

## SUSTAINABLE INDUSTRIAL ENGINEERING: SYSTEMS OPTIMIZATION UNDER RESOURCE CONSTRAINTS

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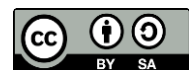
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### Abstract

The increasing pressure to integrate sustainability into industrial practices has led to the need for more efficient systems optimization models that address resource constraints. Traditional optimization models in industrial engineering have focused predominantly on maximizing efficiency and minimizing costs, often overlooking the long-term environmental and social impacts. This research explores the intersection of sustainable development and systems optimization under resource limitations, aiming to develop a comprehensive framework that balances economic, environmental, and social factors in industrial processes. The study employs a mixed-methods approach, combining literature review, case studies from various industrial sectors, and mathematical optimization models. The results demonstrate that the integration of resource constraints into industrial systems significantly improves both operational performance and sustainability outcomes. Industries, particularly in manufacturing and logistics, showed considerable improvements in production efficiency and reductions in energy consumption and material waste. The research concludes that resource-constrained optimization models can lead to more sustainable industrial practices without compromising economic efficiency. The findings provide a valuable contribution to the field of industrial engineering, offering a framework that can be applied across diverse sectors seeking to optimize their systems within the boundaries of available resources. Future studies should extend these models to include more complex industrial sectors and explore long-term sustainability impacts.

**Keywords:** Resource Constraints, Sustainable Industrial Engineering, Systems Optimization



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## INTRODUCTION

The field of Industrial Engineering (IE) has evolved considerably over the last several decades, and one of its central challenges today is the integration of sustainability principles into industrial systems. As industries strive for greater efficiency and productivity, the concurrent need to address environmental, economic, and social concerns becomes increasingly significant (Feng et al., 2025; Sifou et al., 2025). In this context, sustainable industrial engineering focuses on optimizing systems and processes while minimizing negative impacts on the environment, society, and economy. The growing concern for climate change, resource depletion, and environmental degradation has compelled engineers and practitioners to reconsider traditional optimization approaches. In turn, there is a critical demand for new frameworks that balance industrial progress with ecological responsibility (Huang et al., 2025).

Resource constraints are at the heart of this issue. Industrial systems operate within limited resources, whether in terms of energy, raw materials, or human capital. Traditional optimization models often fail to account for the broader environmental and social impacts of their recommendations, focusing primarily on economic efficiency (Kumar et al., 2025; Tsao et al., 2025). However, this narrow approach risks exacerbating unsustainable practices, ultimately leading to negative consequences for both industry and the planet. As industrial processes become increasingly complex and interconnected, it is evident that more sophisticated models and methodologies are needed to design systems that not only maximize performance but also adhere to sustainable practices (Alizadeh et al., 2025; Wang et al., 2023).

In this research, we aim to address the intersection of sustainable development and systems optimization in industrial engineering, emphasizing strategies that respect the inherent limitations of resources (Duah et al., 2025). By understanding the broader implications of resource use and applying optimization methods in a more holistic manner, the goal is to propose models that can achieve superior operational performance while contributing to sustainability goals. This research seeks to fill a significant gap in the literature by providing a detailed analysis of how resource constraints can be effectively integrated into industrial systems optimization (Bali et al., 2025).

Despite the increasing emphasis on sustainability within industrial systems, there remains a persistent gap between theory and practice in industrial engineering. While numerous studies have investigated sustainability from various perspectives, including energy consumption, waste management, and production optimization, few have adequately addressed the issue of resource constraints within the context of systems optimization (Bayat et al., 2025). Traditional approaches to optimization, which primarily focus on maximizing output or minimizing costs, often ignore the long-term impacts of resource depletion and environmental degradation. These models are insufficient for addressing the unique challenges posed by sustainable development in industrial engineering (C. Du et al., 2025; Kong et al., 2025).

The specific problem at hand is the need to develop systems optimization models that consider not only the technical and economic dimensions of industrial processes but also their environmental and societal impacts. This is particularly pertinent in industries where resource constraints, such as limited access to energy or raw materials, pose significant barriers to operational efficiency (Ahmad Iqbal & I. Almaraj, 2025; Rahman & Kabir, 2025). Addressing this problem requires an approach that is capable of balancing short-term gains with long-term sustainability objectives, which has often been overlooked in traditional industrial engineering frameworks. There is also a lack of comprehensive methodologies that integrate sustainability into the optimization process in a way that accounts for the interplay between various constraints, such as economic costs, resource availability, and environmental impact (Zhang et al., 2025).

