

A Blockchain-Supported Framework for Transparent Resource Trading and Emission Management in Eco-Industrial Parks (EIPs)

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ABSTRACT

Sustainable industrial development depends on optimizing resource and energy integration within Eco-industrial parks (EIPs), combined with stringent carbon emissions reduction policies. The main challenge is ensuring transparency, accountability, and data privacy while optimizing the conversion of raw materials and energy into valuable products and controlling emissions within EIPs. This research introduces an innovative framework to design optimized EIPs and deploy a blockchain-enabled trading platform for resources and emissions management, tackling these key issues. The proposed framework integrates EIPs with emission control policies, supported by two distinct smart contracts: one dedicated to blockchain-based resource trading and another handling financial transactions related to emission control policies, including other regulations such as income tax. The resource trading platform fosters transparency, enabling accurate tracking of material and energy flows. Furthermore, the framework integrates an off-chain Mixed-Integer linear Programming model (MILP) to optimize EIP design and operations, which is seamlessly integrated with smart contracts on the Ethereum blockchain (BC) to ensure data privacy and traceability among processes to meet environmental targets. The model also determines emission reductions and investments in carbon capture technology, promoting operational efficiency. By incorporating identity verification and external entities for compliance, the framework ensures secure and regulated operations. Offering a powerful tool to decision-makers and authorities, this framework enhances comprehension of resource and emissions tracking, paving the way for the development of innovative policies and fostering regulatory compliance. This development promotes sustainable industrial activities and supports environmental goals.

Keywords: Optimization, Sustainable Industry Practices, Transparency, Resource Trading, Emission Reduction Systems, Digital Transformation in Industry, Blockchain Technology

INTRODUCTION

The global push for sustainable development, spearheaded by the United Nations' Sustainable Development Goals (SDGs), highlights the importance of integrated resource management to balance environmental and economic sustainability. While progress has been made in SDG monitoring, critical data gaps remain, hindering comprehensive assessments and the formulation of effective policies [1]. The efficient and transparent management of material and energy resources is essential for mitigating environmental impacts and promoting

the long-term sustainability and adaptability of industrial ecosystems [2]. However, assessments of EIPs have revealed persistent challenges, such as low compliance in resource management and environmental performance, underscoring the urgent need for technological solutions [3]. Addressing these challenges requires innovative strategies that integrate transparent resource management, strict adherence to sustainability standards, and robust compliance with regulatory frameworks.

Significant research has focused on optimizing resource integration to enhance sustainability in industrial systems. A two-step MILP approach was developed to

design cost-effective carbon dioxide (CO₂) reduction networks, integrating renewable energy to reduce mitigation costs [4]. Multi-objective frameworks for CO₂ Capture, Utilization, and Storage (CCUS) supply chains have been proposed, balancing economic, environmental, and safety objectives through Pareto optimization [5]. CO₂ and heat integration approaches have also been explored to minimize net energy demand and emissions, leveraging synergies such as process heat recovery to reduce CO₂ capture costs [6]. Additionally, a MILP-based optimization for CCUS supply chains in the UK demonstrated the economic viability of emissions reduction strategies under CO₂ tax policies, highlighting the role of site selection in minimizing costs and maximizing net present value [7].

For water and energy integration, an extended pinch analysis was used to design water recycling networks [8], while seasonal variations in water-energy systems were addressed using a mixed-integer non-linear optimization framework (MINLP) to ensure robust designs under peak demand [9]. Multi-objective optimization has also been applied to minimize CO₂ and water footprints while maximizing economic returns in industrial clusters [10]. Lastly, integrating renewable energy with CO₂ capture and utilization has been shown to enable net-zero emissions in energy systems through dynamic optimization [11].

While previous research has advanced resource integration strategies in EIPs, a critical challenge remains – the lack of transparency in resource management, emissions tracking, and regulatory compliance. Studies indicate that industrial parks often struggle with inadequate transparency in environmental practices, leading to inefficient resource utilization and unchecked pollution emissions [12]. Additionally, the absence of reliable data-sharing mechanisms hinders effective industrial symbiosis, as firms face barriers such as data inaccessibility, lack of trust, and inconsistent byproduct supply [13]. Policy inconsistencies further exacerbate these challenges, as gaps in the adherence to EIP guidelines and misinterpretations of sustainability principles reduce the effectiveness of implementation strategies [14]. These transparency-related inefficiencies not only limit the potential for industrial collaboration but also weaken the environmental and economic benefits that EIPs aim to achieve.

