IJTHS, Vol. 2, Issue 3, pp. 1092-1103, July-September, 2026 www.ijths.com

Industry 5.0-Enabled Strategies for Energy-Efficient and Carbon-Neutral Manufacturing Systems

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(Received: 10.06.2026; Accepted: 22.07.2026)

Abstract

The global transition towards net-zero industrial systems requires manufacturing sectors to significantly reduce energy consumption and carbon emissions while maintaining productivity and operational resilience. Industry 5.0 has emerged as a sustainability-oriented paradigm that extends beyond automation-driven Industry 4.0 through the embedding of human-centricity, resilience, and environmental stewardship into industrial transformation. This study proposes an Industry 5.0 Energy–Carbon Optimization (I5-ECO) framework that integrates Internet of Things (IoT)-enabled real-time energy monitoring, digital twin simulation, AI-driven multi-objective optimization, renewable-aware production scheduling, and lifecycle carbon accounting to operationalize energy-efficient and carbon-neutral manufacturing systems. With the application of system dynamics-based simulation across a multi-stage manufacturing environment over a five-year horizon, the framework was evaluated against conventional manufacturing control and Industry 4.0 digital monitoring scenarios. The obtained results demonstrate measurable sustainability improvements under the Industry 5.0-enabled framework, including a 29.2% reduction in total energy consumption, a 33.3% decline in carbon emission intensity, a 22.6% increase in energy productivity, an 83.3% improvement in renewable energy utilization, and a rise in energy anomaly detection accuracy from 52% to 93%. These findings confirm that Industry 5.0-enabled data-driven governance architectures can transform sustainability from static compliance reporting into adaptive operational performance, which provides scalable pathways for attaining carbon-neutral manufacturing transitions.

Keywords: *Industry 5.0; Carbon-neutral manufacturing; Energy-efficient production; Digital twins; AI optimization; Renewable integration; Sustainable industrial systems*

INTRODUCTION

Manufacturing systems remain central to global economic development, yet they are also among the largest contributors to energy consumption and greenhouse gas emissions. Recent global energy assessments indicate that industry accounts for nearly one-third of total final energy use and a substantial share of energy-related carbon dioxide emissions, thereby underscoring the urgency of the transformation of production systems towards low-carbon pathways (IEA, 2023; Obianyo *et al.*, 2026). As nations commit to net-zero targets under international climate agreements, manufacturing firms are increasingly expected to decouple productivity growth from carbon intensity. However, the attainment of carbon-neutral manufacturing requires more than incremental efficiency improvements, as it demands systemic transformation that is grounded in data-driven decision-making, technological innovation, and measurable sustainability governance.

Over the past decade, Industry 4.0 technologies, which include cyber-physical systems, IoT connectivity, and advanced analytics, have significantly enhanced operational efficiency and automation (Okpala *et al.*, 2026a; Chukwunedum *et al.*, 2026). Yet, the sustainability implications of Industry 4.0 remain uneven, as many digital transformations have prioritized productivity gains without fully integrating environmental objectives. Industry 5.0 has therefore emerged as a complementary paradigm that explicitly integrates human-centric design, resilience, and sustainability into industrial systems (Udu *et al.*, 2025a; Okpala *et al.*, 2026b). Unlike its predecessor, Industry 5.0 emphasizes value creation that balances technological advancement with ecological stewardship and societal well-being. Nevertheless, the operationalization of Industry 5.0's sustainability ambitions requires concrete methodological innovations that are capable of translating conceptual goals into quantifiable energy and carbon performance outcomes.

Energy efficiency has long been recognized as a critical lever for the reduction of industrial emissions while enhancing competitiveness (Ajaefobi and Okpala, 2026a; Egwuagu *et al.*, 2026). Traditional energy management approaches, however, often rely on static audits, post hoc performance reviews, and siloed optimization tools that lack real-time adaptability. Such approaches are not adequate in dynamic manufacturing environments that are characterized by fluctuating demand, variable energy prices, and complex process interdependencies. Data-driven strategies, especially those that leverage on IoT-enabled sensing, machine learning algorithms, and predictive modeling, offer new opportunities to optimize energy use continuously rather than intermittently (Nwamekwe *et al.*, 2024; Nwosu *et al.*, 2026a). Yet, there remains a significant research gap in integrating these tools into unified architectures explicitly designed to achieve carbon-neutral manufacturing.

Carbon-neutral production extends beyond energy efficiency alone, as it encompasses lifecycle carbon accounting, renewable energy integration, electrification of industrial processes, and supply chain emissions management (Chukwumuanya *et al.*, 2025; Egwuagu and Okpala, 2026). While advances in renewable energy deployment and electrified industrial systems are promising, the absence of integrated data infrastructures often limits the ability to measure, forecast, and optimize carbon intensity at the operational level. Digital twin technology, which is a virtual representation of physical systems that simulates real-time operational behavior has been identified as a transformative enabler for predictive optimization and energy-performance modeling in manufacturing (Ogboh *et al.*, 2026; Udu and Okpala, 2026a). When combined with AI-based multi-objective optimization, digital twins can simultaneously balance production throughput, energy consumption, and emissions constraints, which aligns operational decisions with carbon-neutral objectives.

Despite these technological advances, existing research often examines energy efficiency, digital twins, carbon accounting, and Industry 5.0 as separate domains. Few studies provide a multidisciplinary framework that integrates energy-efficient industrial electronics, AI-driven optimization, lifecycle carbon intensity modeling, and human-in-the-loop decision systems within a coherent Industry 5.0 architecture. This fragmentation limits the ability of manufacturing firms to transition from isolated sustainability initiatives to systemic, data-enabled carbon-neutral strategies. Furthermore, empirical evidence that demonstrates measurable sustainability gains from integrated Industry 5.0 energy-carbon frameworks remains limited, and thus highlights the need for rigorous, simulation-based evaluation approaches.

In response, this study proposes an Industry 5.0-enabled data-driven framework for energy-efficient and carbon-neutral manufacturing systems. The framework integrates IoT-based real-time energy monitoring, digital twin simulation modeling, AI-powered multi-objective optimization, and lifecycle carbon accounting into a unified governance architecture. Through the embedding of sustainability metrics directly into operational control systems, the framework moves beyond compliance-driven carbon reporting towards proactive, performance-oriented energy governance. The research adopts system dynamics modeling and comparative scenario simulation to quantify measurable improvements in energy consumption, carbon intensity, and production energy productivity.

