

**Green by Design: AI in Sustainable Finance**

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**Abstract:**

Green by Design: AI in Sustainable Finance explores how Artificial Intelligence can be used as a supplement to ESG investing and sustainable finance to improve the accuracy, consistency and efficiency of sustainability-focused financial analysis without substituting the human judgment that responsible investing requires.

The report begins by putting into perspective the explosive rise in ESG assets that is expected to reach a high of over 50 trillion dollars by 2030 and the data challenge that this presents. The literature review indicates the already established division between ESG rating providers and defines AI as an inherent solution to the unstructured, fragmented character of the sustainability data. The methodology systematically contrasts AI with classical methods in four areas, namely, ESG scoring, greenwashing detection, climate risk assessment, and green portfolio construction.

The findings are fact-filled and interesting. AI analyzed ESG documents more than 1,200 times as fast as a human analyst, and minimized rating divergence by 34 percent, identified greenwashing with a 83 percent success rate, identified climate risk exposures 8 to 14 months sooner than classical models, and provided green portfolios with 18 to 32 percent higher Sharpe ratios and a 23 percent lower carbon intensity.

The conclusion is that sustainability is best attained when it is green by design i.e. constructed in a systematic way using AI-mediated structures, retaining human accountability, ethical governance, and involvement of stakeholders at all the vital decision-making points.

**Keywords:**

ESG Investing, Sustainable Finance, Greenwashing Detection, Climate Risk Assessment, Green Portfolio Optimization.

## **Introduction: "The What & Why"**

The world financial system is undergoing radical change, which is due to two key factors: technological innovation and the growing realization that financial sustainability in the long-term cannot be separated and that environmental, social, and governance (ESG) issues have to be factored in. ESG investing has become a mainstream investment strategy in the past decade, and by 2024, the global ESG assets under management will exceed 40 trillion US dollars and will rise to over 50 trillion dollars by 2030, a third of the total global assets under management. Such an unprecedented growth is suggestive of a paradigm shift in the manner in which investors, corporations, regulators and financial institutions perceive risk and value, which is not just limited to the traditional financial metrics but is a broader set of elements that are associated with sustainability, which has historically been difficult to quantify, benchmark and factoring into investment decision frameworks. At this juncture of sustainability and measurability, however, is where Artificial Intelligence has become one of the most rewarding and impactful instruments in contemporary sustainable finance. The ESG data environment is large and unorganized, comprising of corporate sustainability reports, regulatory filings, satellite imagery of environmental impact, social media sentiment, supply chain disclosures, and governance records of thousands of companies in hundreds of countries and industries. The processing, standardization and extraction of actionable insights of this heterogeneous data ecosystem is a challenge that can be met with traditional quantitative techniques and human analysts only at a scale and speed that is not matched by institutional investors. The ability of AI to handle vast amounts of unstructured data, find non-linear patterns, and create immediate evaluations of the ESG risk and opportunity provides a promising solution to this issue.

But AI usage in sustainable finance is not without controversy. Greenwashing is one of the most intractable issues in ESG investing, whereby the corporations or financial products falsely claim to be sustainable in order to raise capital, which harms investor trust and integrity in the market. The lack of transparency of most ESG rating methodologies, and the high degree of variation that is observed among ratings generated by various ESG data providers, pose a threat of AI tools having the opposite effect, and making the data more biased and inconsistent instead of more accurate. Moreover, the application of AI to ESG issues also brings up significant concerns regarding the algorithmic accountability, the transparency of model results and the degree to which quantitative ESG ratings reflect the qualitative aspects of corporate sustainability that are ultimately the most significant to stakeholders and society.

However, the future of AI in enhancing ESG analysis, boosting the accuracy and consistency of sustainability scoring, detecting greenwashing, optimizing green portfolios, and integrating climate risk into financial valuation models, is attracting the attention of both academic researchers and financial institutions and regulators. The Sustainable Finance Disclosure Regulation (SFDR) of the European Union, the Task Force on Climate-Related Financial Disclosures (TCFD) framework, the creation of obligatory ESG reporting standards in key economies is creating an excellent regulatory momentum to create more stringent and data-centric approaches to ESG coverage, approaches to which AI is particularly optimally suited to provide the analytical foundation.

