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A Game Theory-Based Framework for Blockchain Adoption under a Cap-And-Trade Policy in A Carbon Complementary Supply Chain

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Abstract

With rising concerns over climate change and stricter cap-and-trade policies, innovative approaches are required to improve transparency and coordination in carbon-constrained supply chains. This study develops an integrated framework combining game theory and blockchain technology to analyze interactions among conventional and renewable energy producers, retailers, and the government. Competition among producers is modeled using Cournot competition, while producer–government relations are represented as a Stackelberg game. The results show that blockchain adoption enhances carbon traceability, reduces transaction costs, strengthens collaboration across supply chain members, and increases overall profitability. Sensitivity analysis further highlights that optimizing renewable energy adoption and managing blockchain implementation costs can yield substantial economic, environmental, and social benefits. These insights provide valuable guidance for policymakers and supply chain managers in designing effective strategies toward carbon reduction and sustainability.

Keywords: Game theory, Blockchain, Cap-and-trade, Carbon complementary supply chains, Social welfare, Carbon emissions.

1 | Introduction

In recent years, global concerns regarding climate change and the environmental consequences of excessive carbon emissions have increased significantly. According to forecasts by the U.S. Energy Information Administration (EIA), if no substantial reforms in policies and technologies are implemented, global energy consumption may increase by nearly 50% over the next three decades, mainly driven by population growth, economic development, and continued dependence on fossil fuels [1]. This trend has encouraged many countries to design and implement a variety of emission reduction policies, including cap-and-trade systems, carbon taxes, and subsidy programs [2].

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Among these policies, cap-and-trade systems are considered one of the most effective market-based mechanisms for reducing emissions due to their economic incentive structures and operational flexibility [3]. A prominent example is the European Union Emissions Trading System (EU ETS), which has been implemented since 2005 and has contributed to nearly a 50% reduction in emissions within the European Union [4]. Similarly, China launched the world's largest carbon emissions trading market in 2021 [5]. In such systems, limited emission allowances are allocated to firms, and any surplus or deficit of allowances can be traded among market participants, including traditional energy producers [6].

Alongside these environmental policies, blockchain technology has emerged as a distributed and decentralized ledger capable of providing transparency, immutability, and reliable traceability of data [7]. The application of blockchain in carbon emission management can ensure accurate recording and reporting of emission data by producers while improving the efficiency of environmental monitoring and regulatory enforcement. Despite these advantages, challenges such as high implementation costs, legal concerns, and privacy issues continue to hinder the widespread adoption of blockchain technology [8].

In addition, Renewable Energy Consumption Obligation (RECO) policies have been introduced in many countries, requiring retailers to supply a certain proportion of energy from renewable sources [9]. Similar to cap-and-trade systems, these policies are designed to stabilize renewable energy markets and reduce carbon emissions. For instance, regions such as California and China have established renewable electricity targets exceeding 20%. Furthermore, complementary mechanisms such as Carbon Capture and Storage (CCS), Certified Emission Reductions (CERs), and investments in green projects are continuously expanding.

A Complementary Carbon Supply Chain (CCSC) is formed through the integration of these mechanisms, where producers, retailers, and consumers interact within a coordinated framework [10]. Traditional energy manufacturers play a critical role in the CCSC as they seek to reduce their carbon footprints through innovative approaches and complementary technologies. By adopting more sustainable energy resources, these manufacturers aim to improve energy efficiency and mitigate negative environmental impacts, thereby contributing to carbon reduction objectives across the supply chain. Meanwhile, competition exists between Traditional Manufacturers (TMs) and Renewable Manufacturers (RMs), as both groups supply energy products to the market.

This study proposes an integrated and coherent framework for a CCSC by combining game-theoretic approaches with blockchain technology. Specifically, the proposed model incorporates Cournot competition and Stackelberg game structures to support continuous strategic interactions alongside carbon emission reduction initiatives. The main contributions and innovations of this research can be summarized as follows: 1) developing a fair, equitable, and standardized approach for emissions trading across different sectors, countries, and regions, 2) employing blockchain technology to establish a decentralized, transparent, and tamper-resistant system for tracking emissions and trading emission permits, and 3) introducing a flexible mechanism for setting and dynamically updating emission targets in accordance with evolving environmental objectives.

