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REVIEW

Comparative study on distributed generation trading mechanisms in the UK and China

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Abstract

The market penetration of distributed generation (DG), particularly for that from renewables, has significantly increased in recent years. This trend will continue with the low-carbon transition of electric power systems, as a part of global efforts to combat climate change. Appropriate trading mechanisms are of great importance for incentivizing the investment in and coordinated operation of DG. The UK and China both have ambitious decarbonization agendas with particular emphasis on the electricity market design. Nevertheless, the UK and China have distinguishing features in electricity market design, particularly in the trading mechanisms for DG. This paper presents a thorough review of DG trading policies and arrangements in both countries, including market structures, connection classifications, economic benefits and practical issues. The strengths, weaknesses, opportunity, and threats-political, economical, social and technological (SWOT-PEST) model features of the mechanisms in both countries were qualitatively identified and compared. A quantitative comparison was conducted between the trading arrangements in the UK and China, with the economic benefits analysed and the implications revealed. Finally, the directions for developing and improving DG trading mechanisms were suggested based on the comparative analysis. The practical experiences of the UK and China can be extended to other countries across the globe.

1 | INTRODUCTION

1.1 | Motivation

Distributed generation (DG) has been a focus of research owing to its rapid expansion in scale and the rapid development of generation technologies [1]. To achieve decarbonization targets, policies and regulations have been launched worldwide for the development of DGs, particularly for distributed renewable energy sources, to improve energy utilization and reduce greenhouse gas emissions [2, 3]. For example, China adopted a bundled trading mechanism for distributed photovoltaics (PV), as introduced in [4]. The feed-in tariff (FIT) was conducted in Argentina but is not as profitable as net billing and net metering schemes for DG [5]. Subsidies and fiscal incentives were implemented in Brazil through research and development programs to promote the development of DG [6].

The aforementioned studies focused on policy implementation in a specific region. However, the strengths and weaknesses of these policies cannot be fully demonstrated without a comparison to practices in other representative regions. Accordingly, the international experience of DG policies was analysed in [7], including the tax credit policy in the US and the pricing mechanism in Germany, to provide suggestions for developing clean DG in China. Policy documents on peer-to-peer electricity trading for DG have been examined in the EU and China to analyse any gaps and similarities [8]. Therefore, a comparative study of regional policies and their corresponding effects could improve regulations and market management.

The macro-environment and situation analysis model, also known as the SWOT-PEST model, was adopted to study development strategies and long-term planning [9]. The SWOT analysis includes studies of four aspects [10]: strengths, weaknesses, opportunities and threats, whereas the PEST analyses policy, economy, society and technology [11]. In combination with the SWOT-PEST matrix, features and strategies can be determined for future planning. For example, the financial status of the PV industry was demonstrated in [12] based on the PEST model, and the obstacles and opportunities for development were examined accordingly. The energy storage industry in China was studied in [13] based on the SWOT-PEST model, and strategies for developing the industry were provided. Similarly, the SWOT-PEST model was adopted in [14] as a strategy analysis tool to explore the development of the Chinese bioenergy industry.

However, the SWOT-PEST model had not been previously applied for studying the DG trading mechanism, and the above pieces of policy analysis lack practical and statistical economic comparisons in the context of decarbonization. Therefore, a review of the practical DG trading mechanisms of the UK and China is presented in this paper. Based on the analysis of the main market features and the SWOT-PEST model on the pros and cons of the mechanisms in both countries, suggestions are provided for the future development of DG.

1.2 | Development of distributed generation in the world

The definition of DG can be traced back to the latter half of the 20th century, before generally-accepted addressing of such small-scale generations was formed, and DG was referred to as "embedded generation," "dispersed generation," or "decentralized generation" in different countries [15]. The forms of DG vary based on the generation of technical development levels and the enhancement of environmental benefits. Specifically, traditional DG forms include wind turbines (WT), PV, fuel cells (FC) and combustion turbines (CT) [16], whereas cogenerations and micro-combined heat and power systems (Micro CHP) are additions to modern DG [17]. Currently, PV is the most popular DG technology, and it accounted for a dominant proportion of the DG installed capacity in several countries in 2020 [18].

In addition to the environmental concerns that drive the utilization of DG technologies, the low cost of energy delivery, recovery of residual fuels, optimal production cost solutions to decentralized consumers and flexible ramp-up and shut-down features are also reasons for the rapid growth of DG capacities in the world. Furthermore, among all DG technologies, PV has the highest growing potential because of its low investment costs and flexible deployment policies, particularly in regions with higher system balancing costs [19]. Therefore, it has been forecasted that PV will remain the dominant technology across the globe, the capacity of which will reach 530 GW by 2024, increasing by over 49% compared to that observed in 2021 [20]. In China and Europe, the numbers will increase to 205 GW and 130 GW by 2024, respectively.

