CARBON EMISSION TRADING ON THE BLOCKCHAIN: A GAME-THEORETIC FRAMEWORK

Monzure-Khoda Kazi and M.M. Faruque Hasan*
Artie McFerrin Department of Chemical Engineering, Texas A&M University,
College Station, TX 77843-3122, USA
Texas A&M Energy Institute, Texas A&M University,
College Station, TX 77843-3372, USA

Abstract

Imposing a price on carbon emissions is likely an effective approach to reduce the greenhouse gas (GHG) emissions from many sectors. There are primarily two ways to assess a price for carbon emissions, namely carbon tax and emission trading system (ETS). The traditional ETS has several obstacles in carbon credit allocation, determining purchase quantities, and trading in a fair manner. In addition, it lacks effective participant willingness for emission amount verification, transparent monitoring/reporting, identifying a realistic cap limit for each sector, and in accounting the actual cost of emission reduction efforts (such as the costs associated with carbon capture technology). Blockchain's underpinning characteristics such as anonymity, decentralized integrity, immutability, latency, security, traceability, and transparency makes this emerging technology as an ideal candidate for solving the bottlenecks of current ETS. In this work, a game theoretic framework is used to find a mutually benefited way for peer-to-peer carbon management within the industrial ecosystem. This is performed on the blockchain using smart contracts to enable strategic planning for carbon trading leveraging the shared data. A conceptual framework and game-theory-based ETS formulation have been proposed to obtain an optimal ETS framework for completely transparent automated trading and CO_2 control measures.

Keywords

Blockchain, Game theory, Carbon emission trading system, Smart contract, Decentralized application.

Introduction

"Carbon neutrality" has emerged as a consensus objective for the global response to the climate issue. Numerous initiatives have been done by governments, multinational corporations, non-profit organizations, and other groups in support of this consensual objective. From the "Kyoto Protocol" of 1997 through the "Glasgow Climate Pact" of 2021, over 200 nations will join forces to restrict the increase of the Earth's temperature to less than 1.5 degrees Celsius by solidifying progress on funding for climate action, adaptation, and loss and damage (UKCOP26, 2021). However, "carbon neutrality" also requires actions from carbon sink suppliers, industrial enterprises, and individual consumers. In reality, "carbon neutrality" may be achieved by using market trading systems to combine these factors.

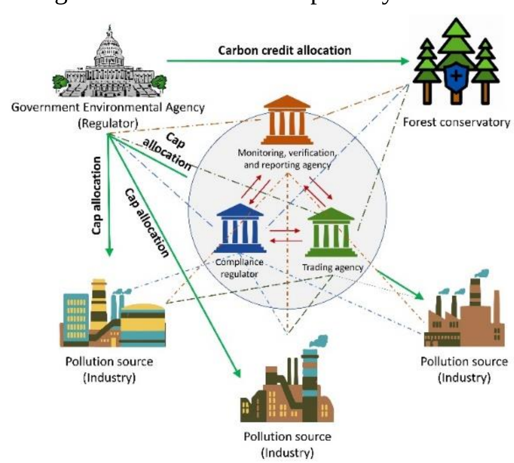
Carbon pricing is one of the most extensively utilized policy tools for cost-effective GHG reduction, with 57 GHG pricing programs worldwide in 2019 and 96 Parties contemplating the use of carbon price (Schletz et al., 2020; World Bank Group, 2019). Heterogeneous climate markets may use distinct governance and technology. Information regarding mitigation outcomes (MOs) or emission reductions is recorded in spreadsheets and registries with varying degrees of detail. These disparities may hinder market integration and complicate transaction monitoring and recordkeeping. A new infrastructure is needed to facilitate transparency and increase the tradability of climate assets between countries while preserving trade integrity. The Kyoto Protocol and its Doha amendment used the UNFCCC's International Transaction Log (ITL) to ease communication between registries and assure proper accounting and verification of planned transactions (UNCC, 2013). Article 6.2 of the Paris Agreement outlines a market framework to encourage collaboration between Parties in attaining their nationally determined contributions (NDCs) through internationally transferred mitigation outcomes (ITMOs) (UNFCCC, 2022). Climate negotiators are still discussing whether a centralized infrastructure should persist, the services it may perform, and the market processes or transactions it would apply to under Article 6.2 of the Paris Agreement. Consistent with the Paris Agreement's bottom-up ethos, linking registry systems peer-to-peer is valuable (World Bank Group, 2019).

