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Towards Sustainable Development: Synthesizing Optimal Integrated Peer-to-Peer Eco-Industrial Parks (EIPs) with Blockchain Technology

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The seamless integration of material and energy resources across industrial processes is imperative to achieve sustainable development goals (SDGs). A critical challenge lies in ensuring transparency and accountability in resource exchange while identifying conversion processes that collectively synergize raw materials and energy resources into value-added products. This paper introduces a framework designed to synthesize optimal integrated blockchain-based peer-to-peer Eco-Industrial Parks (EIPs), addressing this crucial requirement. To uphold data privacy and traceability standards, the Mixed Integer Linear Programming (MILP) model is intricately integrated with smart contracts on a blockchain platform, facilitating transparent resource integration. A novel and versatile problem representation enhances transparency for any process during its interaction with resource lines, enabling the seamless tracking of material and energy resources. The model effectively determines the acquisition and sale of material and energy resources by each module. This proposed framework not only equips decision-makers and regulatory agencies with a powerful tool to comprehend the intricate interactions among diverse modules transparently but also aids in formulating new policies and adhering to regulations through the utilization of smart contracts and blockchain technology's (BC) inherent characteristics.

1. Introduction and Overview of blockchain technology and smart contracts

The urgent quest for sustainable development has become a global priority, underscored by the United Nations' Sustainable Development Goals (SDGs), which emphasize the critical need for integrated management of natural resources to ensure environmental sustainability and economic viability (United Nations, 2023). Efficient and transparent management of material and energy resources is essential not only for mitigating environmental impacts but also for promoting the resilience of industrial processes (Ahmad Termizi et al., 2023). Despite the increasing adoption of advanced technologies in resource management, significant challenges remain, particularly in achieving the transparency and accountability necessary to foster sustainable practices across diverse industries (Tseng et al., 2021). These challenges highlight the need for innovative solutions that can synthesize optimal transparent resource integration while adhering to stringent sustainability metrics.

A diverse array of methodologies has emerged for resource integration within EIPs, each enhancing aspects of efficient resource management. Alnouri et al. (2015) introduced water reuse networks with centralized and decentralized systems to improve efficiency in industrial cities. Bishnu et al. (2014) developed a multi-period planning model for EIPs to respond to industrial demands and reduce costs. A systematic framework to minimize resource footprints in response to economic and climatic changes for the water-energy nexus was proposed by Fouladi et al. (2017), while Oqbi et al. (2022) designed networks to handle seasonal demand variations. Al-Mohannadi et al. (2016) advanced carbon management by integrating CO_2 and natural gas networks, and Hassiba et al. (2017) optimized CO_2 heat integration for emission reduction and enhanced energy efficiency. Lastly, Ahmed et al. (2020) synthesized integrated EIPs using a method that optimizes the use of material and energy resources, showcasing the sophistication of strategies for sustainable industrial development.

In the realm of EIPs, enhancing transparency and accountability is pivotal. Bellantuono et al. (2017) demonstrated how improved information-sharing systems within EIPs optimize resource management and

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bolster sustainability practices. The lack of transparent data sharing can impede effective industrial symbiosis, emphasizing the need for improved transparency to foster collaboration and efficiency among firms Song et al. (2018). Addressing barriers to information exchange, Cervo et al. (2020) introduced industrial sector blueprints as a tool for facilitating the sharing of confidential data, enhancing industrial symbiosis opportunities. Ahmad Termizi et al. (2023) advocated integrating BC technology in EIPs to simplify data management and boost transparency, leveraging Industry 4.0 to enhance sustainable development in EIPs management.

While the literature presents various strategies for enhancing resource integration and management of EIPs, significant gaps remain, particularly in achieving seamless and transparent resource exchanges across diverse industrial processes. Current frameworks, although progressively incorporating advanced technologies like BC for data management and transparency, typically do not fully synthesize the integration of material and energy resources in a manner that optimizes economic and environmental outcomes simultaneously. Most models lack a comprehensive approach that addresses both the design of EIPs and the transparent trading of resources within the processes. This work introduces a novel multistage framework that builds on existing models for resource integration, enhancing them with a digital marketplace for resource trading using BC technology and smart contracts. This approach ensures transparency and traceability of transactions, optimizing resource use and enhancing exchange transparency. By addressing both the structural design and dynamic operational needs of EIPs, it provides a comprehensive solution that meets stringent sustainability and efficiency standards, filling key gaps identified in the literature.