The remainder of this paper is organized as follows. Section 2 reviews the related literature. Section 3 presents the proposed model. Section 4 discusses the numerical results, and the final section concludes the paper and provides directions for future research.

2 | Literature Review

This study investigates supply chains under carbon regulatory frameworks, the adoption of blockchain technology in supply chain management, and the application of game theory.

2.1 | Supply Chains Under Carbon Emission Regulations

In recent years, carbon reduction policies have attracted significant attention from both academic and practical perspectives and have become a critical global issue [11]. Researchers have extensively examined the impacts of various carbon regulations on supply chain management and the ways in which firms can reduce carbon emissions [12]. Consequently, growing interest has emerged in integrating carbon emission regulations into supply chain operational decisions. Evidently, the structure of the supply chain plays a vital role in shaping the implementation of such regulations. A large portion of previous studies has focused on classical two-echelon supply chain structures, such as manufacturer–retailer systems [13] and government–manufacturer interactions [14]. Similarly, the present study considers a classical two-echelon structure; however, it differs by incorporating two manufacturers, one retailer, and a governmental authority responsible for enforcing carbon policy constraints.

Beyond the supply chain structure perspective, several previous studies have specifically investigated different carbon emission regulations within supply chain operations. Most of these studies have primarily focused on operational decisions under cap-and-trade carbon policies. The present study mainly emphasizes cap-and-trade mechanisms and government subsidy policies. From the perspective of combining cap-and-trade regulations with subsidies for carbon emission reduction, the study by Hussain et al. [15] is the closest to the present research. Nevertheless, to the best of our knowledge, no published study has simultaneously integrated carbon emission regulations including cap-and-trade policies, carbon taxation policies, and RECO policies with blockchain technology.

As the most extensively studied carbon policy, cap-and-trade mechanisms have received substantial attention from researchers. For example, Bai et al. investigated optimal pricing and carbon emission reduction strategies in centralized and decentralized supply chain systems [16]. Furthermore, Amiri-Pebdani et al. examined pricing interactions in energy supply chains under governmental interventions and cap-and-trade regulations, demonstrating that such policies can significantly influence pricing strategies and operational decisions within energy supply chains [17]. According to Xu et al., firms should consider carbon trading prices and emission quotas in their production decisions, as these factors directly affect operational costs and profitability [18]. Overall, the implementation of cap-and-trade policies can preserve firms' competitiveness by creating incentives for emission reduction, promoting sustainability, and aligning corporate strategies with effective carbon cost management.

2.2 | Blockchain Adoption in Supply Chains

Blockchain is fundamentally a distributed ledger technology that integrates existing technologies such as distributed databases, digital cryptography, networking systems, and the Internet of Things (IoT) to establish and manage decentralized ledgers [19], [20]. One of the most prominent applications of blockchain in the energy sector is peer-to-peer energy trading, where electricity is treated as a tradable commodity.

The traceability and information-sharing capabilities of blockchain technology play a significant role in improving supply chain efficiency [20]. In their study, Olsen and Tomlin emphasized the potential of blockchain technology to eliminate information intermediaries, enhance transparency and traceability, and fundamentally transform supply chain structures [21]. Blockchain can also address several existing challenges in carbon emission trading systems, including monitoring and reporting emission reductions, preventing double counting, improving financial flows, strengthening trust, enhancing transparency, supporting standardization, and reducing transaction costs [22].

However, adopting blockchain technology may also impose substantial costs, including technology development and maintenance expenses, product information storage, validation procedures, auditing, and system updates required to ensure accurate disclosure of product information [18–23]. Although the use of blockchain technology may raise concerns regarding consumer privacy, it is still regarded as one of the most secure and reliable solutions for preventing fraud and manipulation [24].

3 | Problem Definition

This study investigates the impact of blockchain technology on the decision-making processes of members within a CCSC. The considered supply chain consists of four key players: A Traditional Manufacturer (TM) with high carbon emissions that produces energy products using fossil fuels (q_{TM}), a Renewable Manufacturer (RM) with zero carbon emissions that generates energy products from renewable resources (q_{RM}), a retailer that purchases energy products from both manufacturers at the market price (P_e), and a governmental authority seeking accurate and transparent information regarding the carbon emissions of the TM.