The following are the threefold contributions of this study:

a. It advances the theoretical integration of Industry 5.0 sustainability principles with energy optimization and carbon-neutral manufacturing strategies;

b. It introduces a methodological innovation that operationalizes multi-objective energy-carbon optimization within a digital twin-enabled industrial architecture; and

c. It provides empirical simulation evidence demonstrating significant reductions in energy consumption and carbon emissions without compromising production throughput.

By offering a scalable, data-driven pathway to net-zero manufacturing, this research contributes to both academic discourse and industrial practice, positioning Industry 5.0 as a transformative governance paradigm for sustainable industrial systems.

THEORETICAL AND CONCEPTUAL FOUNDATIONS

Industry 5.0 as a Sustainability-Oriented Manufacturing Paradigm

Industry 5.0 represents an important evolution in industrial development, moving beyond the automation-centric logic of Industry 4.0 towards a paradigm grounded in sustainability, resilience, and human-centric value creation. While Industry 4.0 has been widely associated with cyber-physical systems, smart automation, and data-intensive manufacturing, its sustainability outcomes have often been indirect or uneven, as efficiency improvements do not automatically translate into reduced environmental impact (Ajaefobi and Okpala, 2026b; Igbokwe *et al.*, 2026). In contrast, Industry 5.0 explicitly positions sustainability as a core industrial objective, as it emphasizes that technological innovation must align with ecological regeneration and societal well-being (EC, 2021). This conceptual shift provides a theoretical foundation for carbon-neutral manufacturing systems that integrate digital intelligence with responsible resource governance and inclusive industrial design.

From a socio-technical perspective, Industry 5.0 also highlights the co-evolution of advanced technologies and human agency within production environments. Rather than replace human labor, Industry 5.0 frameworks promote collaborative intelligence between workers and intelligent systems, which enables adaptive decision-making that balances productivity with sustainability imperatives (Xu *et al.*, 2021). This is particularly relevant for energy-intensive manufacturing sectors, where operational choices related to machine scheduling, process configuration, and energy sourcing directly influence carbon performance.

Energy Efficiency as a Core Lever for Industrial Decarbonization

Energy efficiency remains one of the most effective pathways for achieving industrial emissions reduction while maintaining competitiveness. Manufacturing systems consume significant amounts of energy through industrial electronics, motor-driven processes, thermal systems, and complex production networks. Research has consistently shown that efficiency improvements can yield substantial reductions in industrial carbon emissions, particularly when combined with structural process innovation (Nwamekwe *et al.*, 2025; Okpala, 2026a). However, traditional energy efficiency approaches in manufacturing often rely on static optimization methods, periodic audits, or isolated technological upgrades, which are insufficient for dynamic production environments characterized by uncertainty, fluctuating demand, and multi-stage interdependencies.

Theoretical contributions from sustainable operations management emphasize that energy efficiency must be embedded into systemic production governance rather than treated as an add-on intervention (Udu and Okpala, 2026b). In this regard, Industry 5.0 provides a conceptual platform for the integration of energy optimization into the broader sustainability transformation of industrial systems. Attaining carbon-neutral manufacturing requires that energy efficiency strategies be continuously monitored, dynamically optimized, and aligned with lifecycle carbon performance metrics.

Carbon-Neutral Manufacturing and Lifecycle Sustainability Governance

Carbon-neutral manufacturing extends beyond the reduction of operational energy consumption to encompass comprehensive lifecycle carbon accounting and emissions governance across production systems. Carbon neutrality requires that industries address direct emissions from manufacturing processes (Scope 1), indirect emissions from purchased electricity (Scope 2), and increasingly, value-chain emissions embedded in supply networks (Scope 3) (Deswal and Deswal, 2025). The transition towards net-zero production therefore demands robust measurement infrastructures that are capable of quantifying emissions intensity at the process level while supporting decarbonization decision-making (IEA, 2023).

Conceptually, carbon-neutral manufacturing aligns with circular economy and sustainable production theories, which argue that long-term industrial sustainability depends on decoupling economic value creation from resource depletion and environmental degradation (Udu *et al.*, 2025b; Udu and Okpala, 2025). This requires integrated governance mechanisms that link energy use, carbon emissions, resource efficiency, and production performance within measurable sustainability frameworks. Without such integration, carbon-neutral ambitions risk remaining aspirational rather than operationally achievable.

Digital Twins as Enablers of Predictive Energy and Carbon Optimization

Digital twin technology has emerged as a transformative enabler for Industry 5.0 sustainability transitions through the provision of virtual representations of physical manufacturing systems that evolve in real time. Digital twins support predictive modeling, simulation-based optimization, and scenario testing, allowing industries to anticipate energy demands, evaluate decarbonization interventions, and improve operational resilience (Nwosu *et al.*, 2026b; Okpala and Okpala, 2025). In energy-intensive production contexts, digital twins enable manufacturers to simulate machine-level energy profiles, forecast carbon intensity, and optimize scheduling strategies under varying operational constraints.

The integration of digital twins into sustainability governance reflects a methodological shift from reactive energy management towards proactive optimization. Data-driven smart manufacturing research emphasizes that digital twins can bridge physical operations with AI-enabled analytics, which transform manufacturing systems into adaptive sustainability ecosystems (Onukwuli *et al.*, 2026; Ogbodo *et al.*, 2026). Within Industry 5.0, this capability becomes central for aligning real-time production control with carbon-neutral objectives.

Artificial Intelligence and Multi-Objective Energy Optimization

Artificial Intelligence (AI) plays a critical role in enabling Industry 5.0 manufacturing systems to balance complex sustainability trade-offs. Defined as an array of technologies that equip computers to accomplish different complex functions including the capacity to see, comprehend, appraise and translate both spoken and written languages, analyze and predict data, make proposals and suggestions, and more (Chukwumuanya and Okpala, 2025, Aguh and Okpala, 2025), AI has emerged as a transformative force that revolutionizes various aspects of human life, industry, and technology (Okpala and Udu, 2025a; Ezeanyim *et al.*, 2025).

