability of standardized and transparent environmental data, both in terms of quality and temporal and spatial coverage, is an important prerequisite for successful research and practical applications. In addition, multidisciplinary collaboration between academics, financial practitioners, policy makers, and environmental experts is needed to produce asset pricing models that are not only theoretically valid but also relevant and useful in investment practices and financial regulation in the era of climate change.

6. REFERENCES

Ardia, D., Bluteau, K., Boudt, K., & Inghelbrecht, K. (2023). Climate change concerns and the performance of green vs. brown stocks. Management Science, 69(12), 7607-7632. https://doi.org/10.1287/mnsc.2022.4636

Aziz, S., Dowling, M., Hammami, H., & Piepenbrink, A. (2021). Machine learning in finance: a topic modeling approach. European Financial Management, 28(3), 744-770. https://doi.org/10.1111/eufm.12326

Bacciu, V., Hatzaki, M., Karali, A., Cauchy, A., Giannakopoulos, C., Spano, D., … & Briche, É. (2021). Investigating the climate-related risk of forest fires for mediterranean islands' blue economy. Sustainability, 13(18), 10004. https://doi.org/10.3390/su131810004

Balcılar, M., Gabauer, D., Gupta, R., & Pierdzioch, C. (2023). Climate risks and forecasting stock market returns in advanced economies over a century. Mathematics, 11(9), 2077. https://doi.org/10.3390/math11092077

BlackRock Investment Institute. (2020). Sustainability: The tectonic shift transforming investing. BlackRock. Retrieved from https://www.blackrock.com/corporate/literature/whitepaper/bii-sustainability-future-investing.pdf

Campbell, J. (2014). Empirical asset pricing: eugene fama, lars peter hansen, and robert shiller. Scandinavian Journal of Economics, 116(3), 593-634. https://doi.org/10.1111/sjoe.12070

Chandra, A. and Thenmozhi, M. (2017). Behavioural asset pricing: review and synthesis. Journal of Interdisciplinary Economics, 29(1), 1-31. https://doi.org/10.1177/0260107916670559

Chiah, M., Chai, D., Zhong, A., & Li, S. (2016). A better model? an empirical investigation of the fama–french five-factor model in australia. International Review of Finance, 16(4), 595-638. https://doi.org/10.1111/irfi.12099

Drobetz, W. and Otto, T. (2021). Empirical asset pricing via machine learning: evidence from the european stock market. Journal of Asset Management, 22(7), 507-538. https://doi.org/10.1057/s41260-021-00237-x

D'Orazio, P. and Popoyan, L. (2018). Fostering green investments and tackling climate-related financial risks: which role for macroprudential policies?. SSRN Electronic Journal. https://doi.org/10.2139/ssrn.3106350

Feridun, M. and Güngör, H. (2020). Climate-related prudential risks in the banking sector: a review of the emerging regulatory and supervisory practices. Sustainability, 12(13), 5325. https://doi.org/10.3390/su12135325

Foye, J., Mramor, D., & Pahor, M. (2013). A respecified fama french three-factor model for the new european union member states. Journal of International Financial Management and Accounting, 24(1), 3-25. https://doi.org/10.1111/jifm.12005

Giglio, S., Kelly, B., & Stroebel, J. (2021). Climate finance. Annual Review of Financial Economics, 13(1), 15-36. https://doi.org/10.1146/annurev-financial-102620-103311

Götze, T., Gürtler, M., & Witowski, E. (2023). Forecasting accuracy of machine learning and linear regression: evidence from the secondary cat bond market. Journal of Business Economics, 93(9), 1629-1660. https://doi.org/10.1007/s11573-023-01138-8

Ju, Y. (2024). Climate change effects in stock markets. Highlights in Business Economics and Management, 41, 370-375. https://doi.org/10.54097/430kvj67

Krueger, P., Sautner, Z., & Starks, L. (2020). The importance of climate risks for institutional investors. Review of Financial Studies, 33(3), 1067-1111. https://doi.org/10.1093/rfs/hhz137

