A Local Energy Market for Industrial Parks Considering Carbon Emission Quota

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***Abstract*—Carbon emission reduction has become a research hot spot in energy sector due to the growing environmental crisis. With the improvement of the carbon emission quota, different entities in the energy market should consider the cost when exceeding the quota. In this paper, we propose a local energy market with Double-side Auction Mechanism considering carbon costs. The bidding/offering prices of market entities (i.e., electricity producers and consumers) are decided by their generation cost functions or utility functions, respectively. These prices form the supply and demand curves to determine the market clearing price and quantity. Market-related information is collected and distributed by the independent system operator (ISO) to all entities through the blockchain network. The ISO assigns and settles the carbon quotas according to the clearing results of the market. Several case studies are presented to demonstrate the proposed local energy market mechanism. We find that introducing carbon costs benefits the renewable energy sources and the enterprises with low-carbon technologies.**

***Index Terms*—carbon emission quota, Double-side Auction, industrial parks, local energy market**

I. Introduction

The development goals of carbon peaking and carbon neutrality propose low-carbon demand. The power industry is currently one of the industries with the largest carbon emissions in countries around the world. The transition to a low-carbon power industry is important to future development. However, urban industrial parks, which have high carbon intensity, consume a lot of energy and emit a lot of exhaust, such as carbon dioxide. Carbon emissions in some industrial parks are almost entirely from energy consumption. For example, energy-related carbon emission accounts for 97% and 94% of the carbon emissions of the industrial parks in Beijing and Suzhou, respectively [1]. Therefore, the reduction of the energy-related carbon emission in industrial parks deserves attention.

In many countries, some schemes have been proposed to effectively control the carbon emissions of industrial parks. In Ref. [2], it is pointed out that the carbon quota and its associated carbon trading market can effectively reduce regional carbon emissions at the long term. Carbon emission quota is the carbon emission rights within a specific period for an entity, usually in “tons of carbon dioxide equivalent”. Considering its environmental value, carbon emission quotas become scarce resources, of which the economic value is highlighted. Thus, carbon emission quota markets are established in some countries, of which the carbon emission quota distribution method is an important basis [3].

For the effective operation of the carbon market trading mechanism, carbon emission quota distribution methods are designed by governments or institutions. The quota distribution methods mainly include free distribution, paid distribution and the mixed use of the two methods. The initial quota can be calculated by several methods, including the historical emission method, the historical carbon intensity reduction method and the industry baseline method. In Ref. [2], the historical emission method is proved to be the most effective method to facilitate carbon emission reduction.

Another necessary step of carbon market trading process is carbon accounting. Carbon accounting is adopted to measure the carbon emission of market entities in a trading cycle. Carbon accounting methods fully reflect the characteristics of each industry. The method of measuring carbon emissions of electricity consumer enterprises is based on the type of electricity purchased in the industrial park, while the carbon emissions of power generation enterprises are measured according to the process of producing electricity and capturing carbon.

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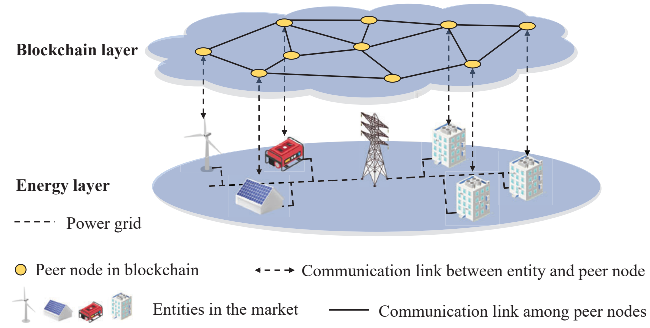


Fig. 1. The system schematic of an industrial park considering energy and carbon trading through blockchain network.

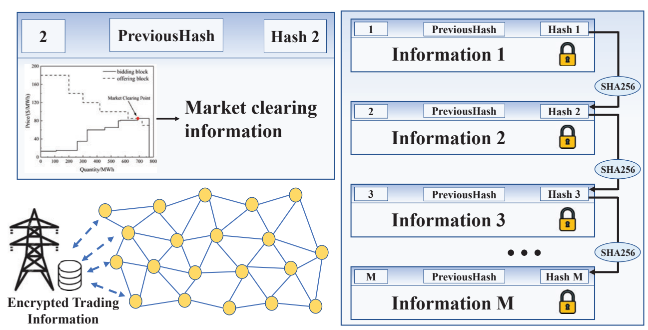


Fig. 2. Blockchain for the trading process of the proposed local energy market considering carbon emission quotas.