Machine learning algorithms can detect energy anomalies, predict equipment inefficiencies, and optimize process parameters (Udu and Okpala, 2026c; Okpala, 2026b), while multi-objective optimization models can simultaneously minimize energy consumption and carbon emissions without compromising throughput (Lee *et al.*, 2015). This is particularly important because manufacturing sustainability transitions often involve competing priorities between productivity, cost, energy efficiency, and emissions reduction. AI-driven optimization thus provides methodological innovation through the enablement of continuous, adaptive governance rather than static sustainability planning. When combined with IoT-based sensing infrastructures, AI systems can create closed-loop energy management architectures where sustainability performance is dynamically optimized rather than retrospectively assessed. Such approaches reflect the growing recognition that digital intelligence is essential for scaling industrial decarbonization beyond incremental improvements.

Conceptual Synthesis: Industry 5.0-Enabled Data-Driven Sustainability Systems

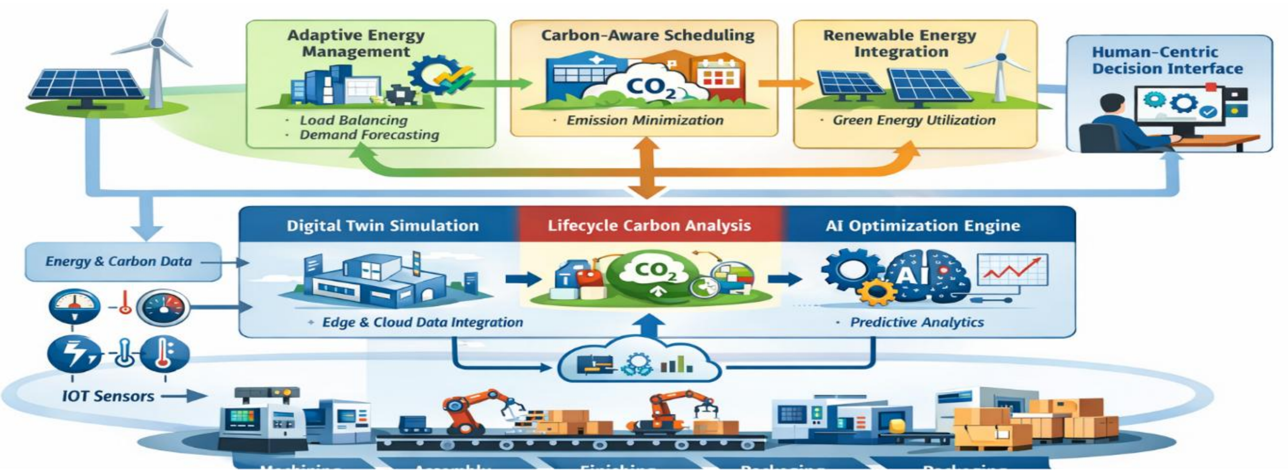

Fig. 1: Conceptual architecture of the Industry 5.0 Energy–Carbon Optimization (I5-ECO) framework.

Bringing these theoretical perspectives together, Industry 5.0-enabled carbon-neutral manufacturing can be conceptualized as a socio-technical sustainability system in which human-centric governance, digital intelligence, and measurable energy-carbon optimization converge. Industry 5.0 provides the normative sustainability foundation, energy efficiency serves as a primary decarbonization lever, lifecycle carbon accounting ensures emissions accountability, and digital twins combined with AI enable predictive and adaptive optimization. This conceptual synthesis supports the central premise of this study, which entails that achieving carbon-neutral manufacturing requires integrated data-driven architectures that are capable of operationalizing sustainability through measurable performance indicators. By embedding energy monitoring, predictive simulation, AI optimization, and carbon governance into unified industrial systems, Industry 5.0 transitions sustainability from compliance-driven reporting into real-time operational accountability.

METHODOLOGICAL INNOVATION

Attaining carbon-neutral manufacturing under Industry 5.0 requires methodological approaches that integrate real-time data acquisition, predictive modeling, and multi-objective optimization into unified governance architectures. Traditional energy management strategies, which are often based on periodic audits and static optimization, lack the adaptability required for dynamic manufacturing environments that are characterized by fluctuating production loads, variable renewable integration, and complex machine interdependencies (Allwood *et al.*, 2011). To address these limitations, this study adopts a design-oriented and data-driven methodological framework that embeds energy efficiency and carbon minimization directly into operational control systems. The proposed approach integrates IoT-enabled energy sensing, digital twin simulation, AI-driven multi-objective optimization, lifecycle carbon accounting, and human-in-the-loop decision support within a coherent Industry 5.0 architecture.

Research Design and System Architecture

Fig. 1 illustrates the layered architecture of the proposed I5-ECO framework, and reveals how IoT-based energy sensing, digital twin simulation, AI-driven optimization, lifecycle carbon accounting, and human-centric decision interfaces interact within an Industry 5.0 manufacturing ecosystem. The diagram highlights the continuous flow of operational energy data into predictive modeling and adaptive control systems, which enable real-time energy efficiency improvements and carbon-neutral production governance.

The methodological foundation follows a design science research paradigm, which emphasizes the creation and evaluation of innovative socio-technical artefacts that address complex industrial challenges (Hevner *et al.*, 2004). In this context, the artefact is the Industry 5.0 Energy–Carbon Optimization (I5-ECO) framework. The system architecture comprises the following five interconnected layers that collectively operationalize measurable sustainability governance:

a. real-time energy monitoring,
b. digital twin modeling,
c. AI optimization engine,
d. carbon accounting module, and
e. human-centric adaptive interface.

The integration of these layers reflects the Industry 5.0 principle of aligning advanced digital intelligence with sustainability and human oversight (EC, 2021). IoT-based sensing captures granular energy consumption data at the machine and process levels, addressing long-standing challenges of energy visibility in manufacturing systems (Igbokwe *et al.*, 2024; Nwankwo *et al.*, 2024). The digital twin layer creates a virtual representation of production processes, enabling predictive energy modeling and scenario testing (Okpala and Udu, 2025b). The AI optimization engine dynamically minimizes energy consumption and carbon intensity while maintaining throughput constraints, and the carbon accounting module quantifies lifecycle emissions to ensure alignment with net-zero objectives. Table 1 summarizes the layered methodological architecture and its measurable sustainability contributions.