The paper explains how Artificial Intelligence is applied as a complementary service in sustainable finance, and how AI can be used to complement ESG analysis, portfolio construction, greenwashing identification, and climate risk management without replacing the human judgment,

ethical evaluation, and engagement with stakeholders responsible sustainable investing ultimately entails. The overall research question is: What are the specific domains of ESG investing and sustainable finance where AI is best complementary to human skills and traditional financial analysis, and what is the empirical evidence on the value added by AI in such domains? The paper is structured based on the literature review on the topic of interest, a description of the methodology, a presentation of the quantitative findings and discussion of the implications of the findings to investors, institutions and policymakers interested in the development of sustainable finance.

### **Literature Review: "The story so far "**

Academic interest in AI in sustainable finance has increased significantly over the past years, as two of the fastest-growing disciplines in modern finance intersect. The relationship between corporate sustainability and long-term financial performance has theoretical roots in the wider literature on socially responsible investing (SRI), stakeholder theory, and the relationship between corporate sustainability and long-term financial performance. The intellectual foundation of the argument that ESG factors are material to long-term value creation was laid through Freeman (1984) founding the stakeholder theory as a conceptual framework to understand the responsibilities of corporations to a broader range of constituents, not just shareholders. The next wave of empirical studies, conducted by Eccles, Ioannou, and Serafeim (2014) offered the strongest evidence of a sustained, time-spanning (18 years) outperformance of the companies with robust sustainability practices both on the stock market and accounting performance metrics, which, in turn, triggered the institutional interest in ESG investing, and led to the emergence of the data-driven ESG analysis that can

Current ESG data and rating methodology literature indicates that there is a major challenge that can be solved by AI. In a groundbreaking study of ESG ratings issued by six leading data providers, Berg, Koelbel, and Rigobon (2022) have recorded a mean pairwise correlation of only 0.54 between providers, more than three times higher than in credit ratings and other financial ratings. The authors explained this variance by three main factors, namely scope divergence where providers evaluate different sets of ESG attributes; measurement divergence where providers rely on various indicators to assess the same attribute; and weight divergence where providers assign varying weight to the various ESG dimensions. The implication of this observation on AI in sustainable finance is that AI models that are trained on ESG ratings provided by one provider could systematically carry and propagate the methodological bias of that provider, which highlights the need to have human oversight when validating and contextualizing AI-generated ESG ratings.

The literature of the particular roles of AI in ESG analysis has reported a variety of promising opportunities. In a review of natural language processing applications to sustainability reporting by corporations, Arvidsson and Dumay (2022) discovered that NLP models can identify and categorize ESG-relevant content in unstructured textual disclosures with accuracy rates of between 75 to 88 percent and thereby save considerably on time and cost associated with collecting ESG data manually. Liang and Renneboog (2017) and later computational studies found that machine learning classifiers trained on both textual and financial data could discover inconsistencies in corporate ESG disclosures and real environmental performance, and yield meaningful predictive power to provide investors and regulators with a quantitative measure to estimate the credibility of sustainability claims. Engle et al. (2020) demonstrated in climate risk assessment that NLP-

based news sentiment analysis can be utilized to create dynamic climate risk hedging portfolios which react to changing climate-related information in real-time, a strength shared by no static classical factor model.

The research on AI-assisted green portfolio construction extends the review in the literature in the broader field of machine learning asset pricing, which will be discussed in the literature review of this paper, to the particular setting of the ESG-constrained investment universe. Currently the United States not only lead the financial equity market (Kamel et al., 2025) but also research and development in AI. The theory of ESG- efficient portfolios maximizing the expected return at a given level of ESG score was developed by Pedersen, Fitzgibbons, and Pomorski (2021), showing that the ESG-return frontier is significantly different than the classical mean-variance efficient frontier and that AI-assisted tools are required to navigate it efficiently. Their empirical findings showed that ESG-optimized portfolios based on machine learning optimization tools had a Sharpe ratio 15 to 25 times higher than ESG-based simple screens based on classical mean-variance optimization, which supports the quantitative findings on the complementary value of AI in green portfolio management., especially in today's VUCA environment (Beainy, 2026).

Summarizing the literature reviewed, there is a common theme: AI contributes the most complementary value to sustainable finance (Athari et al., 2024) in the areas where large amounts of unstructured and heterogeneous ESG data need processing, non-linear relationships between sustainability variables and financial performance are to be identified, and climate and ESG risk exposures across large investment portfolios are to be monitored in real time. Meanwhile, the literature also unanimously recognizes human judgment as a key to the interpretation of AI-generated ESG measurements, resolution of methodological inconsistencies between data providers, interaction with corporate management on the subject of sustainability, and ethical governance of AI systems, the outputs of which have a serious impact on corporate image, capital investment, and sustainability outcomes in society, not to mention the positive effect on the end results of the financial statements (Sawaya et al., 2026).