Carbon emission quota trading is being used by more and more countries or regions to solve the global warming problem. The carbon price in most carbon markets fluctuates according to the balance between supply and demand, while it is also influenced by government regulation. Usually, the government sets the carbon emission cap of some carbon-intensive enterprises, such as the electricity production industry, the building material industry and the steel industry. The government also awards extra quotas to the emission reduction enterprises, such as the renewable energy industry and tree farms. Extra quotas can be sold to those enterprises with quota shortage, such that the emission reduction enterprises can benefit from reducing their carbon emission. Zhang *et al.* [3] point out that the carbon market will affect the production mode of enterprises, and adjust the energy structure. Chen *et al.* [4] point out the carbon market can trigger the revolution of low-carbon technology.

The research on the energy market is very mature, while the research on the carbon market and the coupling market is not enough. Sun *et al.* [5] propose a coupled electricity and carbon market, while the electricity market and the carbon market are traded separately. There is no close connection between the two markets and they cannot interact. Hua *et al.* [6] propose that the key to coupling the two markets is the time scale of unified trading. Usually, the time scale of carbon trading is annual, which is too long for energy trading, such that the coupling between the electricity market and the carbon market is weak. However, Pan *et al.* [7] point out that the spot market of the carbon market has disadvantages in terms of detecting carbon prices, long-term emission reduction of enterprises, and improvement of market liquidity. While coal-fired power plants are not motivated to participate in the spot market due to the cost of shutting down and restarting thermal power units. Trading in the day-ahead market or spot market is not attractive enough for every energy enterprise. Based on the above reasons, the monthly market with large electricity transactions is a trade-off. Cheng *et al.* [8] propose to calculate the carbon cost of the enterprise by tracking the carbon flow. However, the impact of the carbon cost on the energy market is not clearly revealed. Wang *et al.* [9] aim to limit the total carbon emissions of the whole power system within a given cap. Since the carbon emission caps are generally set over a long-term timescale, e.g. yearly, it is difficult to allocate the emission caps for short-term operation problems. This study selects the monthly market to trade electricity and carbon emission quotas.

In this paper, we design a monthly local energy market considering the energy cost and the carbon cost. The historical emission method is adopted to calculate the initial carbon emission quotas for each entity. Double-side Auction Mechanism (DAM) is adopted to determine market clearing price and quantity. After a trading cycle ends, we use several methods to determine the carbon emission of different enterprises. The results of the accounting would generate fines and rewards for the enterprises, which also have an impact on the next trading cycle. Several case studies are designed to demonstrate our proposed mechanism in different scenarios.

The contributions of this paper are twofold:

1) A monthly DAM is proposed considering the interaction between the carbon emission trading market and the electricity market. The DAM can impact the cost of each entity and is conducive to low-carbon transformation of the energy sector.
2) A rolling factor is designed for quantifying the impact of the carbon emission trading market in subsequent cycle transactions. Experimental studies illustrate that renewable energies are conducive to the reduction of production costs of enterprises.

The remainder of this paper is organized as follows. Section II presents the framework of the local energy market based on blockchain technology. Section III shows the trading process of the proposed market considering carbon emission quota. Numerical studies and results are presented in Section IV. Finally, Section V concludes this paper.

II. Framework of the Local Energy Market Based on Blockchain

This section first designs the market transaction mechanism and builds the framework of the transaction market. Afterward, a standardized transaction process based on blockchain is designed.

A. System structure

The urban industrial park includes two layers, which are the energy layer and the blockchain layer. Fig. 1 shows the whole structure of the local energy market in the industrial park. Each entity in the energy layer corresponds to a peer node in the blockchain layer, through which all market information is transmitted. We divide the enterprises into the energy consumption side and energy production side. The energy consumption side includes the Internet enterprises, the heavy industry enterprises, and light industry enterprises. Their differences in electricity consumption behavior and utility function are discussed in the next section. On the energy production side, there is a photovoltaic power production enterprise, a wind power production enterprise, two fossil fuel power production enterprises, and two fossil fuel power production enterprises equipped with low-carbon power production technologies. There exists a third-party entity, Independent System Operator (ISO), which provides power transmission and power dispatching services to ensure the safe and reliable operation of the power grid. For the industrial park scenario in this study, we choose the consortium blockchain as a reliable trading platform.