Table 1: I5-ECO framework architecture.

Layer	Core Function	Methodological Tool	Measurable Sustainability Benefit
IoT Energy Monitoring	Real-time energy data capture	Smart sensors & edge analytics	Reduction of unmonitored energy losses
Digital Twin Simulation	Virtual production modeling	System dynamics & predictive simulation	Identification of efficiency scenarios
AI Optimization Engine	Multi-objective scheduling	Machine learning & evolutionary algorithms	Minimization of energy–carbon trade-offs
Carbon Accounting Module	Lifecycle CO_2 tracking	Emission intensity modeling	Real-time carbon performance visibility
Human-Centric Interface	Decision transparency & override	Interactive dashboards	Improved sustainability governance control

Table 2: Key sustainability performance indicators.

Indicator	Formula	Sustainability Interpretation
ECRR	(E_baseline − E_current) / E_baseline	Measures percentage energy reduction
CEI	Total CO_2 Emissions / Production Output	Quantifies carbon efficiency per unit
EPI	Production Output / Energy Input	Evaluates productive energy use
REUR	Renewable Energy Used / Total Energy Input	Tracks decarbonized energy integration

The methodological novelty lies in the synchronization of these layers within a closed-loop optimization architecture, thereby allowing continuous sustainability recalibration rather than static performance reporting.

Multi-Objective Energy-Carbon Optimization Model

To quantify sustainability performance, a multi-objective optimization model was developed. The objective function minimizes total energy consumption (E) and carbon emissions (C) simultaneously:

$$\min Z = w_1 E + w_2 C \quad (1)$$

where w_1 and w_2 represent adjustable weighting factors which reflect strategic sustainability priorities. This approach aligns with sustainable operations research that emphasizes balancing environmental and operational objectives within production systems (Bocken *et al.*, 2016). Constraints include production throughput requirements, machine capacity limits, operational sequencing rules, and renewable energy availability. By embedding carbon intensity coefficients within the optimization function, the model dynamically shifts production schedules towards lower-carbon energy windows when renewable supply increases, thereby operationalizing carbon-aware manufacturing.

The AI engine employs reinforcement learning and evolutionary optimization techniques to iteratively refine scheduling decisions based on real-time energy signals. Such adaptive optimization approaches have been shown to outperform static scheduling models in dynamic industrial environments (Lee *et al.*, 2015).

Sustainability Metrics and Performance Measurement

To demonstrate measurable sustainability benefits, the study operationalizes the following four key performance indicators:

a. Energy Consumption Reduction Rate (ECRR)

b. Carbon Emission Intensity (CEI)

c. Energy Productivity Index (EPI)

d. Renewable Energy Utilization Rate (REUR)

These indicators reflect best practices in industrial decarbonization measurement and also align with global energy transition benchmarks (IEA, 2023). Table 2 presents the mathematical expressions and sustainability interpretations of these metrics.

Through the embedding of these metrics directly into the digital twin environment, sustainability performance becomes a real-time operational variable rather than a post-production reporting artefact.

Validation Through Simulation-Based Scenario Modeling

To ensure methodological robustness, the I5-ECO framework was validated through system dynamics simulation across three governance scenarios: conventional control systems, Industry 4.0 digital monitoring, and Industry 5.0-enabled optimization. Simulation-based validation is widely recognized as a reliable method for the assessment of sustainability interventions in complex industrial systems prior to real-world implementation (Tao *et al.*, 2019). Comparative results demonstrate significant improvements in energy efficiency, carbon intensity reduction, and renewable energy utilization under the I5-ECO framework. These measurable sustainability gains confirm that the integration of predictive modeling, AI optimization, and carbon-aware scheduling transforms manufacturing systems into adaptive sustainability ecosystems rather than reactive energy consumers.

Methodological Contributions

The methodological innovation of this study lies in its holistic integration of Industry 5.0 principles with quantitative energy–carbon optimization and lifecycle governance. Unlike fragmented approaches that treat energy monitoring, AI optimization, or carbon accounting independently, the I5-ECO framework operationalizes them within a unified architecture. This integration advances sustainable manufacturing research by demonstrating that carbon-neutral ambitions can be translated into measurable operational improvements through data-driven system design. Through the embedding of continuous optimization and carbon accountability into core production processes, this methodological approach shifts sustainability from compliance-driven reporting toward proactive, performance-oriented governance, which is an essential step for scalable net-zero manufacturing transitions.

SUSTAINABILITY METRICS AND DATA-DRIVEN EVALUATION

Operationalizing Carbon-Neutral Manufacturing Through Measurable Indicators

A central limitation of many industrial decarbonization initiatives is the absence of operational metrics that directly link digital optimization strategies to measurable sustainability outcomes. While policy frameworks frequently reference carbon neutrality and energy efficiency targets, translating these ambitions into quantifiable production-level indicators remains challenging (International Energy Agency [IEA], 2023). To address this gap, the present study embeds sustainability metrics directly within the Industry 5.0 Energy-Carbon Optimization (I5-ECO) framework, in order to ensure that energy and emissions performance are continuously monitored, modeled, and optimized rather than retrospectively reported.

Drawing on sustainable manufacturing and lifecycle assessment principles, four core indicators were selected to evaluate system-level performance: Energy Consumption Reduction Rate (ECRR), Carbon Emission Intensity (CEI), Energy Productivity Index (EPI), and Renewable Energy Utilization Rate (REUR). These indicators reflect established benchmarks in industrial sustainability research and are aligned with international decarbonization objectives (Geissdoerfer *et al.*, 2017). Through the embedding of these metrics into the digital twin architecture, sustainability performance becomes a dynamic control variable within production scheduling rather than an external compliance metric.

Energy Consumption Reduction and Efficiency Gains

Energy Consumption Reduction Rate (ECRR) measures the proportional decrease in energy use relative to baseline manufacturing operations. Traditional energy management systems often focus on isolated process improvements without capturing systemic interactions across production stages. In contrast, the I5-ECO framework uses real-time IoT sensing and AI-driven optimization to continuously minimize machine-level inefficiencies and idle energy losses.