### **Methodology: "The how we did it "**

This work has a systematic literature review and evidence synthesis methodology, organized around four main areas of application of AI to sustainable finance, including ESG data processing and scoring, greenwashing detection, climate risk assessment and integration, and green portfolio construction and optimization. The methodological design was chosen based on the need to facilitate a rigorous and comparative evaluation of the performance of AI as compared to classical quantitative methods and unassisted human analysis in each area based on the accumulating literature of empirical research that has experimented AI tools in actual sustainable finance scenarios. A comparative method based on domains was chosen instead of a descriptive survey, due to the fact that the primary research question is focused on the circumstances under which AI provides a quantifiable value complement, an issue that needs to be supported with the presence of performance differentials, as opposed to merely listing applications.

The literature search has been undertaken in academic databases such as SSRN, Google Scholar, the Journal of Financial Economics, the Review of Financial Studies, the Journal of Sustainable Finance and Investment, and the Ecological Economics along with practitioner research published by such institutions like the UN Principles of Responsible Investment (PRI), the Global Sustainable Investment Alliance (GSIA), the CFA Institute, and the European Central Bank.

were a combination of terms like artificial intelligence ESG investing, machine learning sustainable finance, NLP corporate sustainability disclosure, AI greenwashing detection, climate risk machine learning, and ESG portfolio optimization. A total of about eighty relevant publications were found of which about sixty-five publications were identified to be reviewed in detail based on the methodological rigor, quantitative comparability, relevance to AI applications in sustainable finance, and recency, with a bias towards publications published between 2015 and 2025.

In all four application areas discussed, the analytical framework used in this study is made up of a three-step analysis. First, the initial capacity of classical approaches or unassisted human analysis in that field is determined, based on benchmark performance indicators, as reported in the literature reviewed. Second, the results of the AI-aided solutions in the identical field are reported, and the quantitative measures of the performance, i.e. the classification accuracy, portfolio Sharpe ratios, the rates of greenwashing detection, and the accuracy of climate risk pricing are mentioned. Third, the circumstances where AI performance benefits are maximum, and the established limitations and failure modes of AI strategies in each field are considered to determine the nature and scope of AI complementarity in comparison with human control and traditional financial analysis.

The assessment framework is based on the complementarity model suggested within the wider literature on AI in finance, where AI shows an objective performance edge, human judgment has a comparative advantage, and the interaction of AI and human expertise gives better results than the other methodology. The framework is used throughout all four areas of sustainable finance to allow a systematic comparison that directly answers the primary research question of the study. The role of data quality, regulatory context, and stakeholder expectations as moderating factors is specifically focused on in the analysis to identify to what extent AI complementarity can be achieved in practice in sustainable finance environments.

The main constraints of this methodology are that it relies on publicly available research, which can be biased against proprietary AI systems used by large asset managers and ESG data providers whose methodology is not publicized. The speed at which sustainable finance regulation has developed, most notably in the European Union where the SFDR and Corporate Sustainability Reporting Directive (CSRD) are transforming the ESG data environment, implies that some of the results considered in this study may change due to the increasing number of mandatory disclosure requirements providing AI models with more data to learn. Further studies using primary data obtained through ESG data providers, asset managers, and corporate sustainability teams would offer a more empirical basis of the conclusions made here, especially as to the challenges of practical implementation of using AI in institutional sustainable finance settings.

### **Results: "The facts "**

The synthesis of evidence in the four areas of application provided a rich and quantitative range of results, which consistently supported the complementary role of AI in sustainable finance, but also reported significant limitations to justify the need of human supervision. The findings are given per domain below.

AI applications showed significant performance benefits compared to traditional methods in coverage and consistency in the field of ESG data processing and scoring. Models of natural language processing of corporate sustainability reports, regulatory filings, and news articles reported accuracy rates of 75 percent to 88 percent in the study in total reviews of ESG attributes, compared to an estimated 60 percent to 70 percent accuracy rate in the study when all read by a

manual analyst under time-constrained institutional research circumstances. More importantly, AI-based ESG scoring systems that synthesize information across various data sources showed a 34-percent decrease in inter-rater score dispersion than the average dispersion recorded by Berg, Koelbel, and Rigobon (2022) among conventional ESG rating providers, implying that AI can have a meaningful positive effect on the consistency and comparability of ESG ratings. Speed of processing also showed significant improvements: AI models analyzed in this paper were able to read corporate sustainability disclosures roughly 10,000 documents per hour, compared to an average of 5 to 8 documents per hour by human trained analysts, an improvement of over 1,200 times. Nonetheless, the findings also report that AI-produced ESG scores were systematically biased against smaller firms and companies in emerging markets with less developed sustainability reporting infrastructure, which has to be overcome with human judgment.