Emission Trading System (ETS) and its challenges

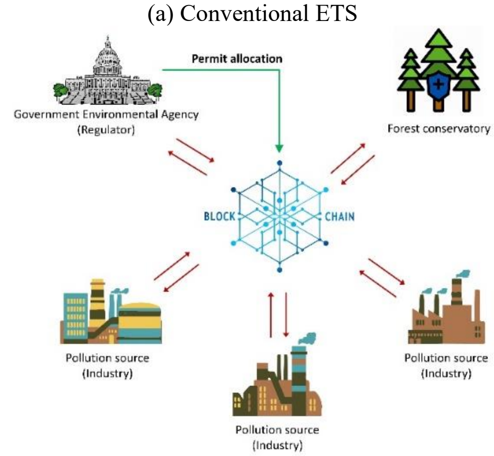
The Emission Trading System (ETS) was created by the Kyoto Protocol to enable governments to trade carbon credits (Woo et al., 2020). It is based on the notion of "cap and trade," in which countries get CO_2 permits according to their emission reduction goals (Al Sadawi et al., 2021). If an entity has extra credits, it may sell them to other market players. This allows these organizations to meet their carbon quota. However, the majority of carbon Emission Trading Systems (ETS) depend on a centralized system to perform transactional duties and are susceptible to security risks, non-transparency and corruption (Hu et al., 2020; Schletz et al., 2020). These present carbon market mechanisms still lack a legislation and tracking system that stores and verifies the information required to monitor and track global transactions (Hanle et al., 2019). This kind of tracking system is necessary to eliminate corruption and double counting. Another issue with carbon trading is the complex allocation of carbon allowances that results in an unfair distribution of allowances among participants (Al Sadawi et al., 2021). Also, there is a lack of integration in the carbon markets that would reduce the efficiency of the trading mechanism and creates fewer options for carbon mitigation. In addition, there is need of extending or re-investigating the existing auction strategies for ETS to offer an incentivized trading for buyers and sellers and to overcome the homogeneous multiunit allocation problem. Therefore, there is a need to resolve the issues of carbon trading.

Blockchain-enabled carbon market and its potentials

Blockchain is one of the industry 4.0's emerging technologies (Wang et al., 2020). It is a revolutionary new protocol for sharing and updating information by linking ledgers or databases in a decentralized, peer-to-peer, open-access network. Blockchain is designed to ensure the data is stored and updated in a secure, tamper-proof and irreversible way. Despite being in its nascent stages, the blockchain research is developing rapidly in different fields, making it imperative to capture the ethical and sustainability implications of blockchain development and implementation (Upadhyay et al., 2021). It has attracted substantial attention from government agencies, financial institutions, start-ups, technology enthusiasts, academic and research communities (Lakshmi et al., 2021). ETS may employ blockchain technology to address the aforementioned problems. Blockchain may be seen of as a transparent, secure, and decentralized information storage and transfer system. With blockchain technology, the verification of transmitted data and information is conducted through a peer-to-peer network rather than the complicated and time-consuming intermediate authorities such as compliance regulator, trading agency or monitoring, verification, and reporting agency services (see Figure 1). In other words, it relies on a peer-to-peer network that maintains highly secure, replicated, and traceable transactions. Carbon markets are increasing fast as countries, organizations, and individuals strive to meet their emissions-reduction goals. Transparency is nonetheless one of the issues carbon market players confront. Blockchain technology may offer a solution by monitoring and reporting emission reduction trade, avoiding double-counting issues, enhancing financial flows, and contributing to the development of trust. In the near future, while being a relatively new technology, blockchain may assist in addressing the difficulties of transparency in carbon trading.