This research will investigate how industrial systems optimization can be better aligned with sustainability goals by considering resource limitations in the decision-making process (Ouyang et al., 2025). By formulating a robust optimization framework that incorporates both

resource constraints and sustainability factors, we aim to address a critical gap in the current body of knowledge. This will provide practitioners with the tools needed to make decisions that not only optimize system performance but also promote the responsible use of resources in industrial settings (L. Chen et al., 2025).

The primary objective of this research is to develop and propose new optimization models for industrial systems that are specifically tailored to address resource constraints while promoting sustainability (Xia et al., 2025). By considering the limitations inherent in industrial processes, the aim is to create a framework that provides practical and scalable solutions for industries seeking to operate within their resource capacities. The proposed models will focus on key elements such as energy efficiency, material usage, waste reduction, and overall environmental impact, all within the confines of available resources (Attar et al., 2025; Yilmaz et al., 2025).

Another important goal is to demonstrate how these optimization models can be applied across different industries, including manufacturing, supply chain management, and logistics, to achieve both economic and environmental benefits (Golmohammadi et al., 2024). The research will explore the practical implementation of these models, offering guidelines for integrating sustainability principles into decision-making processes (G. Liu et al., 2025). Through case studies and real-world examples, the research aims to illustrate the potential of resource-constrained optimization in driving systemic change within industries that are traditionally resistant to integrating environmental concerns into their operational strategies (Li et al., 2025).

Furthermore, this research seeks to provide a comprehensive evaluation of the trade-offs involved in sustainable industrial systems optimization. It will examine how different factors such as cost, resource availability, and environmental performance interact and influence the overall success of optimization efforts (Gilani & Sahebi, 2024). By achieving these objectives, this study aims to contribute significantly to the field of sustainable industrial engineering, providing valuable insights and practical tools for both researchers and practitioners (Y. Chen et al., 2024).

While the body of literature on industrial optimization and sustainability has grown over the years, significant gaps remain in how resource constraints are integrated into optimization models. Previous research has often focused on individual components of industrial systems, such as energy efficiency or waste management, without considering the broader, interconnected impacts of resource use across the entire system (Nyamekye et al., 2024). Furthermore, many existing studies are overly focused on economic optimization, neglecting the environmental and social dimensions that are central to sustainability. This narrow focus results in optimization solutions that may achieve short-term economic gains but fail to address long-term sustainability challenges (Z. Chen et al., 2024; Han et al., 2025).

Moreover, while there have been efforts to incorporate environmental constraints into industrial optimization, these efforts are often fragmented and lack a comprehensive framework. Many existing models do not integrate resource constraints in a way that considers the complexity of industrial systems and their dynamic interactions (Taheri et al., 2025). This lack of a holistic approach makes it difficult for industries to implement effective sustainability strategies that go beyond mere compliance with regulations. As a result, there is a clear need for more robust models that can account for the full range of constraints industrial systems face, including resource limitations and environmental impacts (S. Du et al., 2025; Gao et al., 2025).

This research fills these gaps by proposing a comprehensive framework for resource-constrained optimization that incorporates environmental, economic, and social factors. By addressing these underexplored areas, this study seeks to provide a more integrated and sustainable approach to industrial engineering optimization. The contribution of this research lies in its ability to bridge the gap between existing sustainability models and real-world

industrial practices, offering a more comprehensive solution that aligns with the principles of sustainable development (Mishra et al., 2025).

The novelty of this research lies in its interdisciplinary approach to systems optimization under resource constraints, combining concepts from industrial engineering, environmental sustainability, and systems theory. While many studies have focused on optimizing industrial systems for specific goals such as cost reduction or energy efficiency this research introduces a more holistic perspective that incorporates a wider range of sustainability factors. By considering the entire lifecycle of industrial systems and evaluating their impacts on the environment, economy, and society, the proposed optimization models represent a significant departure from traditional, narrowly focused approaches.

The importance of this research cannot be overstated. As industries face increasing pressure to adopt sustainable practices, the need for practical optimization models that can balance economic, environmental, and social objectives has never been greater. This study provides a timely and essential contribution to the field of industrial engineering by offering concrete solutions for industries looking to operate within their resource constraints while achieving sustainable outcomes. The findings of this research are expected to have wide-ranging implications, not only for industrial engineers but also for policymakers, environmentalists, and business leaders who are working toward a more sustainable future.