Within this framework, blockchain technology is employed as a mechanism to enhance the transparency and traceability of carbon emission data, thereby enabling real-time monitoring of environmental performance. This transparency mechanism can significantly influence production strategies, pricing decisions, and governmental policy-making.

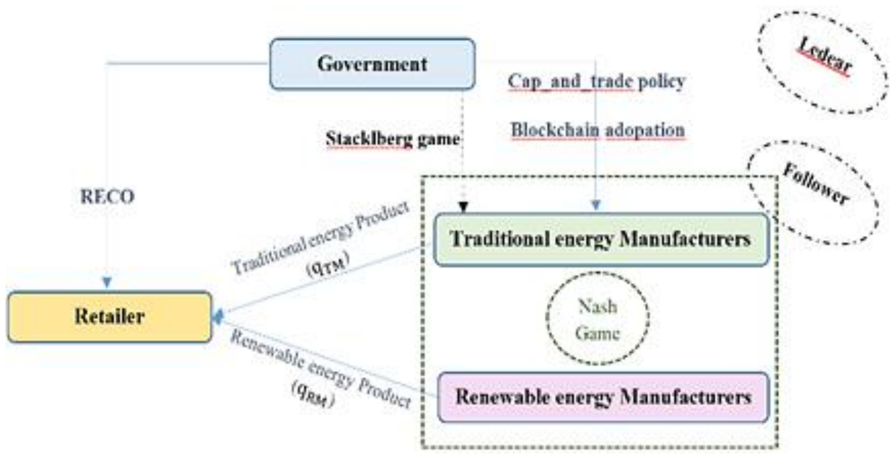

Fig. 1 illustrates the topology of the proposed problem.

Fig. 1. General structure of the proposed problem.

3.1 | Problem Assumptions

In this study, the government provides a subsidy of P_r per unit of product to the RM in order to encourage cleaner production. The production cost functions of both TM and RM are assumed to be quadratic, where (α) and (β) represent positive cost coefficients. Since renewable energy products generally involve higher production costs than traditional energy products, it is assumed that:

$$0 < \alpha < \beta.$$

The products supplied by the two manufacturers possess quasi-public characteristics, and their prices and supply levels depend on production costs and consumer utility ($U(q_D)$) [10]. Following the study by Sun [25], the consumer utility function is defined as

$$U(q_D) = mq_D - \frac{1}{2}nq_D{}^2, \quad (1)$$

where the first derivative of the utility function with respect to demand is positive: $U'(q_D) > 0$ and the second derivative is negative:

$$U''(q_D) < 0.$$

The total market demand (q_D) is equal to the aggregate production quantities in the traditional energy market (q_{TM}) and the renewable energy market (q_{RM}).

If the TM adopts blockchain technology and provides transparent carbon emission information, it receives a subsidy of (P_{bc}) [26]. Furthermore, under the RECO policy, the government determines a minimum renewable energy sales ratio such that:

$$0 \leq q_{RM} \leq \eta q_D.$$

Similar to the study by Ciarreta et al. [27], a penalty function of the following form is imposed for non-compliance: $\frac{s}{2}(\eta q_D - q_{RM})^2$, where (s>0) is a scaling parameter.

The penalty function has a threshold point at:

$$\eta q_D = q_{RM},$$

which implies that retailers do not receive any additional governmental reward even if renewable energy consumption exceeds the required threshold.

3.2 | Mathematical Notation

The notations used in this study are summarized in *Table 1*.

Table 1. Definition of parameters and decision variables.

Parameter	Description	Variable	Description
s	Scaling parameter of the retailer's penalty imposed by the government	q_{TM}	Production quantity of traditional energy products
m , n	Sensitivity coefficients in the utility function	π_r	Retailer's profit function
P_e	Market price of energy products	π_{TM}^{NB}	Profit of TM without blockchain adoption
α, β	Investment cost coefficients for energy production by TM and RM	q_{RM}	Production quantity of renewable energy products
P_r	Government subsidy per unit of renewable energy product produced by RM	π_G	Government profit function
η	Minimum renewable energy consumption ratio specified by the RECO regulation	π_{SC}^{NB}	Total supply chain profit without blockchain adoption by TM
P_{bc}	Unit subsidy for energy products produced through the transparent production process of TM	π_{SC}^{B}	Total supply chain profit with blockchain adoption by TM
G	Total subsidies paid by the government	π_{TM}	Profit of TM with blockchain adoption
b	Blockchain adoption cost per unit	π_{RM}	Profit function of RM
θ	The environmental benefit generated by each unit of the renewable energy product	EV	Environmental benefits of the supply chain
P_{blc}	Government revenue from each unit of energy product generated through TM's transparent production process	SW	Social welfare function of the supply chain
F	Fixed cost of blockchain technology adoption		