(a) Conventional ETS



(b) Blockchain-enabled ETS

Figure 1. (a) Conventional ETS framework and (b) blockchain-enabled ETS framework.

(Muzumdar et al., 2022). Adopting blockchain technology may increase capital market trust and help achieve the goals of reducing climate change at both the local and global levels via consensus processes and interoperability.

Game-theory-informed bidding algorithm

The current limitation of the blockchain-enabled CO_2 management or ETS is the inability of parties to negotiate carbon trading directly (Khaqqi et al., 2018). Either the central authority or the intermediate organizations set the value of carbon trading (Muzumdar et al., 2022). As blockchain provides a platform for communication between each stakeholder in the system, promoting the interactive bidding process for carbon trading would be advantageous. This will enable each member to reconsider the size and technology of their carbon capture, the quantity of CO_2 produced, and even the cost of carbon trading with other participants. A game-theory informed bidding mechanism integrated in a blockchain backend may give ETS players with such an opportunity of optimal bidding. Game theory looks at the conflict and cooperation between rational decision makers. This decision makers or players can interact in a strategic way through a well-defined payoff function (Bagchi et al., 2012). They are rational in the sense that they want to maximize their own payoffs (Krawczyk & Uryasev, 2000). There may be opposing goals among the many stakeholders. In the interactions of the participants, both conflict and cooperation are present. Each participant has a selection of potential tactics. The participants are intelligent enough to select the optimal response techniques. This approach in ETS will not only increase the interest of the participating organizations, but it will also minimize the regulatory burden associated with contract and price negotiations. By researching computational economics approaches to identify Nash equilibrium in infinite games of ETS, carbon source enterprises will be able to determine the most cost-effective strategy to implement their current carbon management plan.

In this work, a generalized Nash game model is developed to simulate the multi-round auction of ETS on a blockchain-based decentralized platform for a hypothetical industrial eco-park. The conceptual blockchain architecture along with the formulation of a multi-variate Nikaido-Isoda function of Nash equilibrium is proposed here for obtaining a robust peer-to-peer carbon emission trading mechanism.

Model for game-theory-informed strategic CO_2 auction

To construct a carbon economy, first we devise a game-theory-based CO_2 auction model in which participants may bid and seek to maximize their carbon management-related rewards. All participating industries are expected to be potential generators of CO_2 and capable of capturing their own CO_2 to serve as carbon sinks. Now, any industry may either serve as a buyer of carbon cap or sell their extra carbon cap if they emit more or less than their allotted limits. The regulatory body will impose a carbon tax, and the entire allocation of carbon emissions will be set. Using the following model equations (Eqs. 1-6), participants in the carbon economy can engage directly with one another to trade CO_2 as a commodity.

$$\sum_i x_i^{gen} - \sum_i \sum_{t\in T_i} x_{i,t}^{cap} - \sum_i \sum_{j\neq i} x_{i,j}^{buy} + \sum_i \sum_{j\neq i} x_{i,j}^{sell} \leq \sum_i \hat{x}_i^{allowance}, \quad \forall i \tag{1}$$

$$\bigvee \begin{bmatrix} y_{i,t} \\ \hat{l}_{i,t} \leq x_{i,t}^{cap} \leq \hat{u}_{i,t} \\ c_{i,t}^{cap} = \hat{\alpha}_{i,t}^{fixed} + \hat{c}_{i,t}^{base}\left(\dfrac{x_{i,t}^{cap}}{\hat{x}_{i,t}^{base}}\right)^{\hat{\beta}_{i,t}} + \gamma x_{i,t}^{cap} \end{bmatrix}, \forall i,t \tag{2}$$