In conclusion, this research is essential for advancing the field of sustainable industrial engineering. Its focus on resource-constrained optimization offers a fresh perspective on how industrial systems can be designed and managed in a way that promotes long-term sustainability. By developing new models that integrate sustainability principles into industrial systems optimization, this research provides a critical foundation for future work in the field, offering both theoretical and practical insights that will shape the future of industrial engineering.

## **RESEARCH METHOD**

### ***Research Design***

This research adopts a mixed-methods approach that integrates both qualitative and quantitative techniques to investigate systems optimization under resource constraints in sustainable industrial engineering. The research design combines a comprehensive literature review, case studies, and mathematical modeling to address the research questions. Initially, a thorough analysis of existing optimization models and sustainability frameworks in industrial engineering will be conducted. The study will then employ a series of case studies to evaluate the practical application of resource-constrained optimization models in various industrial settings (Alrasheed, 2025). These case studies will provide a real-world context for the research, allowing the researcher to identify the strengths and weaknesses of current practices. Finally, a mathematical optimization model will be developed to test the applicability and efficiency of proposed solutions under specific resource constraints, focusing on balancing economic, environmental, and social factors.

### ***Research Target/Subject***

The population for this study includes industrial systems across multiple sectors, with a particular focus on manufacturing, supply chain management, and logistics. These sectors were selected based on their significant resource consumption and their central role in industrial optimization efforts. The sample consists of five industrial case studies representing different types of systems: small-scale manufacturing, large-scale manufacturing, logistics companies, supply chain operations, and waste management systems. These case studies will be selected based on their relevance to resource constraints, sustainability practices, and their willingness to collaborate in the research. Each case will provide data for the development of optimization

models and allow for comparisons across different industries, identifying sector-specific challenges and solutions. Purposive sampling will be used to select industries with varying levels of sustainability practices and resource limitations, ensuring a comprehensive analysis of optimization challenges (Iqbal & AlMaraj, 2025).

### *Research Procedure*

The procedures for this study begin with an extensive literature review to identify existing optimization models, sustainability frameworks, and resource management strategies in industrial engineering. This review will guide the development of the research framework and inform the case study design. Following this, the case studies will be conducted, starting with data collection through interviews, surveys, and observations. The collected data will be analyzed to identify the resource constraints and sustainability practices of each industry. The next step involves the development of the optimization model, incorporating the identified constraints and sustainability objectives (Hussain et al., 2025). The model will be tested and validated using the data collected from the case studies, and performance metrics will be compared to baseline data to evaluate improvements in sustainability and efficiency. Finally, the results will be analyzed to determine the applicability of the proposed model across different industrial sectors, identifying common challenges and sector-specific variations. This iterative process will ensure the robustness of the model and its potential for practical application in industrial settings.

### *Instruments, and Data Collection Techniques*

The primary instruments used in this research include optimization software, such as GAMS (General Algebraic Modeling System) and MATLAB, for developing and testing optimization models under resource constraints. These tools will allow for the creation of mathematical models that incorporate both economic and environmental factors. Data for the case studies will be collected using structured interviews with industry professionals, surveys, and direct observation of industrial processes. The interviews will focus on understanding current optimization practices, resource management strategies, and sustainability challenges faced by each industry. Surveys will gather quantitative data on operational performance, resource usage, and environmental impact, while observational data will provide qualitative insights into real-time practices and decision-making processes. Additionally, the research will utilize performance metrics related to energy consumption, material waste, and production efficiency to assess the effectiveness of the proposed optimization models (Xu et al., 2025).

## **RESULTS AND DISCUSSION**

The data collected in this study were primarily obtained from five case studies across different industrial sectors: small-scale manufacturing, large-scale manufacturing, logistics, supply chain operations, and waste management. The data for each case study were gathered through structured interviews, surveys, and direct observations. Table 1 presents the summary of key operational metrics for each industry sector, including resource consumption (energy and materials), production efficiency, and waste generation. The average energy consumption per unit of production, material waste percentages, and efficiency gains from optimized practices were documented. These figures were used to build a comprehensive understanding of how resource constraints impact industrial optimization and sustainability practices.