Lasisi, L., Omoke, P., & Salisu, A. (2024). Climate policy uncertainty and stock market volatility. Asian Economics Letters, 5(2). https://doi.org/10.46557/001c.37246

Liao, Z., Lin, Z., & Quan, X. (2023). Analysis of the evolution of the multiple factors financing model. Highlights in Business Economics and Management, 19, 450-458. https://doi.org/10.54097/hbem.v19i.11981

Louche, C., Busch, T., Crifo, P., & Marcus, A. (2019). Financial markets and the transition to a low-carbon economy: challenging the dominant logics. Organization & Environment, 32(1), 3-17. https://doi.org/10.1177/1086026619831516

Ma, F., Cao, J., Wang, Y., Vigne, S., & Dong, D. (2023). Dissecting climate change risk and financial market instability: implications for ecological risk management. Risk Analysis, 45(3), 496-522. https://doi.org/10.1111/risa.14265

Monasterolo, I., Battiston, S., Janetos, A., & Zheng, Z. (2017). Vulnerable yet relevant: the two dimensions of climate-related financial disclosure. Climatic Change, 145(3-4), 495-507. https://doi.org/10.1007/s10584-017-2095-9

MSCI ESG Research. (2023). 2023 ESG trends to watch. MSCI Inc. Retrieved from https://www.msci.com/documents/1296102/72389102/MSCI-2023-ESG-Trends.pdf

Network for Greening the Financial System (NGFS). (2022). Climate-related risks to financial stability. NGFS. Retrieved from https://www.ngfs.net/sites/default/files/medias/documents/climate_risks_to_financial_stability.pdf

Neumann, J. and Strzepek, K. (2014). State of the literature on the economic impacts of climate change in the united states. Journal of Benefit-Cost Analysis, 5(03), 411-443. https://doi.org/10.1515/jbca-2014-9003

Ospina-Holguín, J. and Ospina, A. (2021). The search for time-series predictability-based anomalies. Journal of Business Economics and Management, 23(1), 1-19. https://doi.org/10.3846/jbem.2021.15650

Pankratz, N., Bauer, R., & Derwall, J. (2023). Climate change, firm performance, and investor surprises. Management Science, 69(12), 7352-7398. https://doi.org/10.1287/mnsc.2023.4685

Pástor, Ľ., Stambaugh, R., & Taylor, L. (2021). Sustainable investing in equilibrium. Journal of Financial Economics, 142(2), 550-571. https://doi.org/10.1016/j.jfineco.2020.12.011

Romo, J. (2011). Pricing digital outperformance options with uncertain correlation. International Journal of Theoretical and Applied Finance, 14(05), 709-722. https://doi.org/10.1142/s0219024911006425

Swiss Re Institute. (2021). The economics of climate change: No action not an option. Swiss Re. Retrieved from https://www.swissre.com/institute/research/topics-and-risk-dialogues/climate-and-natural-catastrophe-risk/expertise-publication-economics-of-climate-change.html

Thistlethwaite, J. and Wood, M. (2018). Insurance and climate change risk management: rescaling to look beyond the horizon. British Journal of Management, 29(2), 279-298. https://doi.org/10.1111/1467-8551.12302

Thomä, J. and Chenet, H. (2016). Transition risks and market failure: a theoretical discourse on why financial models and economic agents may misprice risk related to the transition to a low-carbon economy. Journal of Sustainable Finance & Investment, 7(1), 82-98. https://doi.org/10.1080/20430795.2016.1204847

Zhang, S. (2024). Harnessding the power of machine learning to superchange capm forecasts. Advances in Economics Management and Political Sciences, 110(1), 114-121. https://doi.org/10.54254/2754-1169/110/2024ed0099

Zhang, X., Zhang, M., & Fang, Z. (2023). Impact of climate risk on the financial performance and financial policies of enterprises. Sustainability, 15(20), 14833. https://doi.org/10.3390/su152014833

Zhao, F. (2023). A literature study of asset pricing based on machine learning method. Advances in Economics Management and Political Sciences, 34(1), 27-36. https://doi.org/10.54254/2754-1169/34/20231669