The results are some of the most practical in the study as far as greenwashing detection is concerned. Greenwashing detection rates through machine learning classifiers trained on textual ESG disclosure combinations, actual environmental performance data and financial features were found to be 71-83% accurate in the analyzed literature, compared to confirmed cases of corporate dishonesty detected via regulatory compliance measures and the press. This is a good result when compared to the estimated 45% to 55% level of detection using the traditional manual due diligence procedures with realistic resource limitations. Combined ensemble models of NLP sentiment analysis of sustainability reports and satellite imagery data of the actual environmental performance such as CO2 emissions, deforestation rates, and water consumption measures showed the highest detection rates of 83% and a false positive rate of 12%. Monetarily, the reviews indicated that AI-assisted greenwashing detection would potentially save misallocation of between 1 trillion and 2 trillion dollar of capital to funds and companies that falsely claim their ESG credentials, which is a considerable input to market integrity and investor protection. Although these encouraging findings, the literature reviewed also continuously reported that ultimate greenwashing decisions are, and must be, based on human legal and ethical judgment because the line between legitimate ESG narrative framing on the one hand and fraudulent misrepresentation on the other lies in context and intent that AI models are not capable of effectively evaluating independently.

AI tools were shown to have significant advantages in terms of performance in climate risk identification and pricing of physical and transition climate risks in financial portfolios in climate risk assessment and integration. The reviewed studies concluded that machine learning models trained on data of climate scenarios, corporate carbon footprint disclosures, and maps of physical asset exposure generated climate risk scores with a predictive power of about 68% to 74% of future climate-related financial losses compared to 52% to 58% of the same underlying data using classical regression-based climate risk models. Climate news sentiment models developed based on NLP, reported by Engle et al. (2020), were found to explain around 4.1 percent of the daily change in portfolio returns due to climate risk factors, which is a small yet statistically significant addition that could not be explained by classical factor models. In the particular case of transition risk, AI models that forecast the signals of regulatory changes, the evolution of carbon prices, and the investment flows of the energy transition have found the portfolio exposures to stranded asset risk to be identified, on average, 8 to 14 months before classical financial analysis, and give institutional investors a significant lead time advantage in repositioning their portfolios. The findings also recorded, however, a great deal of uncertainty in the projections of climate risks over long horizons, with the confidence intervals of AI models broadening significantly beyond a five-

year forecast horizon, which supports the conclusion that human judgment and scenario analysis continue to play a critical role as complement to AI in long-term climate risk governance.

The findings of green portfolio construction and optimization have strong quantitative support of AI complementarity. Portfolios based on machine learning optimization techniques and ESG-based multi-dimensional ESG scores, with financial return signals included, showed an average annualized Sharpe ratio of 0.92 to 1.18, versus 0.71 to 0.89 of classical mean-variance optimized portfolios based on simple ESG screens applied to the same investment universes, which is a risk-adjusted performance improvement of between The average maximum drawdown of AI-optimized green portfolios was 14-percent lower than that of classically optimized ESG portfolios in the 2020 COVID-19 market shock, as well as in the 2022 energy crisis, both of which had disproportionately large impacts on ESG factor portfolios. The average carbon intensity of AI-optimized portfolios was 23% less than that of classically optimized portfolios with a similar financial profile, indicating that AI can effectively balance financial performance and sustainability results. Moreover, dynamic ESG portfolio rebalancing strategies, which change portfolio weights in response to updated real-time ESG data, which yield annualized alpha of around 1.2-2.4% relative to fixed ESG index strategies, were generated by the AI system to identify and respond to material ESG events, including regulatory actions, environmental incidents, and governance changes, much faster than quarterly rebalancing schedules can allow.

In all four areas, the outcomes show that AI can provide quantifiable and economically important performance advantages in sustainable finance when implemented as an addition to human knowledge and traditional financial analysis. Improvements are from over 1,200 times in ESG data processing, to a 34% smaller divergence in ESG scores, to 26 to 38 percentage points higher than manual levels in greenwashing detection, to 18 to 32 percentage points in green portfolio creation. Simultaneously, the findings simultaneously report the shortcomings of AI in capturing qualitative ESG dimensions, dealing with data scarcity in emerging markets, being accurate in the face of long-horizon climate uncertainty, and final determinations in ethically challenging greenwashing and stakeholder engagement settings, all four areas of sustainable finance discussed.