Originally developed for Bitcoin by Satoshi Nakamoto in 2008, BC technology has become a transformative method for managing data and transactions securely, transparently, and without tampering. This decentralized ledger enhances data security using cryptographic techniques, eliminates central oversight, and requires consensus for data modifications, reducing fraud and increasing transparency (Devi et al., 2023). Its flexibility supports both public and private networks, adapting to various applications (Habib et al., 2022). Smart contracts, conceived by Szabo in 1994, are self-executing contracts embedded in BC that activate when conditions are met, streamlining transactions and agreements without intermediaries and ensuring secure and reliable transaction validation through mechanisms like Proof of Work or Proof of Stake (Hewa et al., 2021). Together, BC and smart contracts are set to revolutionize business processes by ensuring data integrity and facilitating automated, transparent transactions.

In finance, BC has revolutionized transaction security and minimized fraud through smart contracts. In supply chain management, it ensures traceability and accountability, enhancing the provenance tracking of goods. Healthcare has seen its use for secure patient record management, protecting data privacy and integrity (Hewa et al., 2021). These applications underscore blockchain's potential to enhance transparency and operational efficiency in EIP management by providing a decentralized, immutable record of resource transactions and compliance activities. This cross-industry overview not only illustrates the versatility of BC but also underscores its potential to foster regulatory compliance and sustainability in EIPs, paralleling improvements seen in sectors like energy, where it facilitates peer-to-peer trading and real-time data management in microgrids.

2. Methodology

This study introduces a multi-stage methodology to develop a BC-based marketplace for trading resources within an optimized EIP. Initially, the process selection stage utilizes a MILP model, previously developed by Ahmed et al. (2020), to select processes and determine their capacities. The EIP is modeled using resource lines for each process's waste or emissions, enabling the recovery and transformation of valuable materials into high-quality resources. This modeling approach facilitates the identification of potential interactions between processes and optimizes the combination of processes based on specific performance criteria and EIP constraints. The model optimizes economic outcomes by aiming to maximize total profit, calculated as the difference between total revenue from selling resources and the sum of capital and operating costs, as expressed in Eq(1):

$$Max\ Profit = Total\ Revenue - Capital\ Cost - Operating\ Cost \tag{1}$$

Resource and process balances are integral to the model. Resource lines, which may import, export, receive, or send resources to processes, adhere to the mass balance represented via Eq(2):

$$Inlet\ flow\ of\ fresh\ resource + Resource\ exchange\ with\ processes - Outlet\ flow = 0 \tag{2}$$

Similarly, the mass balance for each process is defined by Eq(3):

$$Resource\ exchange\ with\ process - Flow\ parameter\ \times Process\ Capacity = 0 \tag{3}$$

Process capacities and resource imports/exports are constrained by upper and lower limits. This stage establishes the optimal capacities for activated processes, which then participate in a smart-contract-based digital marketplace designed to manage resource exchanges within the EIP.

The subsequent stage introduces an automated system to facilitate transparent data sharing and resource exchange among stakeholders. Several BC platforms offer distinct advantages for EIPs management. Ethereum is renowned for its comprehensive smart contract capabilities, enabling automated, decentralized processes crucial for dynamic industrial environments. Hyperledger Fabric, developed by the Linux Foundation, excels in creating private and permissioned networks, offering high modularity and configurability ideal for enterprises requiring confidentiality. IBM Blockchain, built on Hyperledger, provides enterprise-grade solutions that ensure enhanced security and compliance with regulatory standards (Nanayakkara et al., 2021). OpenChain distinguishes itself by managing digital assets with high scalability and simplified transaction processes, suitable for high-volume applications (Bhutta et al., 2021). Lastly, Stellar facilitates fast and efficient cross-border financial transactions, optimizing payment processes and financial exchanges across global supply chains, enhancing operational efficiencies in industrial settings (Ghaemi Asl and Roubaud, 2024). Each platform is tailored to meet specific needs in EIPs, from security and privacy to efficiency and scalability.