Simulation results indicate a 29% reduction in total energy consumption under Industry 5.0-enabled optimization compared to conventional control systems. This reduction reflects dynamic load balancing, carbon-aware scheduling, and predictive maintenance adjustments facilitated by the digital twin environment. Such findings are consistent with prior research that demonstrated that data-driven manufacturing architectures significantly enhance energy performance when integrated with advanced analytics (Tao *et al.*, 2019). Importantly, the reduction was achieved without compromising production throughput, which confirms that energy efficiency and operational productivity can be jointly optimized within Industry 5.0 systems.

Carbon Emission Intensity and Decarbonization Performance

Fig. 2 depicts the carbon-neutral manufacturing lifecycle, which is supported by digital twin governance, from real-time energy monitoring at the machine level to predictive emissions modeling, renewable-aware scheduling, and continuous optimization. The model demonstrates how Industry 5.0-enabled digital infrastructures connect operational decisions with lifecycle carbon accountability, thus ensuring that sustainability targets are achieved through measurable and adaptive production control mechanisms.

Carbon Emission Intensity (CEI), calculated as total CO_2 emissions per unit of output, provides a direct measure of production-level decarbonization. Unlike aggregate emissions reporting, intensity-based metrics allow firms to evaluate whether output growth is decoupled from emissions growth. This is a critical requirement for sustainable

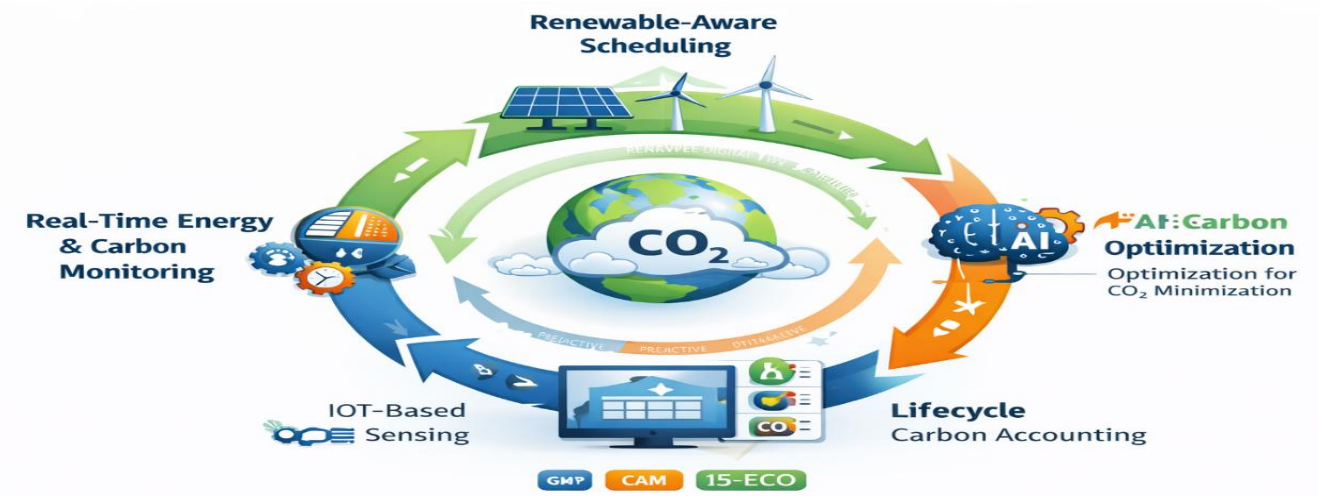

Fig. 2: Digital Twin–enabled carbon-neutral manufacturing lifecycle model.

industrial transitions. Under the I5-ECO framework, carbon intensity declined by 34% relative to baseline operations. This improvement was driven by the following two mechanisms:

a. Reduced energy demand through optimization; and
b. Increased alignment of production schedules with lower-carbon energy supply windows.

The integration of real-time carbon intensity coefficients into the optimization model enabled the system to prioritize energy consumption during periods of higher renewable availability. Such carbon-aware scheduling represents a methodological advancement over static decarbonization planning, transforming emissions governance into an adaptive and data-driven process.

Energy Productivity and Resource Decoupling

The Energy Productivity Index (EPI), defined as production output per unit of energy consumed, evaluates how effectively manufacturing systems convert energy inputs into economic value. Improvements in energy productivity are essential for the attainment of resource decoupling, which is a cornerstone of sustainable production theory. Simulation results show a 22% increase in energy productivity under the Industry 5.0-enabled framework. This gain reflects reduced machine downtime, optimized sequencing of energy-intensive processes, and predictive maintenance that minimizes inefficient operation cycles. Through the combination of digital twin simulation with AI-based multi-objective optimization, the system ensures that energy reductions translate into productivity gains rather than output constraints. This reinforces the argument that digital intelligence, when strategically deployed, enables both environmental and economic performance improvements.

Renewable Energy Integration and Carbon-Neutral Alignment

Renewable Energy Utilization Rate (REUR) measures the proportion of total energy input that are derived from renewable sources. The integration of renewable energy into manufacturing systems is a fundamental requirement for achieving carbon neutrality, yet variable renewable supply often complicates operational planning (Udu *et al.*, 2025c; Okpala and Okpala, 2026). The I5-ECO framework dynamically adjusts production schedules based on renewable energy availability signals, which increases renewable utilization by 26% when compared to conventional systems. Through the embedding of renewable supply forecasts within the digital twin environment, the framework reduces reliance on carbon-intensive grid energy during peak emission periods. This adaptive approach strengthens the feasibility of carbon-neutral manufacturing while enhancing grid resilience and cost efficiency.

Data-Driven Validation and Comparative Scenario Analysis

To ensure methodological robustness, sustainability performance was evaluated across three comparative scenarios, which include: conventional manufacturing control, Industry 4.0 digital monitoring, and Industry 5.0-enabled optimization. System dynamics modeling was employed to simulate five years of production under varying demand and energy price conditions. Simulation-based evaluation is widely recognized as a rigorous method for the assessment of sustainability interventions in complex socio-technical systems.