To address these transparency gaps, emerging technologies such as BC have been proposed to enhance data integrity, traceability, and regulatory enforcement in industrial ecosystems. Permissioned BC frameworks have been explored for CO₂ emission trading, aiming to reduce fraud, improve monitoring, and facilitate secure, automated transactions [15]. In the context of CCUS supply chains, BC-based smart contracts have been shown to enhance tracking, compliance, and cost efficiency by reducing reliance on third-party verifiers [16]. Beyond

emissions management, BC is increasingly recognized as a solution for data governance in EIPs, offering decentralized platforms that enable peer-to-peer resource exchange, transparent record-keeping, and enhanced industrial collaboration [17] [18]. These developments highlight the potential of integrating optimization models with BC-based smart contracts to create a secure, transparent, and efficient framework for managing resource flows and emissions within EIPs.

Despite advancements in resource integration and the application of BC for transparency, existing frameworks still exhibit significant limitations. Most models focus either on optimization-based resource integration or BC-enabled trading mechanisms but rarely synthesize both in a way that ensures simultaneous economic, environmental, and operational efficiency. Additionally, while BC applications have been explored for CO₂ markets and CCUS supply chains, they often lack comprehensive integration with broader EIP resource flows, including water, energy, and materials. Furthermore, transparency challenges persist in data tracking, regulatory compliance, and secure material, energy, and financial resource exchanges, as many frameworks do not incorporate accurate monitoring of industrial symbiosis. This research addresses these gaps by introducing a hybrid optimization-BC framework that integrates a MILP model for EIP design with smart contract-based resource exchange. By leveraging BC's architecture, the proposed framework ensures secure, transparent, and efficient management of resource flows, emissions, and financial transactions. This approach not only enhances trust and compliance within EIPs but also establishes a scalable and adaptable solution for industrial ecosystems aiming to meet sustainability targets while maintaining operational resilience.

FUNDAMENTALS OF BLOCKCHAIN AND SMART CONTRACTS

BC is a decentralized digital ledger that enables secure, transparent, and tamper-proof transactions across various industries, including finance, healthcare, supply chains, and energy systems [19]. Unlike centralized databases, it eliminates intermediaries, reducing fraud and enhancing security through cryptographic hashing and consensus mechanisms such as Proof of Work (PoW) and Proof of Stake (PoS) [20]. Transactions, once validated, are stored in linked blocks, ensuring immutability and trust, making BC ideal for applications requiring secure financial transactions, identity verification, and supply chain tracking [21].

Key BC features include decentralization, which prevents system failures and reduces fraud [20]; immutability, ensuring a tamper-proof and auditable record of transactions [19]; and transparency, allowing participants