Ethereum was chosen as the primary BC platform for its robust support of complex smart contracts, widespread industry adoption, and an active development community that enhances its stability and feature set, crucial for managing operations in Eco-Industrial Parks. Two smart contracts developed in Solidity underpin the system's functionality. The first, ‘IdentityEnrolment.sol’, handles tasks such as the registration and retrieval of information for new processes, external entities, and verifiers, ensuring data integrity and preventing duplication. The second, ‘ResourceExchange.sol’, integrates with ‘IdentityEnrolment’ smart contract to manage resource trading. It supports activities such as registering resource offers and requests and initiating trades, detailing resource type, provider details, availability, conditions, quality, and price. This blockchain-based architecture enhances the EIP’s operational transparency and efficiency.

In our framework, optimized flows from the MILP model are transmitted into the BC, where manual initiation of trades is expected to allow for greater human oversight, which can be crucial in complex decisions. Subsequent automatic checks ensure trade completion, streamlining the entire process. The smart contract incorporates multiple automated checks to enhance the digital market's efficiency and reliability. Before allowing resource exchanges, it mandates participant registration and complete resource information to prevent data omissions and duplicate entries. It verifies the adequacy of resource flows prior to initiating trades and tracks the transaction status throughout the trading process. Trade completion requires explicit confirmation from both parties before updating the trade status to "Completed". Transactions proceed to creation only if all specified conditions are met and, upon verification approval, are added to the blockchain. Both smart contracts have been developed, compiled, debugged, and thoroughly tested for optimal functionality on the Ethereum blockchain. The architecture and algorithms of these smart contracts are detailed in Table 1, with the overall multi-stage framework for this blockchain-based resource integration within the EIP illustrated in Figure 1 where Pm represents processes and Rn denotes resources, m and n are the sets of processes and resources.

Table 1: Overview of the algorithms used in the developed smart contracts

Identity Enrolment and Resource exchange smart contracts
IdentityEnrolment.sol: Initializing resource exchange.
1. Declare a contract called IdentityEnrolment.
2. Define structs for processes, external entities, and verifiers considering relevant information such as name, address, contact information, email, and ID.
3. Create mapping variables to map process, external entities, and verifiers ID to process, external entities and verifiers structs.
4. Create events for new processes, external entities, and verifiers.
5. Define functions to register processes, external entity verifiers, and retrieve their profiles.
ResourceExchange.sol: Transaction process
1. Declare a contract called ResourceExchange.
2. Define the structure for resources, including relevant information such as name, ID, flow, temperature, pressure, quality, and price.
3. Define struct for trades.
4. Create mapping variables to map resource/trade ID to the resource/trade struct.
5. Create events for new resources and requests, initiate trade, and manage trades.
6. Define functions to register new resources, resource query, initiate and manage trades.

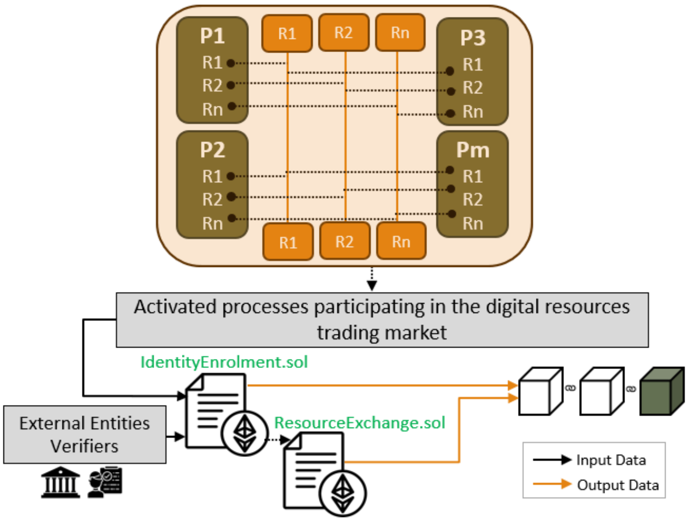

Figure 1: Schematic representation of the proposed multistage blockchain-based system