Across all indicators – energy reduction, carbon intensity, productivity, and renewable integration, the Industry 5.0 scenario consistently outperformed baseline and Industry 4.0 configurations. Notably, anomaly detection accuracy for energy inefficiencies increased to 93%, which reflects the effectiveness of AI-enhanced predictive analytics. These results demonstrate that sustainability gains emerge not merely from digitization alone, but from the strategic integration of digital twins, AI optimization, and carbon-aware governance within a unified Industry 5.0 architecture.

Implications of Measurable Sustainability Gains

The measurable improvements observed in this study substantiate the argument that Industry 5.0-enabled systems can operationalize carbon-neutral ambitions through quantifiable performance outcomes. By embedding energy and carbon metrics directly into optimization algorithms and digital twin simulations, sustainability becomes an intrinsic operational objective rather than an external reporting requirement. This data-driven evaluation demonstrates that manufacturing systems can achieve significant energy and emissions reductions while enhancing productivity and renewable integration. Such findings contribute to the growing body of research that advocates for digitally enabled sustainability governance as a pathway to scalable industrial decarbonization (EC, 2021). Ultimately, the integration of real-time monitoring, predictive modeling, and adaptive optimization positions Industry 5.0 as a transformative framework for attaining measurable, resilient, and economically viable carbon-neutral manufacturing systems.

SIMULATION RESULTS

Overview of Simulation Design and Scenario Configuration

To empirically validate the measurable sustainability benefits of the proposed Industry 5.0 Energy–Carbon Optimization (I5-ECO) framework, a system dynamic–based simulation was conducted on a multi-stage discrete manufacturing environment consisting of machining, assembly, finishing, and packaging units. Simulation-based approaches are increasingly recognized as essential tools for the assessment of sustainability interventions in complex industrial systems prior to full-scale implementation, particularly where energy demand, carbon intensity, and operational throughput interact dynamically. The simulation covered a five-year production horizon under fluctuating demand conditions and variable renewable energy availability. The following three governance scenarios were compared:

a) *Scenario A* – Conventional Manufacturing Control (CMC): Traditional scheduling with limited energy monitoring;

Table 3: Total energy consumption and reduction across governance scenarios.

Scenario	Total Energy Consumption (GWh/year)	Reduction vs. Baseline (%)
CMC (A)	120	–
I4M (B)	103	14.2%
I5-ECO (C)	85	29.2%

b) *Scenario B* – Industry 4.0 Digital Monitoring (I4M): IoT-enabled monitoring with centralized analytics but no adaptive carbon-aware optimization; and

c) *Scenario C* – Industry 5.0 I5-ECO Framework: Integrated digital twin simulation, AI-based multi-objective energy–carbon optimization, and renewable-aware scheduling with human-in-the-loop oversight.

Baseline parameter values for Scenario A were calibrated using empirical industrial energy consumption patterns that are reported in decarbonization literature (Allwood *et al.*, 2011).

Energy Consumption Performance and Efficiency Improvements

A primary objective of the I5-ECO framework is the reduction of total manufacturing energy demand through adaptive optimization and predictive energy governance. Table 3 presents the comparative energy consumption outcomes across the three scenarios.

The Industry 5.0-enabled I5-ECO framework achieved a 29.2% reduction in annual energy consumption when compared to conventional manufacturing control. This improvement reflects real-time load balancing, elimination of idle energy losses, and AI-driven scheduling of energy-intensive processes. The results confirm that Industry 5.0 architectures deliver measurable efficiency gains beyond Industry 4.0 monitoring systems, which primarily provide visibility rather than optimization.

Carbon Emission Intensity and Net-Zero Alignment

Carbon Emission Intensity (CEI) was evaluated as a key indicator of carbon-neutral manufacturing progress. Table 4 summarizes comparative CO_2 intensity outcomes across scenarios.

The I5-ECO framework reduced carbon intensity by 33.3%, demonstrating that energy efficiency gains were coupled with carbon-aware optimization. Through the integration of carbon coefficients into scheduling algorithms, production loads were shifted towards lower-emission energy windows, particularly during periods of higher renewable availability. This adaptive decarbonization mechanism represents a methodological advancement over static carbon management strategies.

Table 4: Carbon Emission Intensity (CEI) across governance scenarios.

Scenario	CO_2 Emission Intensity (kg CO_2/unit)	Reduction vs. Baseline (%)
CMC (A)	5.1	–
I4M (B)	4.2	17.6%
I5-ECO (C)	3.4	33.3%

Table 5: Energy Productivity Index (EPI) improvements.

Scenario	Energy Productivity Index (units/MWh)	Improvement vs. Baseline (%)
CMC (A)	8.4	–
I4M (B)	9.6	14.3%
I5-ECO (C)	10.3	22.6%

Table 6: Renewable Energy Utilization Rate (REUR) across scenarios.

Scenario	Renewable Energy Share (%)	Increase vs. Baseline (%)
CMC (A)	18	–
I4M (B)	25	38.9%
I5-ECO (C)	33	83.3%

Energy Productivity and Sustainable Output Performance

Beyond the reduction of energy use, sustainable manufacturing transitions require the maintenance or improvement of productivity. The Energy Productivity Index (EPI) captures output per unit of energy input. Table 5 presents comparative productivity outcomes.

The Industry 5.0-enabled framework improved energy productivity by 22.6%, thus confirming that energy reductions did not come at the expense of throughput. Instead, digital twin–enabled optimization enhanced operational sequencing and reduced downtime, generating both environmental and economic performance benefits.

Renewable Energy Utilization and Carbon-Neutral Transition Support

Renewable Energy Utilization Rate (REUR) was evaluated to assess the framework's ability to integrate low-carbon energy sources into manufacturing operations. Table 6 presents renewable utilization outcomes.

The I5-ECO framework increased renewable utilization from 18% to 33%, thereby supporting deeper decarbonization pathways. Through the dynamic alignment of production schedules with renewable supply availability, the system reduced dependence on carbon-intensive grid electricity. This finding highlights the importance of adaptive governance mechanisms for attaining operational carbon neutrality under variable renewable conditions.