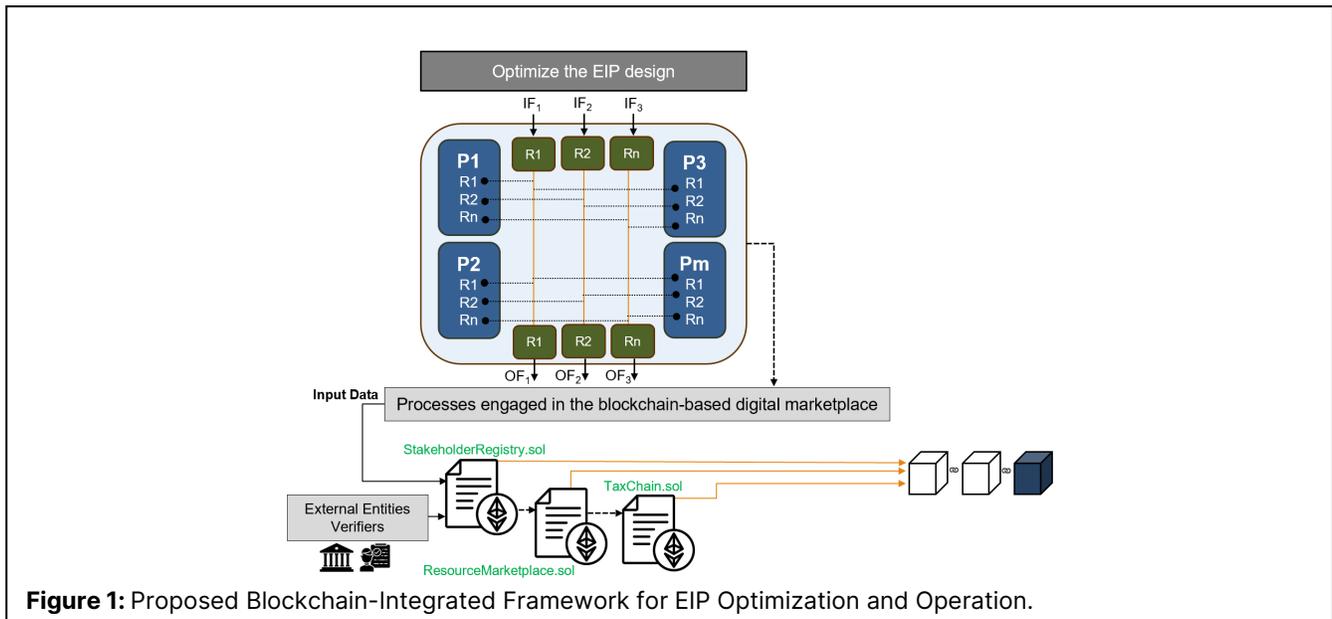


Figure 1: Proposed Blockchain-Integrated Framework for EIP Optimization and Operation.

to access synchronized data, promoting accountability [21]. Security is reinforced through cryptographic encryption, protecting data from cyber threats [22], while smart contracts automate transactions, streamlining operations and reducing the need for intermediaries [23].

These features drive BC adoption across multiple sectors. In healthcare, it ensures secure patient data management and prevents counterfeit pharmaceuticals [24]. Supply chain management benefits from BC's immutable records, enhancing product traceability and fraud prevention [25]. In energy systems, BC facilitates peer-to-peer energy trading, reducing dependency on centralized grids and supporting renewable energy adoption [26]. It also enhances electoral security in government systems [23], and secures machine-to-machine transactions in smart manufacturing [27]. Furthermore, BC optimizes financial transactions by supporting cryptocurrencies, decentralized finance and automated smart contracts [28]. With its secure and transparent architecture, BC transforms industries by enhancing data security, fraud prevention, and operational efficiency, driving digital innovation and sustainable development.

PROPOSED FRAMEWORK AND METHODOLOGY

This study presents a multi-stage optimization and BC-based framework to enhance resource integration, transparency, and emissions management within an EIP. The methodology comprises two primary components: (1) Optimization of the EIP design using an extended MILP model which was initially proposed by [10], and (2) BC-enabled smart contracts for transparent resource trading and financial transactions. Figure 1 illustrates the architecture of the proposed system.

1. Optimization of the EIP Design

The first stage of the methodology involves optimizing the selection and capacity of industrial processes within the EIP. A MILP model is employed to identify the optimal set of processes, ensuring maximum economic profitability while adhering to environmental constraints, including CO₂ emissions cap and zero untreated wastewater discharge. The objective function is defined as:

$$\text{Max Profit} = \text{TR} - (\text{CC} + \text{OC} - \text{Taxes}) \quad (1)$$

where TR, CC, and OC represent the total revenue, capital cost, and operating cost, respectively. Total Revenue is generated from resource exchanges, and Capital/Operating Costs are associated with process operation. Taxes include CO₂ tax for excess CO₂ emissions and income tax, incentivizing industries that collaborate within the EIP. The mass balances for resource exchanges among processes is defined using:

$$\text{IF} - \text{RE} - \text{OF} = 0 \quad (2)$$

where IF, RE, and OF represents the input flow of the resource, resource exchange, and outlet flow respectively. For each process, mass balance constraints ensure:

$$\text{REP} - (\text{FP} \times \text{PC}) = 0 \quad (3)$$

where REP, FP, and PC represent the resource exchange with processes, flow parameter, and process capacity, respectively. Process capacities and resource imports/exports are bounded by upper and lower limits, ensuring realistic operational feasibility. Additionally, a constraint is imposed to eliminate untreated wastewater discharge, forcing all generated wastewater to be treated before release. CO₂ emissions are constrained based on a predefined CO₂ cap. If the emissions exceed the limit, a CO₂ tax is applied to the excess amount:

$$CE - (CCA + TCA) \leq CA_{cap} \quad (4)$$

where CE, CCA, TCA, and CA_{cap} represent the CO₂ emissions, captured CO₂ emissions, taxed CO₂ emissions, and the predefined CO₂ cap, respectively. The model dynamically adjusts process operations to optimize the costs of CO₂ taxation and CO₂ capture units.