$$max\left[\sum_{j(j\neq i)} P_{i,j}^{sell} x_{i,j}^{sell} - \sum_{j(j\neq i)} P_{i,j}^{buy} x_{i,j}^{buy} - \sum_{t\in T_i} c_{i,t}^{cap} - \hat{P}^{tax}\left(\hat{x}_i^{gen} - x_i^{cap}\right)\right], \forall i \in I \tag{3}$$

$$P_{i,j}^{sell} \leq \hat{P}^{tax}, \qquad P_{i,j}^{buy} \leq \hat{P}^{tax} \tag{4}$$

$$x_{i,j,k+1}^{sell} = \lambda x_{i,j,s}^{sell} + (1-\lambda)\, x_{i,j,k}^{buy} \tag{5}$$

$$P_{i,j,k+1}^{buy} = \lambda P_{i,j,s}^{buy} + (1-\lambda) P_{i,j,k}^{sell} \tag{6}$$

Here, eq. 1 assures that the overall emission of carbon is less than the allowable limit for the eco-park, where i={ind_1, ind_2,…ind_i} is the available participants in the carbon economy. x_i^{gen} is the amount of CO_2 generation from each industry, $x_{i,t}^{cap}$ is the capacity of carbon capture from available technologies, $x_{i,j}^{buy}$ is the amount of CO_2 credit that industry i wants to buy from other industy $_j$, $x_{i,j}^{sell}$ is the amount of CO_2 credit that industry i wants to sell to industry j and $\hat{x}_i^{allowance}$ is the total allowable limit of the considered eco-park set by the regulatory authority based on the industrial profiles. Equation 2 describes the sizing of the carbon capture technolgies, T_i={t_1,t_2,…t_n}, for the industries. Each industry will choose their suited technology based on the pricing and amount negotiations. Therfore, these equations are discrete in nature depending on the selection of the technology. The varialbe CAPEX and OPEX of each technology and their lowest and highest operating size are considered for making the consicous choice of technology in terms of economy. Equation 3 is the main objective function of the game theory model, where the overall profit of each industry is maximized. $P_{i,j}^{sell} x_{i,j}^{sell}$ represents the profit generated by the CO_2 cap sell from each industry, wherease $P_{i,j}^{buy} x_{i,j}^{buy}$ denotes the cost associated with CO_2 cap buy, $c_{i,t}^{cap}$ denotes the carbon capture cost, and $\hat{P}^{tax}(\hat{x}_i^{gen} - x_i^{cap})$ identifies the carbon tax amount if there is any extra CO_2 emission over the permissible limit. Equation 4 are the constraints which keep the selling or buying price of CO_2 cap under the carbon tax amount. Equations 5-6 use the relaxation algorithm to find the Nash equilibrium of the infinite game using Nikaido–Isoda function (describe in eqs. 7-8), where relaxation parameter λ value varry between 0 to 1. In these equations, in iterative at step k+1 is constructed as a weighted average of the improvement points ($x_{i,j,s}^{sell}$ and $P_{i,j,s}^{buy}$) and current points ($x_{i,j,k}^{buy}$ and $P_{i,j,k}^{sell}$), which also ensures the convergence of the algorithm under certain conditions, as stated in theorems 3.1 and 4.2 of Krawczyk et. al., 2000 work on relaxation algorithms to find Nash equilibria (Krawczyk & Uryasev, 2000). According to the definition, a point $x^*=(x_1^*, \ldots, x_n^*)$ is called the Nash equilibrium point, if, for each i,

$$\phi_i(x^*) = max_{(x_i|x^*)\in X} \phi_i(x_i|x^*) \tag{7}$$

Where, $\phi_i: X_i \to \mathbb{R}$ be the payoff functions of players I = 1, …, n. Then the Nikaido-Isoda function $\psi: (X_1 \times \cdots \times X_n) \times (X_1 \times \cdots \times X_n) \longrightarrow \mathbb{R}$ is defined as