The proposed multi-stage BC-based system for resource integration in EIPs offers significant advancements in sustainable industrial management. This system is designed to identify optimal candidate processes and their capacities within an EIP, enhancing efficiency and resource allocation. By facilitating transparent data sharing and tracking of resource exchanges, the system not only promotes the detection of integration opportunities but also ensures a high level of transparency in resource management. Additionally, it adapts dynamically to changes such as fluctuations in resource prices, EIP expansion, and other temporal variations, supporting scalable and flexible industrial operations. The system also records sustainable practices among industries, providing valuable data that can assist policymakers in crafting regulations and initiatives to foster and promote sustainable practices. Overall, this approach not only enhances resource efficiency within EIPs but also supports broader sustainability goals by integrating dynamic changes and expanding integration opportunities. A decentralized application could further demonstrate the capabilities of this smart-contract-based market.

The proposed system may face some challenges. BC's transparency promotes data sharing but creates data privacy and security challenges. Immutable data raises risks for sensitive information. Solutions are needed to balance data protection regulations with BC's inherent transparency and traceability. Implementing and maintaining a BC infrastructure demands substantial computational resources and technical expertise. Scalability is another critical concern, as the system must manage increasing data and transactions efficiently as the EIP expands. The adoption of this technology relies on participants' willingness to embrace new protocols and technologies, which can be hindered by resistance to change or lack of technical skills. Regulatory and legal frameworks may also lag behind, creating compliance risks for decentralized and automated systems.

3. Case Study

To demonstrate the proposed system, a case study on CO_2 capture, utilization, and storage within an EIP was conducted. The EIP processes 120,000 t/y of CO_2, targeting at least 90 % sequestration or conversion into value-added products. The system incorporates key inputs such as air, water, and renewable electricity. The processes evaluated include ammonia (NH_3) and urea production, as well as the production of soda ash (Na_2CO_3) and sodium bicarbonate ($NaHCO_3$), with CO_2 sequestration also considered. Carbon capture and utilization units are specifically implemented in the urea and sodium bicarbonate processes. Hydrogen production is facilitated through an electrolyzer, and an air separation unit (ASU) is also utilized. Data for the soda ash and sodium bicarbonate processes were sourced from Abraham et al. (2021), while data for the other processes came from Ahmed et al. (2020). The maximum process capacity is set at 100,000 t/y, except for CO_2 sequestration, which is capped at 120,000 t/y. The project's lifespan is 20 y. Required data includes Capital (CAPEX) and operating (OPEX) cost parameters and resource flow parameters, which are expressed in tons per ton of the main product (t/t Ref) for each process. CO_2 mass composition in urea and sodium bicarbonate are assumed at 26 % and 20 %, while the composition from the flue gas of capturing units is assumed to be 6 % and 3 %.

4. Results and discussion

4.1 Results

The first stage of the proposed framework utilized a MILP model to establish the optimal design of the EIP, focusing on selected processes and their capacities while aiming for 90 % CO_2 conversion. The optimal configuration, depicted in Figure 2, outlines resource flows in kt/y, except for electricity in GWh/y, and highlights an annual profit of $ 20 million with a CO_2 consumption of 109,000 t/y. The optimal processes include ASU, hydrogen production via electrolyzer, and CO_2 sequestration, besides ammonia and urea production, with a urea carbon capture unit. Notably, soda ash and sodium bicarbonate processes were excluded from the design due to high raw material costs, specifically sodium hydroxide. The system captures CO_2 emissions from the urea process for recycling, utilizes fresh water for hydrogen production in the electrolyzer, and sells oxygen from the ASU and electrolyzer. The total capital investment for this design is estimated at $ 415 million, positioning the EIP's design as a cost-effective alternative compared to conventional CO_2 mitigation strategies. The selected processes were registered via IdentityEnrolment.sol smart contract and the optimal flows were recorded to facilitate the resource exchange and trade process between different entities.