2. Blockchain-Based Resource Exchange and Taxation

Once the optimal EIP configuration is determined, the activated processes participate in a BC-based digital marketplace for secure and transparent resource transactions. Ethereum is chosen as the BC platform due to its robust smart contract functionality and wide adoption.

2.2 Blockchain Transaction Process

The BC-based resource exchange mechanism follows a structured process to ensure secure and transparent transactions within the EIP. Initially, processes register through the StakeholderRegistry.sol smart contract, which verifies and maintains the identity of each participant. Once registered, industries list their available resources on the ResourceMarketplace.sol contract, specifying key attributes such as flow rate, quality, pressure, temperature, and price. When a process initiates a trade, the smart contract verifies resource availability, compliance with EIP constraints, and pricing conditions. Upon successful validation, the trade is executed, and the transaction is recorded on the BC, ensuring an immutable record of resource exchanges. Additionally, financial transactions, such as CO₂ tax and income tax payments, are automated through TaxChain.sol, which deducts applicable taxes from the EIP and transfers the payment to the regulatory authority. This decentralized mechanism eliminates manual oversight, reducing delays and ensuring compliance with environmental and financial regulations. By integrating BC into resource exchange and taxation, the system fosters trust, efficiency, and automated enforcement of sustainability policies within the EIP.

2.3 Advantages, Considerations, and Challenges

Ensuring trust, traceability, and regulatory compliance in industrial symbiosis is a major challenge. The proposed BC-enabled system enhances transparency by maintaining immutable records, minimizing fraud and data manipulation. Smart contracts automate verification, ensuring only registered processes participate in trades while meeting environmental and economic criteria. By requiring complete resource data before execution, the system prevents omissions, duplicates, and unauthorized transactions. The decentralized ledger allows external audits without intermediaries, while automated compliance checks enforce emission limits, wastewater treatment, and taxation policies, reducing administrative burdens. This framework ensures regulatory adherence

and incentivizes industries to adopt sustainable practices.

The proposed MILP-BC framework enhances EIP efficiency by integrating process optimization with smart contract-based resource trading, ensuring optimal resource allocation, cost reduction, and emissions control. Automated CO₂ and income tax enforcement simplifies compliance, while BC's immutable ledger strengthens data security, transparency, and fraud prevention. Additionally, decentralization fosters accountability, promoting sustainable industrial practices while improving financial performance. However, several challenges must be addressed. Balancing data privacy and transparency is critical, as BC's immutability could expose sensitive information. The high computational cost of smart contracts and the lack of clear regulatory frameworks pose further obstacles. Additionally, industry adoption may be hindered by technical complexity and resistance to change. Overcoming these barriers requires scalability improvements, privacy-preserving techniques, and regulatory collaboration to ensure effective deployment and widespread adoption of the framework.

ILLUSTRATIVE EXAMPLE

To evaluate the proposed system, a case study was conducted on an EIP integrating both product-based processes and emissions mitigation strategies. The industrial processes include Air Separation Unit (ASU), Ammonia Plant (AP), Cement Plant (CP), Methanol Plant (MP), Natural Gas Power Plant (NGPP), Seawater Reverse Osmosis (SWRO), Steam Methane Reforming Unit (SMR), Urea Plant (UP), and Wastewater Treatment Unit (WWTU). Emissions mitigation strategies incorporate CO₂ capture technologies (CC), utilization pathways (methanol, urea), enhanced oil recovery (EOR), direct air capture (DAC), and sequestration. The EIP aims to maximize net profit by optimizing resource exchanges and CO₂ capture, while adhering to a CO₂ cap of 250,000 tons CO₂/year, a CO₂ tax of \$40/ton CO₂, and an income tax of 15%. Process data for DAC, sequestration, EOR, NGPP, and its capture unit were sourced from [11], while data for other processes were obtained from [10]. The project lifespan is 20 years, with required inputs including capital and operating costs, as well as resource flow parameters expressed in tons per ton of the main product (t/t Ref).

