Bridging Gaps in Carbon Emission Assessment: Optimization Strategies for Industrial Parks

Junzhong Huang[1] and Xuejun Tao [1,*]

[1]Jiangxi Kaiye Changjian Project Management Consulting Co., Ltd., Nanchang 330038, Jiangxi, China

Abstract. Global climate change necessitates urgent carbon emission reductions, with industrial parks (IP) being significant contributors. Existing evaluation methods often underestimate emissions by overlooking direct industrial processes. This study develops advanced quantification strategies and data-driven models to accurately assess and optimize emissions in IP. Key findings highlight the role of renewable energy integration, smart management, and enhanced policy support. The study offers actionable recommendations, emphasizing technological innovation and international cooperation for effective low-carbon transformation.

1. Introduction

Global climate change poses a serious threat to the subsistence and development of human societies, making the reduction of carbon emissions (carbon emission) a top priority for the world. Carbon dioxide (CO_2) emissions are the largest, accounting for about 75% of global greenhouse gas emissions. Therefore, an international effort to reduce carbon emission is an urgent priority. Industrial parks (IP), as centralized hubs of industrial activities, contribute significantly to carbon emission. These emissions mainly come from energy use (e.g., fuel combustion and electricity consumption), direct emissions from industrial processes (e.g., chemical reactions and solvent use), and waste treatment processes. This study aims to provide IP managers with accurate carbon emission insights by examining existing advanced carbon emission quantification strategies and to contribute to the gradual movement of IP towards a low-carbon, green as well as sustainable future through the development of targeted emission reduction strategies.

2. Evaluation methods, optimization models, and influencing factors of carbon emissions in IP

2.1 Evaluation methods

The evaluation of carbon emission in IP involves data collection, calculation, and analysis to determine the overall emission levels. Wang Y proposed the Life Cycle Assessment and Systems Engineering (LCA-SE) method, which focuses on the synergistic assessment of pollution and carbon emission in IP. By analyzing a case study in Guangzhou, this method highlighted the urgency of controlling greenhouse gas emissions and promoting photovoltaic power generation and energy-saving measures. However, the LCA-SE method only covers indirect carbon emission from energy production and usage, excluding direct emissions from industrial processes. With this oversight, the actual level of carbon emission may be underestimated [1].

Table 1 The research objects, advantages and limitations of different carbon emission evaluation methods.

Method	Object	Pluses	Limitations
EE - IOA	Regional, sectoral	economic compatibility	Data collection, updates
IDA	Driving factors	Less data, simple application	industry linkages
EM	Actors or policies	diversity	Variable prediction, method selection, Statistical test
CEE	DEA	nonparametric, independent, hidden relationships.	Model,variable selection influence results
Simulati-on and others	All	predict the impact of policy and technological	Limitations of different models

A review of 807 studies on carbon emission across various sectors in China between 1997 and 2017 identified five mainstream evaluation methods:

* Corresponding author: kycj-txj2024@qq.com

Environmentally Extended Input-Output Analysis (EE-IOA), Index Decomposition Analysis (IDA), Econometric models (EM), Carbon Emission Control Efficiency (CEE) evaluation, and simulation methods. Table 1 compares these methods based on their research objects, advantages, and limitations, with particular emphasis on EE-IOA's strength in analyzing inter-industry carbon emission linkages and IDA's unique ability to identify driving factors. These comparisons provide valuable references for selecting appropriate evaluation tools in specific contexts [2].

2.2 Optimization models

Optimization models for carbon emission utilize mathematical and computational approaches to pinpoint the most effective strategies for minimizing emissions while considering resource limitations and demand constraints. This process generally entails defining the objective function, setting up constraints, determining decision variables, gathering relevant data, and constructing the model, which is solved using various optimization algorithms. Table 2 compares the pluses and limitations of different carbon emission models.

Table 2. Pluses and Limitations of different carbon emission models.