$$\Psi(x, y) = \sum_{i=1}^{n} [\phi_i(y_i|x) - \phi_i(x)] \tag{8}$$

The eq. 8 represents the sum of the changes in payoff functions and it follows from the definition of the Nikaido–Isoda function that $\Psi(x, x) \equiv 0$. From here, we reach the conclusion that when the Nikaido–Isoda function cannot be made (significantly) positive for a given x, we have (approximately) reached the Nash equilibrium point. Therefore, an element $x^* \in X$ is referred to as a Nash normalized equilibrium point if max $max_{y\in X} \Psi(x^*, y) = 0$. We use this observation in constructing a termination condition for our algorithm.

Blockchain decision framework

The blockchain method starts with participants completing direct peer-to-peer transactions without the need of an intermediary. These transactions may include the transfer of digital assets or data using simple protocols or complicated programming known as smart contracts. These smart contracts execute and transfer digital assets automatically in accordance with preset, programmed regulations (Buterin, 2013). Each participant has a copy of the blockchain record, which they can use to validate the transaction and then publish to the network if they are satisfied. The network validates and compiles the broadcasted transactions into a chronological list called a "block." The network then engages in a consensus procedure to determine whether the current block of transactions should be added to the ledger.

The construction of a consensus mechanism that allows a distributed network of nodes to achieve an agreement is one of the essential building blocks of blockchain. Even in the face of contradictory facts and untrusted network members, a consensus must be reached such that there is always a single state of the ledger (Schletz et al., 2020). This data dispersion may prevent single, centralized failure spots and information imbalance. It specifies how parties may obtain consensus on the activities and states of a blockchain network. Proof of Work (PoW) appears to be the most well-known and commonly utilized consensus technique in blockchain networks. PoW is used by Bitcoin and Ethereum. Upon the network reaching consensus, the block is connected or "chained" to all proceeding blocks. The block is chained using a practically irreversible cryptographic process known as hashing. Hashing summarizes the ledger data into a concise string of characters that warns if the underlying data are changed. Then, each copy of the distributed ledger is updated and a new block containing the freshly generated hash is generated. The network then advances to the subsequent block, and the process repeats.

The required blockchain decision framework for ETS will depend on the trade-offs regarding the degree of system permission (i.e., public, private or hybrid). Permissionless or public blockchain systems are completely decentralized; anybody may become a ledger node to verify data or even alter the protocol's decision-making (if securing sufficient support from other nodes). In most cases, a government-run or heavily regulated system cannot take use of a permissionless system because of the inherent dangers of

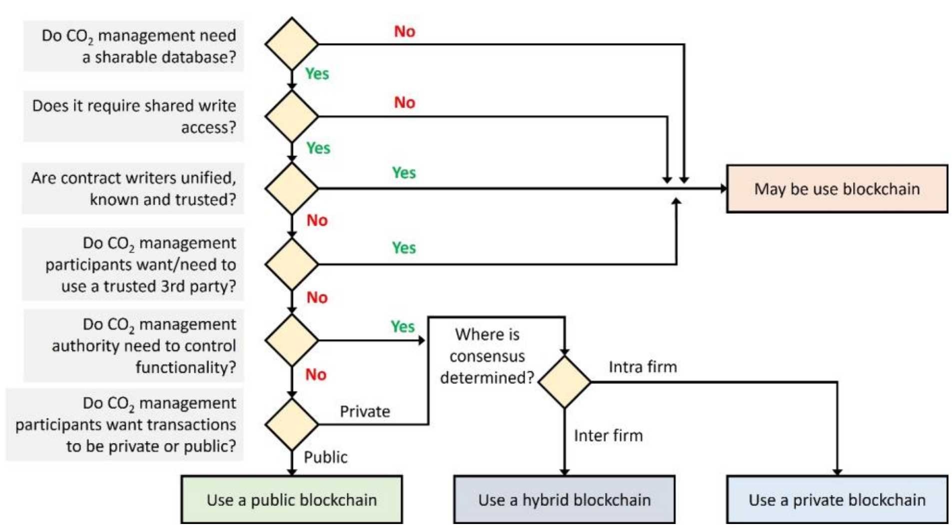


Figure 2. Key characteristics to identify the blockchain decision framework.