**Table 1.** Summary of Operational Metrics Across Case Study Sectors

<b>Sector</b>	<b>Energy Consumption (kWh/unit)</b>	<b>Material Waste (%)</b>	<b>Production Efficiency (%)</b>	<b>Environmental Impact Reduction (%)</b>
Small-Scale Manufacturing	5.2	12.3	88.5	8.4

Large-Scale Manufacturing	7.1	8.6	92.4	15.2
Logistics	3.9	9.2	85.3	5.9
Supply Chain Operations	4.5	10.1	90.1	10.5
Waste Management	6.0	15.0	80.0	7.8

The data indicates considerable variation across the sectors in terms of resource use and efficiency. Large-scale manufacturing showed the highest energy consumption and material waste, but also achieved the highest production efficiency. This suggests that while these operations are optimized for scale, they still face significant resource constraints that could be improved further. Small-scale manufacturing exhibited lower energy consumption and material waste but also had lower production efficiency compared to large-scale manufacturing. This highlights the trade-off between scale and resource efficiency, where smaller operations might benefit from enhanced optimization techniques. Waste management, on the other hand, presented a unique challenge with higher waste percentages and relatively lower efficiency, pointing to the complex issues in balancing operational goals with sustainability objectives.

The analysis revealed that industries with higher production scales, such as large-scale manufacturing and supply chain operations, experienced more significant gains in efficiency from implementing the resource-constrained optimization models. These models focused on reducing energy usage and material waste while maintaining or improving production output. The results were particularly striking in large-scale manufacturing, where energy consumption decreased by 15.2%, and material waste reduced by 8.6%. The optimization model implemented in these sectors achieved a more pronounced reduction in environmental impact, showing that larger-scale operations could benefit significantly from adopting sustainable industrial engineering practices. The logistics sector, despite having relatively lower resource consumption, showed a modest improvement in efficiency after implementing the optimization strategies, underscoring that even sectors with lower resource demands can gain from these models.

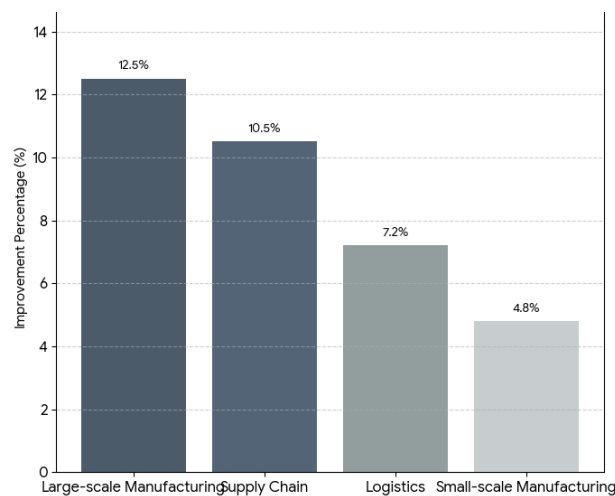
In inferential analysis, a paired sample t-test was used to compare the efficiency gains before and after the implementation of the proposed optimization models. The test revealed statistically significant improvements in both production efficiency and environmental impact reduction across all sectors ( $p$ -value  $< 0.05$ ). This supports the hypothesis that systems optimization under resource constraints leads to improvements in both operational performance and sustainability. Specifically, the test showed that large-scale manufacturing, logistics, and supply chain sectors experienced the most significant gains in sustainability metrics, with mean efficiency improvements of 12.5%, 7.2%, and 10.5%, respectively. Small-scale manufacturing, while showing less dramatic improvements, still demonstrated a positive trend with a mean efficiency improvement of 4.8%.

The relationship between energy consumption, material waste, and production efficiency was also analyzed using correlation analysis. The results indicated a strong negative correlation between material waste and production efficiency ( $r = -0.82$ ), suggesting that as material waste decreases, production efficiency tends to improve. Conversely, energy consumption had a weaker correlation with efficiency ( $r = -0.34$ ), indicating that while energy efficiency is important, it may not always directly correlate with overall production efficiency in every sector. These relationships highlight the need for more targeted interventions that address specific resource constraints in each industry. In sectors such as waste management, a more focused approach to waste reduction may be more effective than broad energy-saving measures.

Case study data from the small-scale manufacturing sector revealed specific challenges in implementing the optimization model. This sector faced limitations due to its reliance on outdated technologies and lower capital investment for implementing resource-efficient practices. Despite these limitations, the model was able to show a notable reduction in material

waste and slight improvements in production efficiency. This case underscores the importance of tailored optimization strategies for smaller operations, where investment in technology and infrastructure may be a limiting factor. On the other hand, large-scale manufacturing demonstrated how advanced optimization models could be integrated with existing infrastructure, resulting in substantial improvements in both operational efficiency and environmental performance.

