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Carbon Emission under Industry 5.0

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Abstract

Industry 5.0 integrates people and machines into production to achieve more personalization, possibilities, and sustainable development. Industry 5.0 has three core elements: Humancentric, sustainability, and resilience. Humancentric emphasizes human-machine collaboration. Talent is the core of industrial operation. Technology is to serve humans better, not to replace humans. The sustainability of Industry 5.0 includes economic, environmental, social, and technological sustainability. In these aspects, Industry 5.0 has new requirements and development directions for sustainability. The carbon footprint runs through every link of the industry. Reducing carbon emissions is the requirement of Industry 5.0 for environmental sustainability. The technological innovation and progress of Industry 5.0, as well as the concept of sustainability, all affect and reduce carbon emissions to varying degrees.

Keywords

Industry 5.0, carbon emissions, environmental sustainability

Introduction

As the world enters a more intelligent era, Industry 5.0 has become a new chapter in the development of manufacturing and technology. This concept was first proposed by the European Commission in 2021, marking the arrival of the "Fifth Industrial Revolution". The European Commission proposed three core elements of Industry 5.0: Humancentric, Sustainability, and Resilience. Industry 5.0 has different degrees of improvement in concept compared with the existing four industrial revolutions, but it pays more attention to human-machine collaboration, personalization, and sustainability (Aheleroff, 2022).

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Figure 1: Core values of Industry 5.0

Sustainability of Industry 5.0 refers to the use of smart technologies and innovative means to improve production efficiency and product quality while minimizing negative impacts on the environment, promoting efficient use of resources, and achieving coordinated development in the three aspects of economy, society, and environment. This concept not only involves the production process itself, but also covers the entire supply chain, product design, energy use, waste management, and other links, aiming to create a more environmentally friendly and sustainable industrial ecosystem (Breque, 2021).

In Industry 5.0, environmental sustainability refers to the full use of advanced technologies and innovative means by enterprises and society in the process of development to minimize negative impacts on the environment, protect natural resources, and support the health and stability of the ecosystem (Leong, 2024a; 2024b, 2024c). Industry 5.0 emphasizes the coordinated development of technological progress and environmental protection and is committed to achieving long-term environmental sustainability.

In the context of continued global warming, it is urgent to control carbon emissions. Industry 5.0 enables enterprises to reduce greenhouse gas emissions such as carbon dioxide generated during the production process through technical means. Enterprises can reduce their dependence on fossil fuels by improving process flows, improving energy efficiency, and introducing clean and renewable energy (such as solar energy, wind energy, and biomass energy), as well as adopting carbon capture and storage technology to reduce the carbon footprint of the manufacturing industry, reduce environmental pollution during energy use, gradually achieve carbon neutrality goals, and reduce the impact on climate change (China, 2021).

Existing research shows that digital technology plays an important role in helping the world cope with climate change. Digital technology can provide networked, digital, and intelligent technical means for the green development of the economy and society, enable the construction of a clean, low-carbon, safe, and efficient energy system, help industrial upgrading and structural optimization, promote green changes in production and lifestyle, and promote the reduction of overall social energy consumption (Leong, 2024c; 2024d; 2024e). Digital technology implements technical improvements and optimized configurations for traditional industries, leads process and service innovation, and has great potential to support low-carbon development. In terms of carbon emission management, it can promote efficient carbon management and carbon emission tracking and monitoring (Chen, 2023; Leong, 2024f).