B. Blockchain network

Blockchain is a distributed ledger technology for the secure sharing of information. To ensure the security and credibility of the transaction, the Hyperledger Fabric, which is one type of consortium blockchain, is selected to conduct the transaction. Each peer node maintains a tamper-proof transaction information record by executing a smart contract that is agreed by all entities. Transaction information is stored in the blocks, which sequentially form the blockchain, as shown on the right side of Fig. 2.

1) Local electricity market: In this paper, the scenario we consider is an urban industrial park, where market entities are divided into electricity producers and consumers. ISO sets carbon quotas for enterprises based on the carbon emission factors of different industries and the historical electricity consumption of each enterprise, which is distributed to enterprises on a monthly basis. For each electricity producer, annual carbon emission quota $Emis_y^{\text{power}}$ can be disaggregated into monthly carbon emission quota $Emis_m^{\text{power}}$. With annual power generation data $GElec_y^{\text{power}}$ and the corresponding generation-related emission factors GEF_y^{power}, we calculate monthly carbon emission quota by:

III. Trading Process of the Local Energy Market

This section describes the overall trading framework under which both electricity and carbon quotas are traded in the local energy market. The entire transaction process is automatically proceeded, with the smart contract of Hyperledger Fabric.

$$Emis_m^{\text{power}} = (1-\alpha)\frac{GElec_y^{\text{power}} GEF_y^{\text{power}}}{12}, \tag{1}$$

where α represent the descending factor; subscripts power, m, y represent power plant, month and year, respectively.

1) Bidding of enterprises: On the energy consumption side, each enterprise selects the optimal bids including electricity prices and quantities according to the utility function. The market allows an enterprise to have multiple bids. The form of utility function satisfies the requirements of zero-crossing, monotonically increasing and saturation. For each consumption enterprise, the utility function is [10]:

$$u_{i,t} = \theta_{i,t} ln(1 + p_{i,t} - r_{i,t}), \tag{2}$$

where $p_{i,t}$ is the power consumption; $\theta_{i,t}$ is the characteristic coefficient of consumer i; $r_{i,t}$ is the electricity consumption of its operation; i and t are the indices for enterprise and time, respectively. The bidding price π of the consumption enterprise is calculated by:

$$\pi_{b,i} = \omega u_{i,t}^{'}, \tag{3}$$

where b is bidding price; ω is the coefficient of profit; $u_{i,t}^{'}$ is the first-order derivative of the utility function.

2) Offering of enterprises: For the fossil fuel power plant, we determine the offering price in the local energy market by calculating the cost of electricity generation. For renewable energy generation enterprises, we use the Levelized Cost of Electricity to determine the offering price [11]. On the basis of the original equipment of the traditional coal-fired or gas plant, diverse carbon capture and storage devices are introduced to form a carbon capture system power plant. The power and carbon emission characteristic of a carbon capture power plant is [12]:

$$Emis_{i,t} = \lambda \frac{CEF_i}{\eta Q_i}, \tag{4}$$

where λ, CEF_i, Q_i, η are the carbon capture rate, carbon emission factor of the plant, the unit calorific value of fuel and the power generation efficiency, respectively.

3) Market clearing: This study uses a monthly transaction DAM. Market entities need to submit trading information to ISO one month in advance, and the information includes the electricity price and the quantity of multiple expected transactions. ISO receives the information through the blockchain and stacks up those offers and bids to form the supply and demand curves according to the smart contract. During a trading session, the bids b_i of electricity consumers are sorted from high to low, and the electricity is accumulated at the same time. Similarly, the offers o_j of power producers are sorted from low to high, and the electricity is accumulated at the same time. The two supply and demand curves can obtain an intersection point. The electricity accumulation value reflects by each offer or bid sorted is marked as S_i and Q_j, respectively. The intersection point of the two curves shows the market clearing price (MCP) and the quantity to be traded. As Fig. 3 showing, the bid prices of consumers on the left-hand side of the intersection point are all higher than the offer prices of producers. The bidding prices of the consumers on the right-hand side of the intersection are all lower than the offer prices of the producers, and this part fails to be cleared. The enterprises whose offers and bids are not cleared in the market are allowed to trade with ISO in the spot market. The ISO broadcasts the market clearing results to all entities in the blockchain network. At this point, a trading cycle ends.