Model Type	Pluses	Limitations
MultiStep Forecasting	High accuracy,Uncertai-nty analysis	Resourceintensive, Datadependent
Hybrid Forecasting	Enhanced accuracy,Flexible	Complex,Requires expertise
ntelligent Algorithms	Adaptive,Captures complex patterns	Overfitting risk,High computational need
3E Framework	Comprehensive, Clarifies energy balance	Complexity,Datas-ensitive
LowCarbon Development	Holistic,Integrates energy & industry	Implementation complexity,Coord-ination required
BiLevel Optimization	Economic incentives,Balanc-ed outcomes	Policy complexity,Regul-atorydependent

Recent progress in forecasting carbon emission can be categorized into three primary prediction models: (1) multi-step forecasting models incorporating deep learning alongside uncertainty analysis; (2) data-driven hybrid forecasting models blending multiple prediction techniques (such as time series analysis and regression analysis); (3) intelligent algorithm models.

Intelligent algorithm models excel in predictive accuracy due to their adaptive solid learning capabilities and ability to capture intricate data patterns [3]. Wei X's research explores electrification and thermal decarbonization pathways by employing the Economy-Energy-Environment (3E) analysis framework to assess the cost-effectiveness, energy requirements, and environmental impact of different pathways. This study outlines specific emission reduction strategies and clarifies the energy balance and conversion efficiency relationships across various energy types [4]. Li K extended the scope to include energy system management and adjustments in industrial structure, developing a comprehensive low-carbon development model for IP [5]. This model successfully addresses the shortcomings of previous studies that focused exclusively on either energy systems or industrial structures. Furthermore, Gu H introduced a novel bi-level optimization model that integrates multi-energy pricing incentives, such as differential energy pricing and subsidy policies, to guide enterprises in optimizing energy use while improving economic and environmental outcomes within IP [6].

2.3 Influencing factors

Various factors influence carbon emission calculations, including energy consumption, industrial processes, consumption patterns, electricity usage, building and infrastructure, environmental policies, and regulations. Among these, energy consumption and industrial processes are the primary sources of carbon emission. Sun Y emphasizes that the core of carbon neutrality lies in balancing carbon sources (e.g., CO2 emissions from fossil fuel combustion) with carbon sinks (e.g., CO2 absorption by forests), thereby ensuring a smooth carbon metabolic cycle and achieving dynamic equilibrium between carbon emission and absorption [7-8]. Table 3 compares the pluses and limitations of different carbon emission influencing factors.

Table 3. Pluses and Limitations of carbon emission influencing factors.

Model Type	Pluses	Limitations
Carbon Neutrality	Balances sources and sinks	Complex, Data-dependent
CCUS	Significant reduction potentia	High cost, Immature technology
Risk Assessment	Early risk detection	Limited adoption, Systemheavy
Wastewater Treatment	Efficient, Supports green growth	Lacks management strategies
Policy Implementation	Long-term impact	Delayed effect, Adjustment needed
Eco-Parks	Technology spread, Regiona impact	Area-specific, Needs projects

Current carbon capture, utilization, and storage (CCUS) technologies need help with economic viability and technological maturity. Their widespread adoption requires further research and policy support, improving capture efficiency, reducing costs, and scaling up technology [9]. Moreover, IP's lack of environmental risk

prevention mechanisms hinders green development. Park managers should establish comprehensive environmental risk assessment and management systems to identify potential risks early and develop contingency plans. Many IPs currently rely on centralized wastewater treatment systems but need more management strategies to support them. Additionally, the effectiveness of carbon reduction policies typically becomes apparent in the second year of implementation, as enterprises and parks require time for technological upgrades and operational adjustments. Establishing demonstrative eco-parks can generate significant spillover benefits within a 450-kilometer radius through technology diffusion and experience sharing, thereby promoting regional low-carbon transitions [10].

3 Case study

These case studies illustrate the diverse technological strategies employed by IP worldwide in optimizing carbon emission management, covering a broad spectrum of techniques from energy management to waste treatment. These technological applications demonstrate regional breakthroughs in low-carbon transitions and reflect the active practices and achievements of different regions in addressing climate change [11-15].

3.1 Energy management

The Suzhou Industrial Park has successfully implemented a low-carbon strategy by using distributed energy systems that combine solar photovoltaic technology with small gas turbines, boosting energy self-sufficiency and reducing reliance on external sources, thus lowering carbon emissions. In Denmark, the Kalundborg Industrial Park has significantly increased renewable energy use by developing wind power and introducing high-efficiency turbines and innovative grid technologies, significantly reducing overall emissions. Similarly, the Chiang Mai Industrial Park has promoted solar and biomass energy, cutting fossil fuel reliance through government support, corporate collaboration, and technological innovation, resulting in a notable decrease in emissions. In Japan's Kawasaki industrial area, hydrogen energy technology, including fuel cells, storage, and transportation systems, has been widely adopted, increasing the use of green energy. However, the broader adoption of hydrogen technology may need to be improved by high costs and technological challenges, affecting its feasibility for large-scale use.