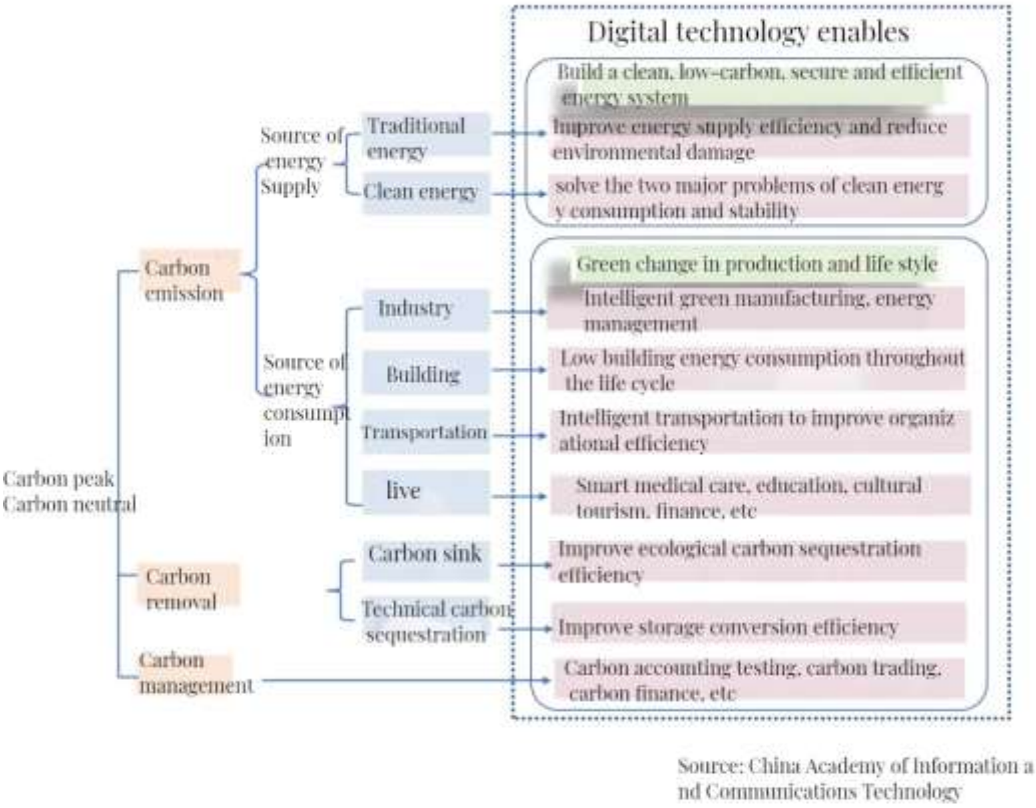

Figure 2: The main ways in which digital technology can help achieve carbon peak and carbon neutrality

Big data and AI can help companies reduce carbon emissions. During the production process, AI can analyze material performance data, supply chain information, and environmental impacts to help companies choose more environmentally friendly and sustainable materials. While improving the environmental performance of products and extending product life, it can also reduce the carbon footprint of products during their life cycle (Gibson, 2023).

AI can integrate data from all links of the supply chain, from raw material procurement to final delivery, to achieve optimized management of the entire process. By reducing inventory backlogs and optimizing production and distribution rhythms, it helps companies reduce additional transportation needs and energy consumption caused by poor inventory management. AI and big data can accurately track the carbon emissions of each task and generate detailed carbon footprint reports. Companies can use this data for analysis, identify high-emission links and take corresponding emission reduction measures. This will more accurately predict the carbon emissions of different task plans, help companies choose the most environmentally friendly method, and adjust strategies in real time during execution to ensure the lowest carbon emissions (Scrucca, 2021).