3.3 | Model Formulation

Based on the assumptions and relationships defined in the previous section, the decision-making problem of the TM can be formulated as follows:

$$\text{Max } \pi_{TM}(q_{TM}) = (P_e + P_{bc} - b)q_{TM} - \alpha\,(q_{TM})^2 - F. \quad (2)$$

In *Eq. (2)*, the first term represents the revenue generated from selling energy products, the second term denotes the production cost of these products, and the final term corresponds to the fixed cost associated with blockchain technology adoption within the CCSC. Similarly, the decision-making problem of the RM is formulated as follows:

$$\text{Max } \pi_{RM}(q_{RM}) = (P_e + P_r)q_{RM} - \beta(q_{RM})^2. \quad (3)$$

In *Eq. (3)*, the first component represents the revenue obtained from selling renewable energy products, whereas the second component reflects the corresponding production costs. The quadratic cost functions imply that production costs increase convexly as the production level rises, meaning that achieving high production levels becomes substantially more expensive than maintaining moderate production levels [11].

Since the adoption of blockchain technology by TM enables the government to monitor carbon emissions more accurately, the government also derives benefits from this system. Accordingly, the government's objective function is defined as follows:

$$\text{Max } \pi_G(q_{TM}.\, q_{RM}) = (P_{blc} - P_{bc})q_{TM} - P_r q_{RM}. \quad (4)$$

In this equation, the second term reflects the subsidy paid by the government to the RM for renewable energy production. Furthermore, the retailer's profit is defined as the revenue obtained from market sales minus the penalty imposed for non-compliance with RECO policies.

$$\pi_r(q_{TM}.\, q_{RM}) = p_e(q_{TM} + q_{RM}) - \frac{S}{2}(\eta(q_{TM} + q_{RM}) - q_{RM})^2, \quad (5)$$

3.4 | Equilibrium Analysis of the Model

Using the model structure and profit functions presented in the previous section, the equilibrium conditions can be derived. First, based on the Nash equilibrium concept, the equilibrium production quantities of the manufacturers are determined. To this end, the negativity of the second derivative of each profit function with respect to production quantity is verified to ensure concavity and the existence of an optimal solution. Subsequently, by setting the first-order derivatives of the profit functions equal to zero and solving the resulting system of equations, the equilibrium production quantities are obtained as follows:

$$q_{TM} = -\frac{n(2b - m + 2bn\beta - 2mn\beta - 2p_{bc} - 2n\beta p_{bc} + p_r)}{3 + 4n\alpha + 4n\beta + 4n^2\alpha\beta}. \quad (6)$$

$$q_{RM} = -\frac{-bn - mn - 2mn^2\alpha + np_{bc} - 2np_r - 2n^2\alpha p_r}{3 + 4n\alpha + 4n\beta + 4n^2\alpha\beta}. \quad (7)$$

Next, using the Backward Induction approach, the optimal values obtained for the follower manufacturer are substituted into the profit function of the TM. Solving the Stackelberg game within this framework yields the optimal government subsidy allocated to the TM when adopting blockchain technology, as expressed below:

$$p_{bc} = \frac{\dfrac{-2bn + mn - 2bn^2\beta + 2mn^2\beta - 2np_r + n(-2 - 2n\beta)P_{blc}}{3 + 4n\alpha + 4n\beta + 4n^2\alpha\beta}}{\dfrac{-2n - 2n^2\beta + n(-2 - 2n\beta)}{3 + 4n\alpha + 4n\beta + 4n^2\alpha\beta}}. \quad (8)$$

By substituting *Eqs. (6)-(8)* into *Eqs. (2)-(4)*, the equilibrium profit values of the supply chain players can be obtained.