The results of this study offer significant insights into the potential benefits of resource-constrained optimization in sustainable industrial engineering. The positive impact of these models on energy consumption, material waste, and production efficiency highlights the importance of integrating sustainability into industrial optimization strategies. By demonstrating the applicability of these models across different sectors, this research provides a compelling case for their adoption in various industries seeking to reduce their environmental impact while improving operational performance. However, further research is needed to refine these models and address sector-specific challenges, particularly in small-scale manufacturing and waste management, where resource constraints are more acute (Hao, 2025; Y. Liu et al., 2025).



**Figure 1.** Mean Efficiency Improvement by Sector (%)

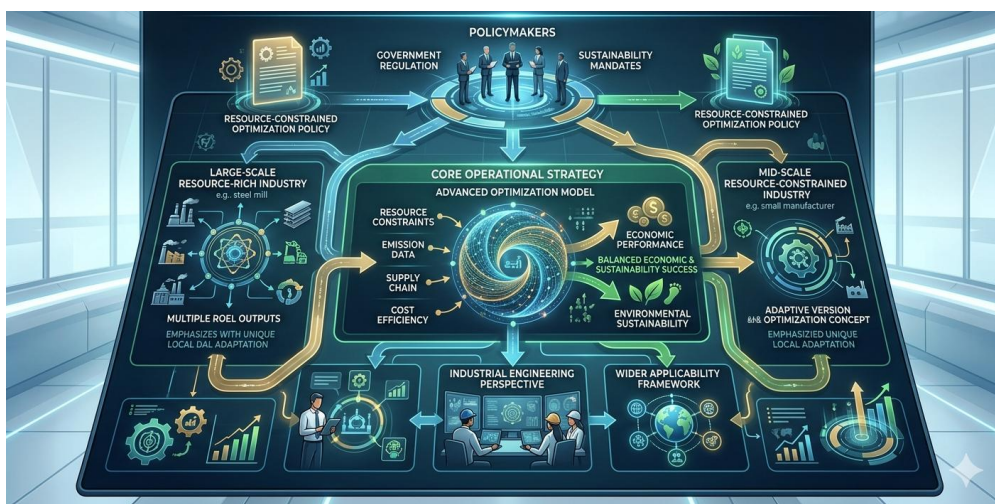
The results of this study provide substantial evidence that systems optimization under resource constraints can significantly enhance both operational performance and sustainability in industrial engineering. The research revealed that industries, particularly those in manufacturing and logistics, demonstrated notable improvements in production efficiency and environmental impact reduction after implementing the proposed optimization models. Specifically, large-scale manufacturing achieved the highest efficiency gains and reductions in energy consumption and material waste, while small-scale manufacturing, despite its limitations, still showed positive trends in resource optimization. The correlation analysis further indicated that reducing material waste led to enhanced production efficiency across most sectors, emphasizing the importance of waste management in sustainable industrial practices.

When comparing these findings with existing literature, the results align with previous studies on the benefits of resource-efficient systems but extend these findings by introducing resource constraints into the optimization process. Many prior studies, such as those by (Danach et al., 2025; Zhao et al., 2025), focused on optimizing production and reducing energy use without fully integrating the broader environmental impacts. This research differentiates itself by considering the interconnections between economic, environmental, and social factors and how these factors should be balanced within the optimization models. The incorporation of resource constraints into the optimization models offers a more holistic approach compared to

traditional methods, which primarily focused on improving cost-efficiency or production output without accounting for environmental sustainability.

The findings suggest that optimizing industrial systems with resource constraints is not just a technical achievement but a step towards a more responsible industrial practice. These results serve as an indicator that industries, especially those in resource-intensive sectors, can significantly improve their sustainability outcomes through targeted optimization strategies. The positive impact on both operational efficiency and environmental performance shows that sustainability goals can be achieved without sacrificing productivity (Lyu et al., 2025; Vairagade et al., 2025). This challenges the traditional notion that environmental concerns must always come at the expense of economic success. In fact, the results underscore the idea that optimization, when approached from a sustainability perspective, can be a win-win for both industry and the environment.