Algorithm 1 Calculate market clearing price and quantity

for each b_i, $i \in [1, 2, .., M]$ **do**
  for each o_j, $j \in [1, 2, ..., N]$ **do**
    if $b_g \geq s_h$ and $S_{(h-1)} \leq Q_g \leq S_h$ **then**
      MCP=s_h
      Quantity=Q_g
    end if
    if $b_g \geq s_h$ and $Q_{(g-1)} \leq S_h \leq Q_g$ **then**
      MCP=b_g
      Quantity=S_h
    end if
    if $b_g < s_h$ **then**
      Trade with ISO
    end if
  end for
end for=0

$$\begin{cases} \pi_{i,t}^{\text{sell}} = \pi_{i,t}^{\text{buy}} = \pi_t^{\text{MCP}}, & \text{if } b_i \geq o_j \\ \pi_{i,t}^{\text{sell}} = \pi_{s,t}, \pi_{i,t}^{\text{buy}} = \pi_{b,t}, & \text{otherwise,} \end{cases} \tag{5}$$

where $\pi_{i,t}^{\text{buy}}$, $\pi_{i,t}^{\text{sell}}$, π_t^{MCP}, $\pi_{s,t}$, $\pi_{b,t}$ represent the buying price of each consumer, the selling of each producer, the MCP, the selling price in the spot market, the buying price in the spot market respectively.

According to the market clearing result and the trading result with ISO, the blockchain smart contract would record the carbon emission quotas. According to the carbon quota excess or surplus, ISO would give enterprises fine or bonus. Carbon emission quota can be calculated by:

$$Emis_{i,t} = \sum_{i=0}^{n} Quan_{i,t} CEF_{i,t}, \tag{6}$$

where $Quan_{i,t}$, $CEF_{i,t}$ are electricity of each consumer and corresponding carbon emission factor.

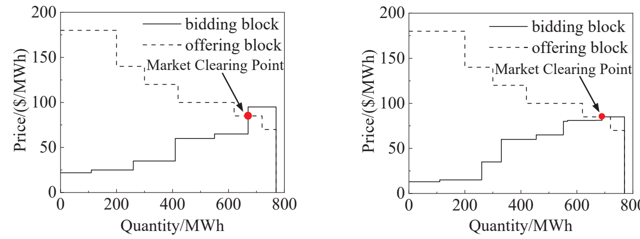
If the carbon quota exceeds, ISO would charge a fine, $\Phi_{i,t}^{fine}$, which is calculated based on a given carbon price π_C:

$$\Phi_{i,t}^{fine} = Emis_{i,t} - Emis_{\text{power},m} \pi_C. \tag{7}$$

Otherwise, a bonus, $\Phi_{i,t}^{bonus}$, is awarded based on the remaining carbon emission balance:

$$\Phi_{i,t}^{bonus} = Emis_{\text{power},m} - Emis_{i,t} \pi_C. \tag{8}$$

The transaction result of each trading cycle will affect the utility function of the consumer enterprises in the next trading cycle. On the basis of the original utility function, a variable is added to reflect this change. The relationship between this variable and the fine paid for exceeding usage of carbon quota can be expressed by the Eq. (9).



(a) without carbon costs. (b) with carbon costs.

Fig. 3. Local energy market clear with/without considering carbon costs.