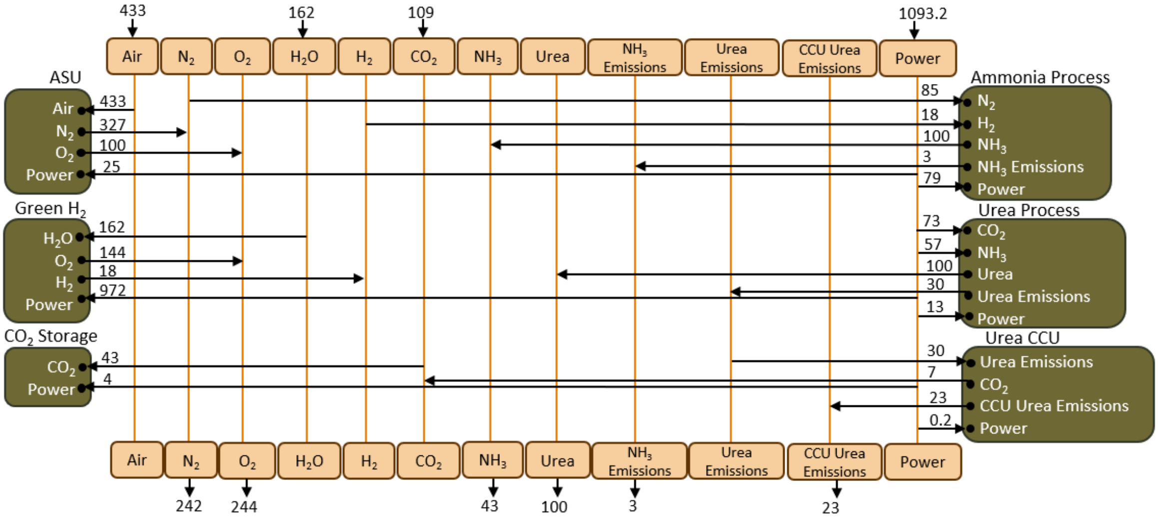

Figure 2: Schematic of the optimal EIP with 90 % CO_2 conversion (Units: kt/y for all except electricity in GWh/y)

4.2 Discussion

The integration of BC in our EIP framework enhances operational efficiency and transparency, particularly after the MILP model establishes optimal process capacities. The blockchain's critical role unfolds as it transitions these theoretical optimizations into real-world applications through smart contracts on the Ethereum platform. These contracts automate resource management based on MILP outputs, ensuring adherence to optimized parameters while providing a transparent, immutable ledger of transactions. This setup supports automated adjustments in resource distribution directly linking BC functionality to improved operational outcomes and sustainability within the EIP. The application of BC bridges the gap between theoretical models and practical implementations, suggesting broader implications for policy-making and industrial regulation in promoting transparent and efficient resource management. By enabling the transparent and accurate reporting of resource usage and emissions, it assists policymakers in developing dynamic, responsive regulations that promote environmental sustainability. For example, policymakers could incentivize BC adoption through tax benefits or subsidies for industries that reduce resource wastage and greenhouse gas emissions. Blockchain's secure, immutable nature supports the creation of standardized environmental credit systems, allowing industries to earn and trade credits for sustainable actions. This enhances transparency and supports a circular economy, providing policymakers with detailed data to refine regulations and encourage innovative, environmentally protective measures.

5. Conclusions

This study demonstrates the implementation of a multistage, BC-based system for optimizing resource integration. By directly linking MILP model outputs to smart contracts on the Ethereum platform, the system not only ensures that the resource management within EIPs adheres to optimized flows but also enhances transparency and accountability in resource exchanges. These functionalities are critical in reducing CO_2 emissions and improving overall efficiency. The BC's immutable ledger provides a reliable and transparent record of transactions, which is essential for monitoring compliance and environmental impact, supporting the development of targeted policies for sustainability. This integration of BC technology not only meets the specific operational needs of EIPs but also provides a scalable model that can be adapted to other industrial settings seeking to enhance efficiency and sustainability through advanced technological integration. This framework underscores the potential of BC to facilitate environmental governance and policymaking for tracking compliance and enhancing enforcement of sustainability standards. Utilizing BC technology for EIP management supports designing future regulations that encourage sustainable practices across industries.

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