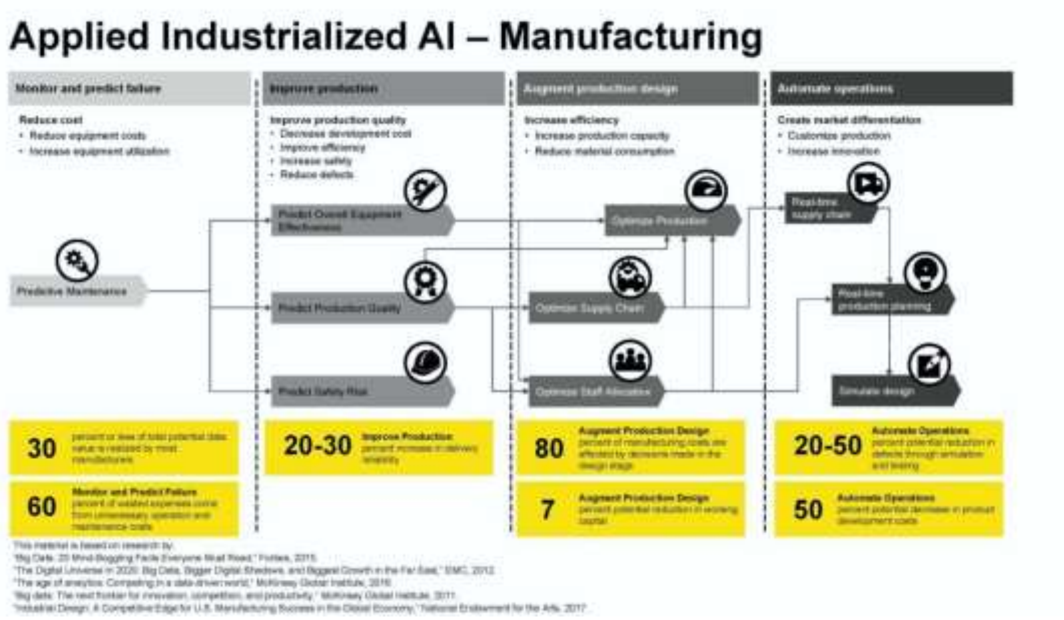

Figure 3：Artificial Intelligence in Manufacturing

Methodology

Carbon emissions refer to the amount of carbon dioxide emissions produced per unit area or unit energy per unit time. There are two methods for calculating carbon emissions: direct calculation and indirect calculation.

a. Direct calculation method: The direct calculation method refers to determining carbon emissions by measuring or estimating energy usage and carbon dioxide content.

i. Calculation of carbon emissions from electricity and heat:

By measuring energy input and carbon content of energy, using the formula $E = P \times C$, where E represents carbon dioxide emissions, P represents energy consumption, and C represents carbon content per unit of energy, calculate carbon emissions.

ii. Calculation of carbon emissions from fuel combustion:

By measuring fuel consumption and carbon content of fuel, using the formula $E = V \times C \times G$, where E represents carbon dioxide emissions, V represents fuel consumption, C represents carbon content per unit of fuel, and G represents carbon oxidation rate of fuel, calculate carbon emissions.

iii. Calculation of carbon emissions from industrial processes:

By measuring the consumption of raw materials and the carbon content of raw materials, as well as the corresponding number of products produced, the carbon emissions are calculated using the formula $E = P \times C \times G$, where E represents carbon dioxide emissions, P represents product output, C represents the carbon content of each unit of raw materials, and G represents the raw material consumption corresponding to each unit of product.

b. Indirect calculation method: The indirect calculation method refers to indirectly estimating carbon emissions by analyzing and calculating the factors affecting economic activities.

i. Production method:

By estimating the energy consumed in the production process of the product and the carbon content of the raw materials, as well as the corresponding product output, the carbon emissions are calculated using the formula E = P × C, where E represents carbon dioxide emissions, P represents product output, and C represents the carbon content of each unit of product.

ii. Consumption method:

Energy consumption and carbon dioxide emissions are estimated by investigating and counting consumers' energy consumption behavior.

iii. Industrial chain method:

By analyzing the supply chain and value chain, the energy consumption and carbon dioxide emissions of each link in the entire industrial chain are calculated, thereby estimating the overall carbon emissions (Trofimova, 2023). Table 1 displays an overview of Industry 5.0 technologies and their roles in emission reduction. Table 2 includes the percentage reduction in emissions contributed by each technology along with a description of their impact. Figure 4 illustrates the reduction across different emission categories.

Table 1. Overview of Industry 5.0 technologies and their roles in emission reduction.