4) Low carbon incentive mechanism: After one cycle of trading ends, the carbon cost becomes an important factor that affects the next cycle of bidding. We design a rolling factor δ related to carbon excess:

$$\delta_{i,t} = \begin{cases} \frac{Emis_{i,t} - Emis_m^{\text{power}}}{Emis_m^{\text{power}}}, & \text{if } Emis_{i,t} \geq Emis_m^{\text{power}} \\ 0, & \text{otherwise.} \end{cases} \tag{9}$$

The fine for exceeding usage of carbon quota in this cycle would affect the bids of electricity companies in the next cycle. Thus, the variable $\delta_{i,t}$ is introduced to the utility function of the consumption enterprises:

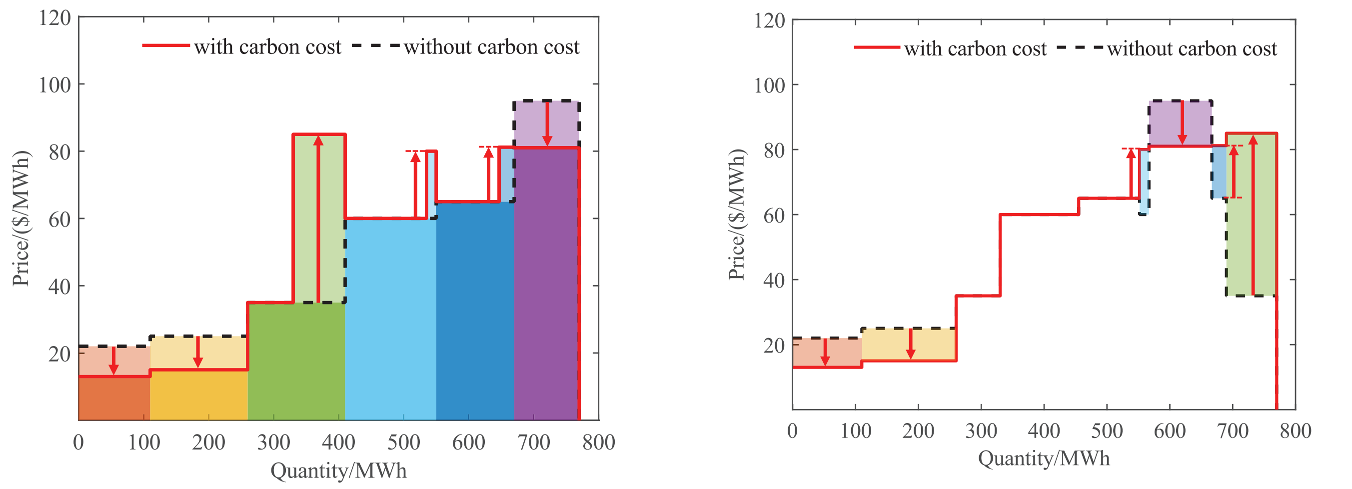
$$u_{i,t} = (1 - \delta_{i,t}) \theta_{i,t} ln(1 + p_{i,t} - r_{i,t}). \tag{10}$$

IV. Case Study

In the case study, we adopt an industrial park model, where power production enterprises and power consumption enterprises participate in the proposed local energy market. The proposed DAM is demonstrated through several case studies.

A. Clearing results with/without considering carbon costs

In this subsection, the clearing results before and after considering the carbon costs are compared. Fig. 3(a) shows the market clearing result in the conventional electricity markets, while Fig. 3(b) shows the market clearing result when considering carbon quota trading. We can observe that under the effect of carbon quotas and carbon price, the bidding prices of power generation enterprises have undergone significant changes. In order to illustrate these changes more intuitively, the supply curve of the generation enterprises is shown in Fig. 4. In Fig. 4, different colors represent the offers of different power generation enterprises, the light color area represents the change of price after the introduction of carbon cost and the arrows represent the directions of changing. We can see that the offering prices of the renewable energy enterprises or enterprises with low-carbon technology decrease, while the coal-fired and gas plants increase. Fig. 4(a) shows that the clearing order in local energy market without carbon cost, while Fig. 4(b) is the clearing order considering the carbon cost. Power generation enterprises with high carbon emissions are at a disadvantage in the scenario of considering the carbon cost.



(a) Order without carbon cost

(b) Order with carbon cost

Fig. 4. Local energy market clearing order after considering carbon cost. After considering carbon cost, the bidding prices of coal-fired and gas power plant increase, leading to disadvantaged of priority in market clearing.