3.2 Smart Management

Germany's Ruhr Industrial Park has adopted a comprehensive evaluation model based on Life Cycle Analysis (LCA), which thoroughly considers economic benefits, social impacts, and environmental protection factors. The park has developed a scientifically sound sustainable development plan and emission reduction strategy, including energy efficiency improvement, pollution control, and resource recycling. In the Dubai Green Industrial Park, an intelligent management system utilizes extensive data analysis and Internet of Things monitoring technologies to optimize real-time energy management, reduce energy waste, and achieve sustainable energy use goals through predictive maintenance and dynamic adjustment. However, implementing intelligent analysis models requires complex infrastructure, technology, and significant data support, which may increase future implementation and maintenance challenges for the park.

3.3 Waste utilization

The Shanghai Chemical Industrial Park has significantly reduced overall energy consumption and carbon emission by using industrial waste heat as a secondary energy source through combined heat and power and district heating systems, achieving efficient resource recycling. The Dalian Circular Economy Demonstration Park has reduced its reliance on primary resources and improved resource utilization efficiency by implementing material recycling and wastewater treatment and reuse measures, achieving waste resource utilization. Meanwhile, the Hebi Economic and Technological Development Zone has introduced advanced waste classification and harmless treatment technologies, effectively reducing hazardous waste emissions and significantly lowering environmental impact. However, market conditions and policy support may need to be revised to maintain the economic feasibility of waste utilization.

3.4 Policy implementation

Policy implementation is crucial for carbon reduction in Industrial Parks (IPs). In Suzhou, China, strict emission standards and clean energy incentives led to a 30% reduction in emissions, though sustainability depends on continued subsidies. Kalundborg, Denmark, leveraged national policies to increase renewable energy to 50%, but faced economic challenges in maintaining energy prices. Dubai's Green Industrial Park reduced energy consumption by 25% using IoT technologies, supported by UAE's Vision 2021, though high costs hinder scalability. Kawasaki, Japan, benefited from carbon taxes and government support for hydrogen energy, achieving a 20% emission reduction, but faced concerns over high investment costs. Overall, while policy-driven strategies significantly reduce emissions, their long-term success depends on balancing environmental goals with economic feasibility and ensuring sustained government support.

3.5 Current carbon capture, utilization, and storage

The Flemish Port Industrial Park has significantly reduced greenhouse gas emissions using advanced CCUS technologies. Captured CO_2 is stored in depleted offshore oil and gas fields, where it is safely sealed and monitored for a long time, making the technology highly scalable. The Shenzhen Yantian Port has established a

comprehensive carbon capture system, using captured CO_2 for waste gas processing and water treatment, thereby increasing the scope of carbon utilization. However, the cost of CCUS remains high, and the technology's application may be limited by investment, policy support, and legal considerations.

4 Conclusion and recommendations

This research explores the latest strategies for low-carbon transformation in industrial parks, focusing on energy management, innovative management practices, waste utilization, and CCUS technologies. It highlights the role of technological innovation, data analysis, and integrated management in cutting carbon emissions. To support sustainable low-carbon transitions in IP, the following recommendations are proposed:

(1) Boost Policy Support: Governments should increase financial incentives, tax breaks, and subsidies while establishing clear regulations for adopting low-carbon technology.

(2) Encourage Technological Innovation: Industrial parks should collaborate with research institutions to promote advances in energy management, waste utilization, and CCS technologies.

(3) Improve Data-Driven Decisions: Big data, AI, and IoT can enhance real-time monitoring and targeted emission reduction efforts.

(4) Promote Public-Private Partnerships: Cooperation between public and private sectors can facilitate resource sharing and drive the commercialization of low-carbon technologies.

(5) Strengthen International Collaboration: Engaging in global initiatives can help share best practices and speed up the adoption of low-carbon technologies.

By implementing these strategies, IP can significantly reduce emissions, support sustainable development, and contribute to global climate change mitigation efforts.

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