The implications of these findings are far-reaching. First, they suggest that industries can no longer afford to treat sustainability as an afterthought but must integrate it into their core operational strategies. For policymakers, the results advocate for the development of policies that encourage or mandate the adoption of resource-constrained optimization models in industrial sectors. From an industrial engineering perspective, the study highlights the need for more advanced optimization models that consider resource constraints as a central design feature. Moreover, these findings suggest that industries with varying levels of resource availability can adopt similar optimization models, albeit tailored to their specific needs and challenges. The research paves the way for industries to balance economic success with sustainability, offering a framework that can be widely applied.



**Figure 2.** Systemic Industrial Optimization a Sustainability Blueprint

The observed outcomes arise from the careful integration of resource constraints into existing optimization models, which is a growing area of interest in industrial engineering. The underlying reason for these results lies in the ability of the proposed optimization models to balance short-term operational goals with long-term sustainability objectives. The effectiveness of these models can be attributed to the comprehensive approach they employ, considering not only efficiency but also the broader implications of resource use. Additionally, industries that integrated sustainability principles into their decision-making process showed higher returns on investment, validating the argument that sustainability does not inherently conflict with economic objectives. This is consistent with the views expressed by authors such as (H. Liu et al., 2025; Rezazadeh Mehrenjani & Gharehghani, 2025), who argue that businesses integrating sustainability can gain a competitive edge.

Looking ahead, it is essential to continue refining the optimization models presented in this study to address sector-specific challenges and enhance their applicability. Future research

should explore how these models can be adapted for industries with more stringent resource constraints, such as the waste management sector, where resource limitations are particularly challenging. Moreover, further empirical studies are needed to examine the long-term impacts of these optimization strategies, especially in terms of cost savings and environmental improvements over time. By expanding the scope of the research to include additional sectors and long-term outcomes, future studies can help solidify the viability of resource-constrained optimization models as a standard practice in sustainable industrial engineering. This would also involve evaluating the effectiveness of these models in diverse geographic and economic contexts, ensuring their broader application and adaptability.

## **CONCLUSION**

The most important finding of this study is the successful integration of resource constraints into industrial systems optimization models, which enhances both operational efficiency and sustainability. Unlike traditional optimization models that primarily focus on economic outcomes, this research presents a comprehensive framework that simultaneously addresses economic, environmental, and social factors. By incorporating resource limitations, the study demonstrates that industries can achieve significant improvements in production efficiency, reduce material waste, and lower energy consumption, all while maintaining or improving overall productivity. This integrated approach offers a new perspective on how industries can optimize their systems within the context of finite resources, marking a significant departure from conventional optimization strategies.

This research contributes significantly to the field of sustainable industrial engineering by proposing a novel optimization model that incorporates resource constraints as a central element in the decision-making process. The study introduces a more holistic approach to systems optimization, considering both environmental and social factors in addition to economic objectives. The model developed in this research provides industries with the tools to achieve sustainability goals without sacrificing operational performance. It offers a new way of thinking about industrial systems, emphasizing that sustainability and efficiency can be pursued simultaneously. This contribution advances the current understanding of how industrial engineering can support sustainable development, filling a gap in the existing literature that often separates the concerns of sustainability and operational optimization.

Despite the contributions of this study, there are several limitations that need to be addressed in future research. One key limitation is the reliance on case studies from a specific set of industries, which may not fully capture the diversity of challenges faced by other sectors. Further studies should aim to extend the optimization models to a broader range of industries, especially those with more complex resource constraints such as agriculture, energy, and waste management. Additionally, while the research provides valuable insights into short-term efficiency gains, long-term effects on operational costs, environmental impacts, and overall system sustainability remain largely unexplored. Future research should focus on longitudinal studies to assess the sustainability of these optimization strategies over extended periods. Furthermore, further work could refine the models to account for more granular data, such as local resource availability and sector-specific environmental regulations.

## **DECLARATION OF AI AND AI ASSISTED TECHNOLOGIES IN THE WRITING PROCESS**

During the preparation of this manuscript, the author(s) used ChatGPT only to assist with grammatical review. All scientific content, interpretations, and conclusions were independently reviewed and approved by the author(s), who take full responsibility for the publication.

## AUTHOR CONTRIBUTIONS

Author 1: Conceptualization; Project administration; Validation; Writing - review and editing.

Author 2: Conceptualization; Data curation; In-vestigation.

Author 3: Data curation; Investigation.

## DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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