relying on a system that is not under the direct control of its creators. In contrast, a limited number of companies administer permissioned or private systems, and only authorized entities are permitted to become ledger nodes or participate in transactions. However, a permissioned system might conflict with the bottom-up ethos of the Paris Agreement (Schletz et al., 2020). Therefore, system permission for ETS is not a bivalent characteristic but a gradual property ranging from permissionless and permissioned depending on the choice of the stakeholders. The final decision of the blockchain framework will depend on the key characteristics of the ETS management and participants' intention (as shown in Figure 2).

Conceptual blockchain architecture with embedded game-theory model

About fifty percent of energy and manufacturing related blockchain applications are created on Ethereum. Peer-to-peer energy trading, which considers electrical energy similarly to other commodities, is the most prominent blockchain use in the energy industry. Whereas, in manufacturing industries mostly the complicated supply chain management issues are attracting the attention of the blockchain researchers and architect developers. Energy and manufacturing industries have some unique characteristics different from other industries (e.g., finance, insurance, healthcare, digital assets management), where blockchain has been applied successfully. Control, distribution, and trade of commodities such as electricity, chemicals and processed products are often subject to physical constraints and reliant on solving constrained objective functions. Currently, blockchains are not specialized for mathematical optimization mainly due to their memory related issues, which makes it difficult to insert computationally intensive portions directly into smart contracts. Therefore, blockchain can be used for communicating and recording critical information, while optimization problems can be embedded in a decentralized file-sharing network such as Interplanetary File System (IPFS) and solved by a classical optimization solver.

In this proposed conceptual blockchain architecture for this work, the developed model of game-theory-informed CO_2 auction has been embedded into a hybrid blockchain (see Figure 3). All input information (e.g., intended buy/sell prices of CO_2 credits and total CO_2 capture amounts) from the industries (customers) is going to a solidity-based smart contract built on the Ethereum Virtual Machine (EVM) in an encrypted manner. An authority will initiate and terminate the game-theory-based bidding process and will allow the smart contract to keep communicating with the IPFS. There will be an embedded GAMS BARON solver and an embedded game-theory-based algorithm in the IPFS, which will return the optimization results in each iteration cycle to the authority. The intermediate equilibrium values will be passed to the customers through a temporal certificate to initiate the next round of bidding. The cycle will continue until there are no significant changes in the bidding, and the authority will terminate the game-theory-based bidding on the blockchain. The final issued certificate mentioning the agreed-upon optimized CO_2 buy/sell price and cap will be issued through the Ethereum-based decentralized application through the credit token. This credit token will match the customer's CO_2 pricing and profile based on the final certificate. This smart contract will automatically burn and mint IRC-20 tokens and update the customers' wallets accordingly. To check the effectiveness of the proposed game-theory-based CO_2 auction, we run our code to an offline GAMS BARON solver for a sample case study where two industries (customers) are bidding for the optimal game-theory-based CO_2 buy/sell price and amount to be traded. It was found