In this research, the performance of the CCSC is evaluated under two different scenarios. In the first scenario, the TM adopts blockchain technology and receives governmental subsidies. In the second scenario, TM does not adopt blockchain technology. Under the second scenario, the profit function of the TM is expressed as follows:

$$\pi_{TM}^{NB}(q_{TM}.q_{RM}) = p_e q_{TM} - \alpha {q_{TM}}^2 \quad (9)$$

The total profit of the CCSC in each scenario is equal to the sum of the profits of all supply chain members, which can be expressed as follows:

$$\pi_{SC}^{B} = \pi_{TM}^{B} + \pi_{RM} + \pi_r + \pi_G. \quad (10)$$

$$\pi_{SC}^{NB} = \pi_{TM}^{NB} + \pi_{RM} + \pi_r + \pi_G. \quad (11)$$

4 | Numerical Analysis

To validate the proposed model, a numerical example is presented. Some parameter values are adopted from previous studies [10], while others are selected based on expert opinions from the energy industry to ensure that the model assumptions hold and that the profit functions remain concave. The parameter values are as follows:

$P_{blc} = 50. S = 3. F = 10. \eta = 0.3. p_r = 25, \ \beta = 0.3 . b = 10. m = 30. n = 10. \alpha = 0.02.$

As previously discussed, this study focuses on blockchain adoption in the CCSC. *Fig. 2* illustrates the effects of changes in the unit blockchain adoption cost on the profits of the TM and the RM. The results indicate that as the blockchain adoption cost increases, the profit of TM increases, whereas the profit of RM decreases.

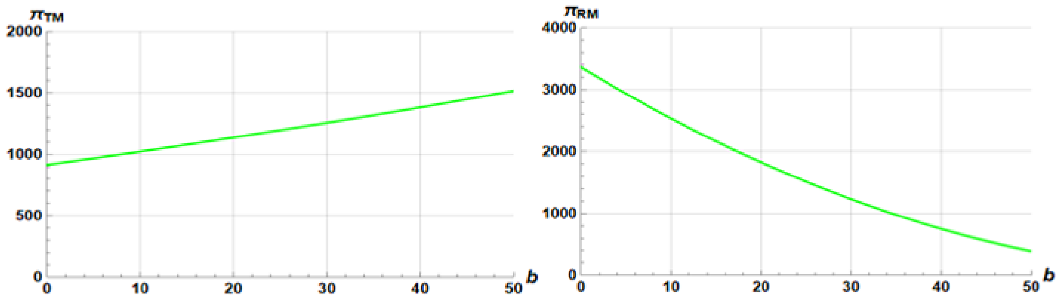

Fig. 2. Relationship between variable blockchain adoption cost and the profits of manufacturers.

Furthermore, *Fig. 3* compares the total profit of the supply chain under two scenarios: when TM adopts blockchain technology and when it does not. The findings demonstrate that the blockchain adoption scenario leads to higher overall supply chain profitability.

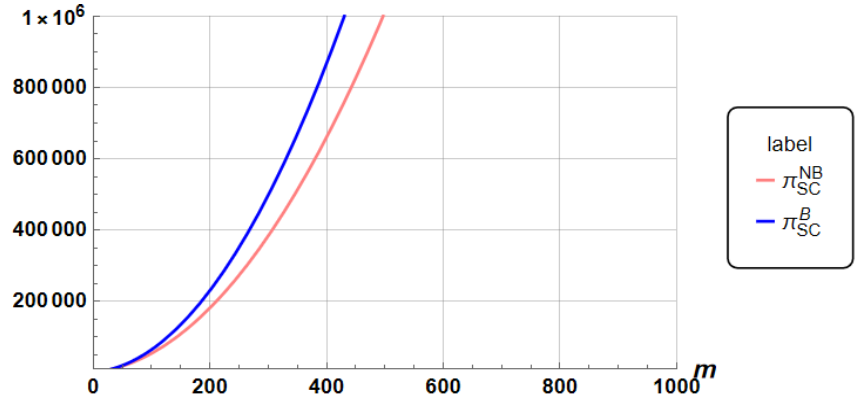

Fig. 3. Comparison of total supply chain profit under the two scenarios.