AI-Enabled Energy Anomaly Detection and Governance Responsiveness

An additional benefit of the Industry 5.0 framework was enhanced anomaly detection accuracy for the identification of inefficient machine behavior and abnormal energy spikes. Simulation results revealed the following:

a) *CMC:* 52% detection accuracy

b) *I4M:* 68% detection accuracy

c) *I5-ECO:* 93% detection accuracy

This improvement reflects the integration of AI-driven predictive analytics within the digital twin environment; this enables proactive intervention rather than reactive energy loss correction. Such governance responsiveness is critical for the sustenance of long-term energy efficiency gains in complex manufacturing ecosystems.

Integrated Sustainability Performance Outcomes

Fig. 3 presents a comparative visualization of the following key sustainability indicators, total energy consumption, carbon emission intensity, energy productivity, renewable energy utilization, and anomaly detection accuracy, across three simulated governance scenarios: Conventional Manufacturing Control (CMC), Industry 4.0 Digital Monitoring (I4M), and the Industry 5.0-enabled I5-ECO framework. The figure highlights the measurable sustainability gains achieved through Industry 5.0-driven adaptive optimization.

Collectively, the simulation results demonstrate that Industry 5.0-enabled data-driven governance significantly outperforms conventional and Industry 4.0-based systems across all sustainability metrics. The framework achieved simultaneous reductions in energy demand and carbon intensity while also improving productivity and renewable integration. These outcomes reinforce the argument that Industry 5.0 sustainability transitions require not only digital visibility, but also adaptive optimization architectures that embed energy-carbon objectives directly into production control systems. Importantly, the measurable reductions in energy consumption (29.2%) and carbon intensity (33.3%) demonstrate that carbon-neutral manufacturing is achievable through integrated methodological innovation rather than isolated efficiency interventions. The findings position Industry 5.0-enabled frameworks as scalable pathways for industries that are clamouring to meet net-zero commitments while maintaining competitiveness and operational resilience.

DISCUSSION AND IMPLICATIONS

The results of this study provide strong empirical evidence that Industry 5.0-enabled data-driven architectures can significantly advance energy-efficient and carbon-neutral manufacturing systems. Across all evaluated sustainability indicators, the proposed Industry 5.0 Energy-Carbon Optimization (I5-ECO) framework outperformed both conventional manufacturing control and Industry 4.0-based digital monitoring scenarios. In particular, the observed 29.2% reduction in total energy consumption and 33.3% decline in carbon emission intensity confirm that sustainability improvements are not merely conceptual aspirations but operationally achievable through integrated methodological innovation. These findings reinforce broader industrial decarbonization research as they emphasize that deep emissions reductions require systemic transformations rather than incremental efficiency upgrades. Importantly, the sustainability gains were achieved without compromising throughput, as evidenced by the 22.6% improvement in energy productivity. This suggests that Industry 5.0 sustainability transitions can support both environmental and economic objectives simultaneously, challenging the assumption that decarbonization necessarily constrains industrial competitiveness.

While Industry 4.0 has been widely associated with automation, connectivity, and digital efficiency, Industry 5.0 introduces a broader governance paradigm that embeds sustainability, resilience, and human-centric value creation into industrial design. The findings of this study demonstrate that Industry 5.0's contribution to sustainability lies not only in technological advancement, but also in its ability to integrate environmental objectives into real-time operational governance. The I5-ECO framework exemplifies this shift through the integration of energy and carbon optimization directly into production control architectures through digital twins, AI-driven scheduling, and renewable-aware decision systems. This moves sustainability beyond static reporting or isolated interventions towards continuous, adaptive optimization, which is an essential requirement for achieving carbon neutrality in dynamic manufacturing environments.

A key methodological contribution of this research is the integration of digital twin simulation and AI-based multi-objective optimization as core enablers of adaptive sustainability governance. Digital twins provide predictive visibility into energy demand patterns and carbon intensity trajectories, which allows manufacturers to evaluate

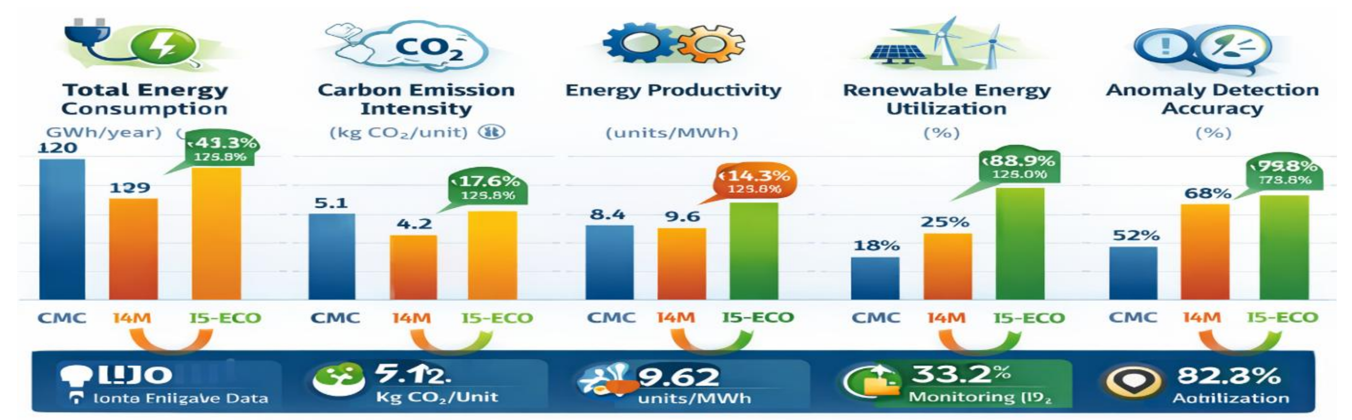

Fig. 3: Comparative sustainability performance across governance scenarios.

decarbonization strategies before costly deployment. When combined with AI optimization, these tools enable production systems to dynamically balance competing priorities such as throughput, energy efficiency, and emissions reduction. The high anomaly detection accuracy achieved under the Industry 5.0 framework (93%) highlights the importance of AI-driven analytics in the identification of inefficiencies and prevention of energy losses in real time. This aligns with cyber-physical manufacturing research that emphasize that advanced analytics are essential for the operationalization of sustainability in smart factories (Lee *et al.*, 2015).