Capacity limits were defined for each unit, with ASU, AP, MP, SMR, UP, and EOR capped at 200,000 t/y, CP and CP CC at 1,000,000 t/y and 500,000 t/y, respectively, NGPP at 600,000 MWh/y, and NGPP CC, SMR CC, and DAC at 1,500,000 t/y. SWRO and WWTU capacities were set at 8,000,000 t/y and 300,000 t/y, respectively, while sequestration was limited to 500,000 t/y. The CO₂ composition in emissions varies across processes, with

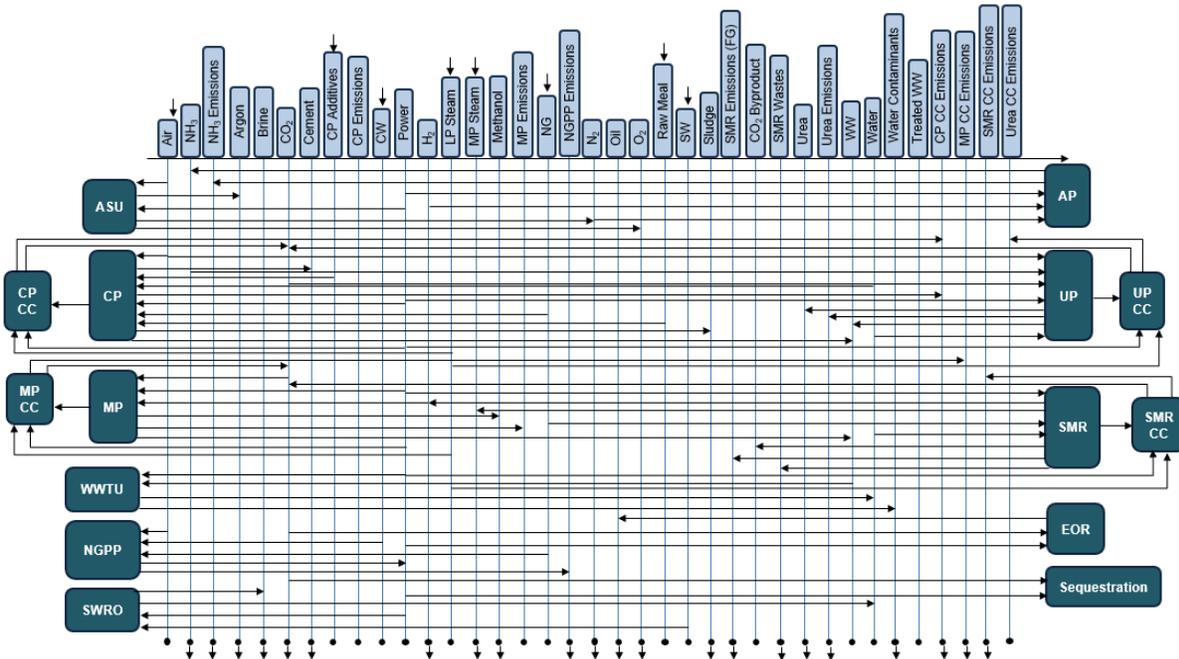


Figure 2: Resource Flow Network in the Optimized EIP.

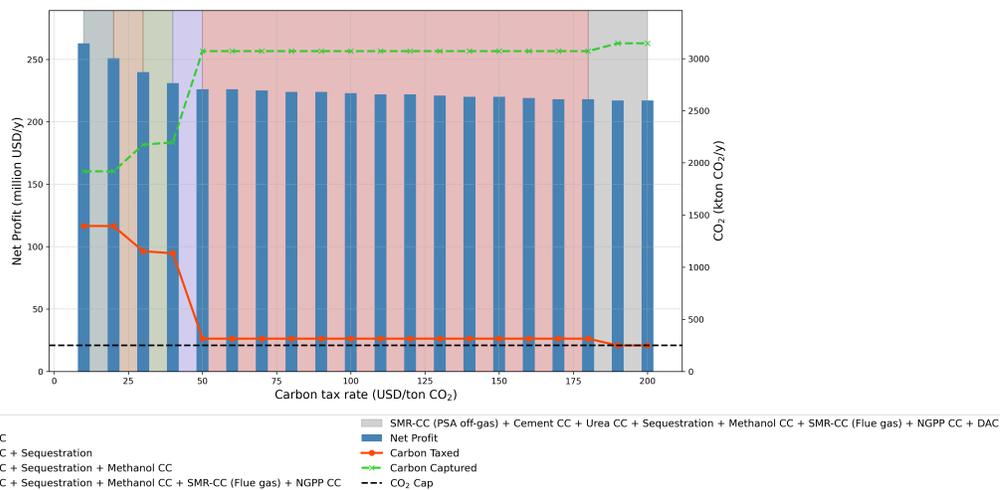


Figure 3: Impact of Carbon Tax Rate on Net Profit and CO₂ Emissions.

values ranging from 0.7% to 82%, depending on the emission source. This case study demonstrates the feasibility of resource optimization and emissions control within an EIP under regulatory and economic constraints.