Technology	Description	Role in Emission Reduction
Digital Twins	Virtual models of physical processes used to simulate and optimize energy usage, reducing waste and emissions.	Reduces energy consumption by optimizing processes.
Artificial Intelligence (AI) for Predictive Maintenance	AI algorithms that predict equipment failures and optimize maintenance schedules, minimizing energy waste.	Prevents unnecessary downtime, saving energy and resources.
Collaborative Robots (Cobots)	Energy-efficient robots that collaborate with humans to reduce production waste and energy consumption.	Reduces energy consumption and waste in production.
Renewable Energy Integration	Integration of renewable energy sources like solar and wind, decreasing reliance on fossil fuels.	Lowers carbon footprint by using clean energy sources.
Carbon Capture and Utilization	Technology that captures carbon emissions post-production, allowing for carbon reduction and potential reuse.	Directly reduces carbon emissions and offers potential for reuse.

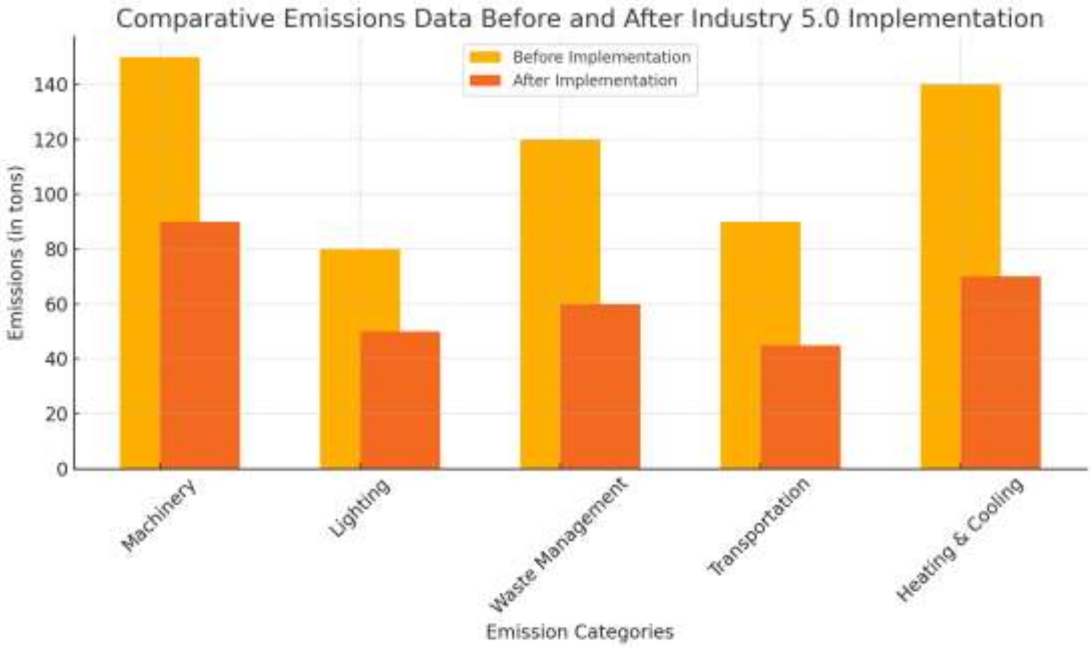

Figure 4: Comparative Emissions Data Before and After Industry 5.0 Implementation

Table 2: Breakdown of emission reductions by technology

Technology	Emission Reduction (%)	Description of Impact
Digital Twins	18	Optimizes energy consumption and reduces process emissions through simulation and adjustment.
Artificial Intelligence (AI) for Predictive Maintenance	12	Minimizes equipment downtime and energy waste by predicting maintenance needs.
Collaborative Robots (Cobots)	10	Reduces energy use and waste in production, contributing to lower emissions.
Renewable Energy Integration	35	Decreases reliance on fossil fuels, significantly reducing carbon footprint.
Carbon Capture and Utilization	25	Directly captures emissions, with potential for carbon reuse or storage.