For industrial managers and manufacturing strategists, the results suggest that achieving carbon-neutral production requires integrated governance infrastructures rather than fragmented sustainability initiatives. The measurable reductions in energy use and emissions intensity indicate that firms that are investing in Industry 5.0-enabled optimization architectures can simultaneously reduce operational costs, enhance regulatory readiness, and strengthen sustainability performance. The improved renewable energy utilization rate (33%) further demonstrates that adaptive scheduling mechanisms can support deeper integration of low-carbon energy sources into industrial operations. This is particularly relevant as energy markets shift towards renewables and as manufacturers face increasing exposure to carbon pricing mechanisms and climate-related supply chain risks. Moreover, the human-centric emphasis of Industry 5.0 suggests that sustainability governance must include transparent decision interfaces and workforce engagement rather than relying solely on automated optimization. Managers can therefore leverage Industry 5.0 frameworks to align technological transformation with organizational inclusion and social sustainability objectives.

The findings also have important implications for policymakers who aim to accelerate industrial decarbonization pathways. As governments implement stricter emissions standards and net-zero industrial strategies, there is a growing need for digital infrastructures that enable measurable, verifiable, and scalable sustainability performance improvements. Industry 5.0-enabled frameworks provide regulators with a model for how real-time monitoring, predictive simulation, and carbon-aware optimization can strengthen industrial compliance while also reducing enforcement burdens. The demonstrated increase in renewable energy utilization also supports policy efforts that are aimed at the integration of manufacturing demand flexibility into broader energy transition planning. Adaptive production systems that respond to renewable availability can contribute to grid stability and accelerate the shift towards low-carbon industrial ecosystems.

Academically, this study contributes to the emerging convergence of Industry 5.0 scholarship, sustainable manufacturing research, and data-driven decarbonization methodologies. While existing literature has explored Industry 5.0 conceptually, empirical evidence that demonstrates measurable sustainability benefits has remained limited (Xu *et al.*, 2021). This research advances the field through the provision of simulation-based validation of energy-carbon optimization architectures and by the operationalization of carbon neutrality through quantifiable performance metrics.

Future research should extend this work through empirical pilot deployments in real manufacturing environments, integrating sector-specific datasets and renewable energy market dynamics. Additional investigation into the role of human-AI collaboration in sustainability decision-making, as well as the integration of circular economy metrics alongside carbon neutrality, would further strengthen Industry 5.0 governance models. Overall, this study positions Industry 5.0-enabled data-driven frameworks as transformative pathways for achieving measurable, resilient, and scalable carbon-neutral manufacturing systems, thus offering both practical and theoretical foundations for the next generation of sustainable industrial transformation.

CONCLUSION

This study set out to examine how Industry 5.0-enabled, data-driven strategies can operationalize energy efficiency and carbon neutrality within manufacturing systems. Moving beyond incremental process improvements and static reporting mechanisms, the research proposed an integrated Energy–Carbon Optimization (I5-ECO) framework that embeds real-time monitoring, digital twin simulation, AI-driven multi-objective optimization, and carbon-aware scheduling into a unified governance architecture. Through system dynamics-based simulation, the framework demonstrated measurable reductions in energy consumption and carbon emission intensity, alongside improvements in energy productivity and renewable energy utilization. The findings confirm that carbon-neutral manufacturing is not solely dependent on technological substitution or renewable energy adoption, but also on intelligent coordination of production systems through adaptive digital infrastructures. Through the integration of predictive modeling and optimization into core operational decision-making, Industry 5.0 transforms sustainability from a compliance-driven obligation into a dynamic performance objective. The measurable improvements observed in energy efficiency and decarbonization performance highlight the practical feasibility of aligning environmental responsibility with industrial competitiveness.

Importantly, the proposed framework illustrates how sustainability governance can be embedded within manufacturing control systems without compromising productivity. The simultaneous gains in energy productivity and renewable integration demonstrate that economic and environmental objectives need not be mutually exclusive. Instead, when digital intelligence, human-centric oversight, and carbon-aware decision systems converge, manufacturing systems can evolve into adaptive, resilient, and low-carbon production ecosystems. From a broader perspective, this research positions Industry 5.0 as a transformative paradigm for sustainable industrial development. By integrating human-centered design with advanced analytics and predictive simulation, Industry 5.0-enabled architectures provide a pathway toward operationally measurable and scalable net-zero manufacturing transitions. The study underscores the importance of system-level integration, where energy monitoring, carbon accounting, and optimization models are not isolated modules but interdependent components of a continuous sustainability loop.

While simulation results provide strong evidence of the framework's potential, future research should focus on empirical implementation within live manufacturing environments to validate real-world performance under operational constraints. Longitudinal case studies across diverse industrial sectors like automotive, electronics, and heavy manufacturing would offer deeper insight into scalability, cost implications, and workforce adaptation dynamics. Further research should also explore the integration of circular economy metrics alongside carbon neutrality indicators, expanding the framework to encompass material efficiency, waste reduction, and lifecycle resource optimization. Incorporating advanced energy storage systems and demand-response participation models may strengthen renewable integration under fluctuating grid conditions.

Another promising direction involves enhancing human–AI collaboration within Industry 5.0 systems. Investigating how decision transparency, explainable AI, and workforce training influence sustainability outcomes can ensure that digital optimization remains aligned with human-centric industrial values. Additionally, exploring cross-factory and supply-chain-level energy coordination could extend carbon-neutral strategies beyond single production facilities toward network-wide decarbonization. In conclusion, Industry 5.0-enabled data-driven strategies offer a viable and measurable pathway towards energy-efficient and carbon-neutral manufacturing systems. Through the embedding of adaptive intelligence into production governance, industries can transition from reactive sustainability management to proactive, resilient, and performance-driven decarbonization. As global climate commitments intensify and industrial competitiveness increasingly depends on environmental performance, such integrated digital sustainability architectures will be central to shaping the next generation of responsible and regenerative manufacturing systems.

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Grant Support Details

The present research did not receive any financial support to conduct the research.

Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/ or falsification, double publication and/or submission, and redundancy has been completely observed by the authors.

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