The results show that the activated product-based processes include ASU, AP, CP, MP, SMR, UP, WWTU, and EOR, with NGPP and SWRO serving as utility plants. Emissions control strategies incorporate CO₂ capture from SMR-PSA off-gas, cement, and urea production, alongside sequestration and CO₂ taxation. The system successfully captured 1,945,930 tons of CO₂ per year, while 882,628 tons were taxed, demonstrating effective CO₂ management and regulatory compliance. Figure 2

presents the optimized EIP configuration, highlighting resource flows, activated processes, and emissions control measures.

The sensitivity analysis on the CO₂ tax rate, shown in Figure 3, explores its impact on net profit, CO₂ taxed, and CO₂ captured across a range of 10 to 200 \$/ton CO₂ with a step size of 10. The activated processes include ASU, AP, CP, MP, NGPP, SWRO, SMR, UP, WWTU, and EOR. The CO₂ cap was set at 250 kton CO₂/year, requiring any excess CO₂ to be either captured or taxed. As the CO₂ tax rate rises, the system shifts toward greater CO₂ capture and lower CO₂ taxation to minimize costs. The net profit decreases as CO₂ mitigation strategies become

more expensive, with higher tax rates making sequestration and capture more viable than direct taxation. The analysis identifies six regions of CO₂ mitigation progression: (1) at 10-20 \$/ton CO₂, capture is limited to SMR-PSA off-gas and cement, with the highest taxed CO₂; (2) from 20-30 \$/ton CO₂, urea capture begins; (3) from 30-40 \$/ton CO₂, sequestration is activated; (4) from 40-50 \$/ton CO₂, methanol capture is added; (5) from 50-180 \$/ton CO₂, capture extends to SMR flue gas and NGPP; and (6) at 180-200 \$/ton CO₂, DAC is introduced, reducing taxed CO₂ to zero at 190 \$/ton CO₂. This transition demonstrates how a rising CO₂ tax incentivizes a shift toward more extensive CO₂ capture, ultimately reducing emissions but at the cost of declining net profit.

The integration of BC in this EIP framework enhances transparency, efficiency, and regulatory compliance, particularly by automating the transition from MILP-optimized process capacities to real-world applications. Smart contracts ensure seamless execution of resource exchanges, taxation, and emissions management, maintaining adherence to optimized parameters while recording immutable, auditable transactions. This approach bridges the gap between theoretical optimization models and practical implementation, providing industries and policymakers with insights into resource utilization and emissions tracking. By ensuring accurate CO₂ taxation and automated compliance verification, BC fosters sustainable industrial operations and could enable incentive mechanisms, such as tax benefits or tradable environmental credits. The secure, transparent nature of BC further supports the development of standardized CO₂ credit trading, promoting a circular economy and data-based policies. This approach is adaptable to other energy-intensive industries such as steel production, chemical manufacturing, and renewable energy systems. In these sectors, the ability to optimize resource use, reduce emissions, and enhance operational transparency is crucial. Digitalization plays a pivotal role by enabling real-time data access, improving decision-making, and ensuring compliance with environmental standards. Thus, our methodology is well-suited to address similar challenges across various industrial contexts, promoting sustainable and efficient practices and supporting broader sustainability goals.

CONCLUSIONS

This study presents a BC-integrated framework for optimizing EIP operations, combining MILP-based optimization with smart contract automation to enhance resource management, transparency, and regulatory compliance. By seamlessly linking optimized resource flows to smart contracts, the system ensures efficient trading, automated taxation, and emissions tracking, reducing CO₂ emissions while maintaining economic viability. The

immutable ledger enables secure, auditable transactions, supporting policy enforcement and sustainability monitoring. This approach improves industrial efficiency and provides a scalable model for broader applications in decarbonization and circular economy initiatives. The integration of BC into EIP management paves the way for data-driven policymaking and enhanced environmental governance, fostering sustainable industrial development.

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