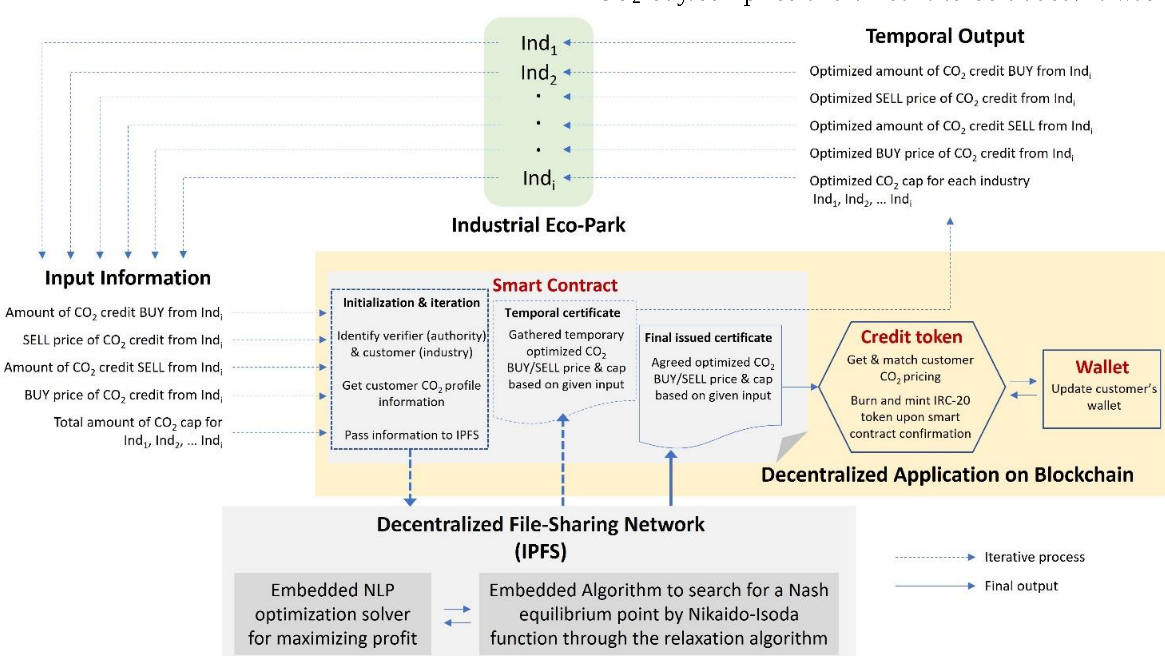


Figure 3. Full blockchain architecture of the game-theory-informed peer-to-peer carbon emission trading system

that the proposed game-theory model presented here (in equations 1-8) was successful in finding the optimum price and amount of CO_2 trading for each industry, as shown in **Table 1**.

Table 1. Game-theory-based optimization results for sample case study.

Industry 1 → Industry 2		Industry 2 → Industry 1	
$P_{1,2}^{sell}$	50 \$/ton	$P_{2,1}^{sell}$	50 \$/ton
$P_{1,2}^{buy}$	50 \$/ton	$P_{2,1}^{buy}$	50 \$/ton
$x_{1,2}^{sell}$	36.87 MTY	$x_{2,1}^{sell}$	1.30 MTY
$x_{1,2}^{buy}$	1.30 MTY	$x_{2,1}^{buy}$	36.87 MTY

In our upcoming work, a decentralized application (DAPPS) will be developed on Ethereum blockchain to demonstrate how this developed game-theory-based algorithm can enable a complete automated emission trading platform without sharing critical information among the industries. Later, the multiple industry scenarios will be investigated to see whether a centralized carbon capture facility is more economically viable or if a separate capture plant for some specific industry is more advantageous from a game-theory perspective.

Conclusion

In this work, a comprehensive blockchain architecture of the game-theory-informed peer-to-peer carbon ETS and a generalized Nash game model are developed to simulate the multi-round auction for completely transparent automated trading and CO_2 control measures. This conceptual framework will act as the backbone for the future DAPPS on Ethereum blockchain. In addition, the blockchain architecture established for carbon trading may be more effective for other applications, such as automated trading of raw materials and chemicals, common utility management, and monitoring the life cycle of any piece of equipment.

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