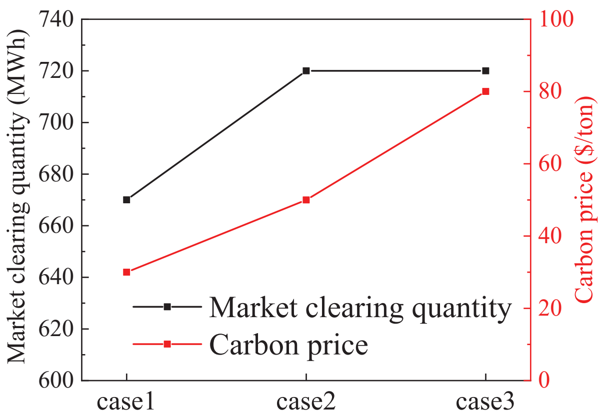


Fig. 5. Effect of changing carbon price on market clearance. The figure shows that a low carbon price would negatively affect market clearing quantity, while that carbon quota trading could be further motivated by the increase of carbon price.

TABLE I
THE CARBON COST PAID BY POWER GENERATION ENTERPRISE AFTER THE MARKET CLEARS.

Enterprise	Carbon cost($/ton)
Wind PP	-1000
PV PP	-1500
Coal PP	4000
Gas PP	300
Coal+CCUS PP	375.84
Gas+CCUS+CCGT PP	-1400

In the Table, PV is photovoltaic, PP is Power Plants, CCUS is Carbon Capture, Utilization, and Storage and CCGT is Combined Cycle Gas Turbine.

We can find the following conclusions from Table I and Table II. For renewable generation enterprises, the introduction of carbon costs can be seen as an environmental value reward for zero-carbon production. For generation enterprises with low-carbon technologies, the usage of these technologies brings direct economic benefits. However, carbon cost is an extra cost for coal-fired and gas plants. Thus, introducing carbon costs facilitates the development of renewable energy sources and low-carbon technologies.

B. Clearing results considering different carbon prices

This subsection compares the impact of different carbon prices on the energy market. Table III shows that a lower carbon price would have a negative impact on the market clearing quantity, because a lower carbon price is equivalent to less penalty to traditional power plants (e.g., coal-fired and gas power plants) and less bonus to the power plants with low-carbon technologies. By contrast, in the scenario with a high carbon price, the power plants with low-carbon technologies will have more initiative to decrease the biding price and obtain more generation share, as shown in Fig. 5.

TABLE II
MARKET CLEARING QUANTITY OF DIFFERENT CONSUMPTION ENTERPRISES IN TWO SUCCESSIVE TRADING CYCLES DUE TO CARBON COSTS.

Consumption enterprise	First month (MWh)	Second month (MWh)
Internet enterprise	300	300
Heavy industry enterprise	300	200
Light industry enterprise	170	120

TABLE III
EFFECT OF CHANGING CARBON PRICE ON MARKET CLEARANCE.

Case	Carbon price($/ton)	Market clearing quantity(MWh)
1	30	670
2	50	720
3	80	720

C. Long-term impact on different consumption enterprises considering carbon costs

Table II shows the difference of carbon costs in two successive trading cycles. The market clearing quantity of the heavy industry decreases in the second month due to the high carbon cost. In other words, enterprises that exceed their carbon quotas would be subject to additional penalties, which affect the utility functions and the bidding prices in the next trading cycle. Enterprises with high carbon emissions are encouraged to use low-carbon technologies to recover their full potential in the local energy market. The introduction of carbon cost benefits the renewable energy production enterprises and the development of low-carbon technologies.

V. CONCLUSION

To facilitate the decarbonization of the energy sector, this paper proposes a DAM in the local energy market, which takes the carbon cost into account. To ensure the security of market operation, we design a blockchain-based framework for the local energy market. We also formulate the models of both the power production enterprises and the power consumption enterprise, considering the carbon quota and the carbon cost. A number of case studies are presented to demonstrate the effectiveness of the proposed local energy market with DAM. By analyzing the case of considering carbon cost and the long-term impact of carbon costs on the market, it is concluded that the introduction of carbon cost is beneficial to the renewable energy production enterprises and the development of low-carbon technologies. The impact of the changing of the carbon price is also investigated, showing that the carbon price could be further increased to motivate the participation rate of the carbon quota trading. We also illustrated that, with our proposed market mechanism, the carbon cost has a long-term impact on the operating strategy of the enterprises. To adapt to the low-carbon or zero-carbon development requirements, the reduction of carbon intensity of the energy sector still has a long way to go, by optimizing the power supply structure and adopting carbon emission reduction technologies.

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