In addition to profit analysis, the present study evaluates Social Welfare (SW) according to *Eq. (12)*, which, similar to the definition proposed by Zheng et al. [27], is equal to the sum of manufacturers' profits and environmental benefits minus the total governmental subsidies. The Environmental Benefit (EV) is calculated using *Eq. (12)*. The total governmental subsidies include subsidies paid to the RM for renewable energy production and subsidies provided to TM for blockchain adoption.

$$EV = \theta * q_{RM}, \quad (12)$$

$$SW = \pi_{TM} + \pi_{RM} + EV - G, \quad (13)$$

By integrating *Eqs. (12)* and *(13)*, the SW function can be expressed as follows:

$$SW = \pi_{TM} + \pi_{RM} + \theta q_{RM} - (p_{bc} + p_r). \quad (14)$$

Fig. 4 illustrates the effects of changes in variable and fixed blockchain adoption costs on SW. The results reveal that as the variable cost increases, SW initially decreases and then starts to increase after reaching a threshold point. In contrast, an increase in fixed blockchain adoption cost leads to a continuous decline in SW.

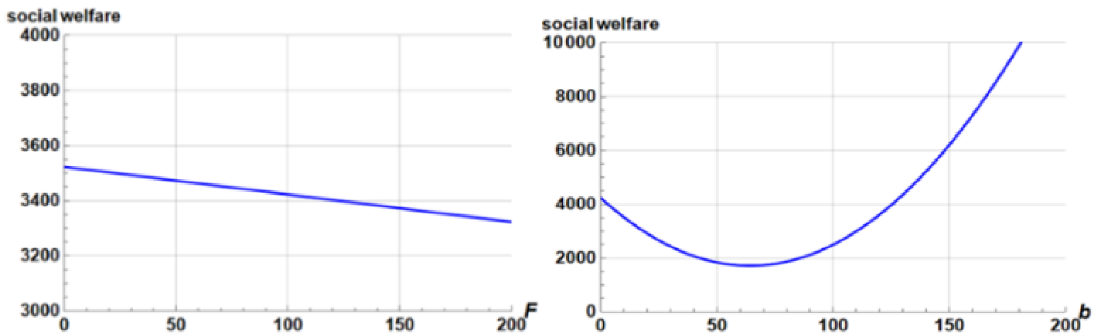

Fig. 4. Relationship between variable and fixed blockchain adoption costs and social welfare.

5 | Conclusion and Future Research Directions

This study investigated the impact of blockchain technology on the development of operational strategies in a CCSC under cap-and-trade regulations. By integrating game theory and blockchain technology, a framework was proposed to optimize production decisions, reduce carbon emissions, and improve transparency. The findings demonstrated that combining cap-and-trade systems with RECO policies and blockchain technology enables accurate carbon emission tracking, prevents double-counting, and reduces transaction costs.

The Stackelberg framework, in which the government acts as the leader and manufacturers as followers, together with Cournot competition between manufacturers, identifies optimal production and pricing equilibria. The results indicate that governmental subsidies for renewable energy manufacturers serve as a key driver for the transition toward clean energy, while subsidies allocated to TMs for blockchain adoption facilitate transparency and encourage their participation in carbon reduction initiatives.

The proposed framework provides a dynamic and flexible mechanism for adjusting emission caps and ensures long-term alignment among economic objectives, environmental requirements, and SW. In addition, competition between TM and RM contributes to lower marginal production costs and increases the market share of clean energy. Blockchain implementation further improves monitoring efficiency, fair allocation of carbon allowances, and retailers' ability to select low-carbon suppliers.

The findings suggest that the innovative integration of game theory, blockchain technology, and carbon policies not only reduces carbon emissions but also enhances stakeholder profitability. Nevertheless, the successful implementation of this approach requires close collaboration among governments, manufacturers, and technology developers.

For future research, investigating financing mechanisms or public–private partnership models to reduce blockchain development and maintenance costs, particularly for small-scale manufacturers, is recommended. In addition, examining financial incentives for investment in renewable energy projects and consumer-oriented policies encouraging the purchase of low-carbon products, such as discounts or reward-based schemes, could provide valuable research directions. For example, offering discounts or rewards for purchasing products generated through low-carbon energy sources may represent an important avenue for future studies. Moreover, incorporating an energy storage company as an additional player in the model could open new and valuable research pathways, especially considering the rapid growth of energy storage technologies and their critical role in the transition toward sustainable and clean energy systems.

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Data Availability

Sufficient data is available upon request.

Conflict of Interest

No potential conflict of interest was reported by the authors.

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