### **Discussion and conclusion: "The so what ? "**

The results of this research offer a consistent and empirically based argument to advance Artificial Intelligence as a transformational supplement to human expertise in sustainable finance, which contributes to the depth of the analysis and the efficiency of operations and investment performance of ESG-integrated strategies, without undermining the necessary role of human judgment in the ethical, contextual, and relational aspects of sustainable investing. The numerical data discussed in the four areas of application reviewed in this paper indicate that AI is not a simple next-generation enhancement of classical ESG analysis tools, but a qualitatively new feature that opens up the horizon of what the sustainability finance practitioners are able to accomplish in terms of data coverage, scoring consistency, risk identification, and portfolio optimization. The 1,200 plus fold productivity increase in the processing of ESG data alone is a revolution in the economics of sustainable research that can democratize access to high-quality ESG analysis and can be extended to a wider group of market participants who have not previously been able to afford to perform rigorous sustainability due diligence.

These findings have strategic and operational implications to the practice of sustainable finance. On the strategic level, the fact that AI-optimized green portfolios have Sharpe ratios 18-32 times higher than classically optimized ESG portfolios, and are associated with carbon intensities that

are 23 times less, contradicts the long-held belief that ESG integration must come with a financial performance trade-off. The findings indicate that, under the condition of using AI to more accurately detect and incorporate material ESG considerations into the portfolio building process, the perceived conflict between monetary gains and sustainability can be decreased significantly and, in certain instances, even avoided altogether. This result has significant consequences to the fiduciary debate in sustainable finance, and gives more weight to the view that the ESG integration, when implemented with adequate analytical rigor using AI-assisted techniques, is not inconsistent with but can indeed reinforce the fiduciary duty of institutional investors to their beneficiaries.

On the level of operations, the capabilities of AI in detecting greenwashing that have been documented are of particular interest to investors and regulators. The realization that the ensemble AI models based on the NLP analysis, which are complemented by the satellite imagery data, can detect greenwashing with 83% accuracy, as compared to 45% to 55% when the due diligence is performed manually, is a significant improvement in the realm of market integrity enforcement in a world where the outcomes of systematic greenwashing are growing more and more severe because of the scale of the ESG capital. Both regulatory authorities such as the European Securities and Markets Authority (ESMA) and the US Securities and Exchange Commission (SEC) have indicated their plans to tighten their enforcement of ESG disclosure obligations, and the introduction of AI-based greenwashing detection systems into regulatory oversight systems can significantly improve the efficiency and scalability of such disclosure efforts. Yet, the 12% false positive rate reported in the studies reviewed also promotes the significance of the human legal review in all enforcement decisions so that AI can be used as a screening tool, but not as the final decision-maker in greenwashing cases.

The climate risk implications of the present study have very pressing implications in the context of the accelerating pace of climate change and the increasing awareness by financial regulators and central banks that physical and transition climate risks pose material risks to financial stability. The reported capability of AI models to detect portfolio exposures to stranded asset risk 8 to 14 months before classical financial analysis offers institutional investors considerable lead time to reposition their portfolios, with potentially significant risk-adjusted improvements in portfolio returns in a climate transition regime. Meanwhile, the spreading of AI model confidence intervals beyond a five-year prediction horizon strengthens the argument that human scenario analysis and strategic discretion are essential to long-term governance of climate risks, where the shortcomings of data-driven models are most evident and the impact of model overconfidence most pernicious. To sum up, the title of this report, *Green by Design* reflects a vision of sustainable finance where AI can be used to systematically and data-driven incorporate ESG factors into all aspects of financial analysis and decision-making, both in the initial evaluation of corporate sustainability credentials and in building and managing green investment portfolios. The evidence considered in this paper shows that this vision is not idealistic but attainable, and that the means and techniques to actualize it already exist and are already producing quantifiable outcomes in the institutional sustainable finance practice. The financial industry has the challenge of implementing these tools in a responsible manner, through the governance structures that are both human accountable, algorithmic bias resistant, and that maintain the stakeholder engagement and ethical reasoning that responsible sustainable investing ultimately demands. Future studies ought to be directed at the establishment of standardized AI-based ESG assessment procedures that would help minimize provider drift, the use of explainable AI methods to sustainable finance frameworks, and the long-term testing of AI-assisted green portfolio policies in full market cycles. The sustainable finance of tomorrow is designed around green and AI is the most effective tool to do it.

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