Figure 5 shows live metrics for carbon emissions, energy consumption, and emission reduction. This visual provides a clear and interactive overview of emissions monitoring in an industrial setting. Table 3 provides a summary of each technology's impact on energy savings, emission reduction, and cost savings.

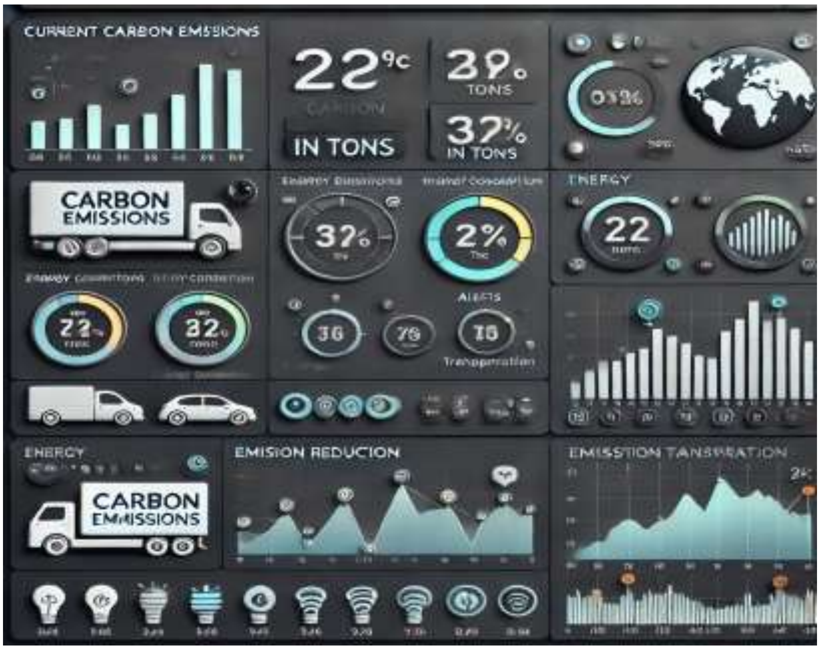

Figure 5: Real-time dashboard for monitoring carbon emissions.

Table 3: Summary of Key Metrics (Energy Savings, Emission Reduction Percentage, Cost Savings)

Metric	Energy Savings (%)	Emission Reduction (%)	Cost Savings (%)
Digital Twins	20	18	15
Artificial Intelligence (AI) for Predictive Maintenance	15	12	10
Collaborative Robots (Cobots)	10	10	8
Renewable Energy Integration	40	35	30
Carbon Capture and Utilization	0	25	5

Results and Discussion

Industry 5.0 is a new generation of industrial concepts, which aims to create a more harmonious industrial ecosystem through the combination of intelligent technology, personalized manufacturing and sustainable development (Xue, 2022). It not only promotes technological progress, but also pays attention to the symbiosis of humans and the environment, and closely combines the improvement of productivity with social progress. The sustainability of Industry 5.0 is multi-dimensional and multi-faceted. It combines the economy, environment, and society to truly achieve sustainable development. Industry 5.0 covers a wide range and involves a wide range of technologies and contents, but the fundamental purpose of Industry 5.0 is to promote the comprehensive upgrading of the industrial system and achieve a more efficient, flexible, and sustainable production method.

During the production process, Industry 5.0 can first analyze material performance data, supply chain information and environmental impact to help companies choose more environmentally friendly and sustainable materials. This not only helps to improve the environmental performance of products and extend product life, but also reduces the carbon footprint of products during their life cycle. Industry 5.0 can also identify the most energy-saving and efficient manufacturing processes. By optimizing production parameters or scheduling, unnecessary energy consumption and equipment idling in the production process can be reduced, and overall energy efficiency can be improved.

The environmental sustainability of Industry 5.0 is exploring the balanced relationship between industry and the environment, using industrial technology to empower the industry, allowing the industry to reduce environmental pollution and carbon emissions, and comprehensively promoting the green transformation and upgrading of the industry from the industrial level, reducing damage to the environment, better management and reducing carbon emissions.

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