Micro CHPs are a promising technology for efficient energy production, leading to an effective reduction in energy costs and emissions, which is particularly the case when installed in buildings with high electricity prices [21]. In the UK, based on the Net Zero Strategy launched by the government [22], proposals have been announced [23] to seek opportunities to extend cogenerations in some regions for greater emission reduction [24]. It has been forecasted that the installation capacity of Micro CHPs will rank second among all DG technologies in 2035 [25], contributing to the decarbonization agenda. The installation of CHPs systems in the UK is mostly centred in major cities such as London, Cardiff, Bristol, Manchester and Glasgow. Specifically, in the Marylebone neighbourhood alone, 1438 GWh heat load can be satisfied by the CHP [26].

In China, with the 2060 carbon neutrality target launched in 2021 [27], Micro CHPs were deployed to satisfy the heat demand in northern areas while limiting emissions [28]. Dozens of pilot areas with Micro CHPs are underway to promote energy utilization efficiency [29]. CHPs are mostly located in major cities and coastal areas in the southern regions of China, including Beijing, Shanghai, Shenzhen and Guangzhou. Specifically, the Shanghai Centre Tower is equipped with a CHP system that can generate 12.36 GWh of electricity per year [30]. More subsidies are under research to improve backup storage for stable operation and deployment of Micro CHPs [31, 32].

1.3 | Brief history of distributed generation trading mechanisms

The initial purpose of installing DG equipment was to reduce energy costs and realize a stable energy supply with higher environmental efficiencies [33]. With the expansion in scale and increase in installation capacity, more advantages are being revealed at the grid level, including a reduction in energy losses compared to long-distance transmission [34], investment and construction cost savings in distribution networks [35], and the independence of DG operation under grid power shortages. The excess energy produced by the DGs can be consumed in a neighbourhood area or transmitted back to the grid to enhance the energy utilization rate. The basis of the DG trading mechanism is that qualified DG companies can compete in the energy market [36] and are allowed to sell energy to the grid based on the net-metering policy [37]. The energy transmitted from distributed consumers to the grid can be quantified by metering [38], and the energy is subsidized by the government to encourage the utilization of DGs.

However, under the net-metering policy, the energy sold by DGs is restricted because there is little benefit for the grid utility from the DG transactions [39]. Therefore, to further encourage the deployment of DG technology and improve energy efficiency, FIT has been implemented, which requires bi-directional metering to record the interaction between the DG owner and the grid [40]. Moreover, investment in DG technologies is largely accelerated in FIT through the long-term cost-recovery contracts offered to DG owners.

However, with the increasing penetration of renewable energy in recent years, grid operation faces greater uncertainties and risks. Under such circumstances, DG owners can provide ancillary services by aggregating and bidding in the transmission-level electricity market, whose capability is similar to that of a traditional power supplier [41]. In addition, DGs can participate and provide demand response services on platforms run by distribution system operators [42]. Moreover, with the development of blockchain technology, peer-to-peer transactions between DG owners and consumers have been designed and realized in several regions to improve transaction transparency with privacy protections, including direct trading between individuals [43], interaction between DG owners and the microgrid [44] and transactions among aggregated energy hubs [45].

1.4 | Selection of UK and China for conducting comparative study

The UK and China are two distinctive countries in terms of DG markets but are representative of several aspects. First, the UK is a developed country where abundant energy sources are accessible, but energy utilization efficiency needs to be improved for decarbonization as a long-term challenge [46]. However, China is a developing country with a large population, where energy can be insufficient or expensive in certain regions under extreme weather conditions. Second, in terms of national territory, the UK is a medium-sized country, whereas China is vast, which incurs distinctions in the length of power transmission lines and the scale of electric demand. Specifically, the 2383 km-long Qishao (Jiuquan-Hunan) ultra-high voltage transmission line, which cost 262 billion RMB, was put into operation in 2017 to relieve the power strain in central China by transmitting renewable generation from the western provinces. On the other hand, a 765 km-long cable is under construction to connect the UK and Denmark for geothermal energy transmission. As for electricity demand, China consumed 7510 TWh in 2020 [47], which is 26 times the power consumption of the UK [48]. Therefore, DG technologies are indispensable in the UK and China, but their reasons are different. For the UK, environmental and energy utilization efficiencies are priorities, whereas for China, reductions in transmission costs and stable energy provisions are priorities.

The background for implementing DG trading mechanisms is essential for conducting a comparative study of the UK and China. First, both countries have conducted power market reforms, but the UK is more experienced since it started the reforms earlier and went through four stages [49], from the pool mode to the decarbonization-based contract for difference (CfD) pricing mode [50]. The developed electricity market constructed in the UK is beneficial for implementing the DG trading mechanism because the developed capacity market helps with the reliable backup of stochastic renewable energy output and the pricing mechanism ensures reasonable cost recovery [51]. On the other hand, China is formulating supplementary regulations to trade and price electricity, based on the relationship between supply and demand. Moreover, the capacity market is still under construction in China, which is temporarily replaced by a contract transfer trading mechanism [52] to ensure the cost recovery of coal-fired generators induced by backup capacities. Under such circumstances, the current pricing mechanism leads to unreasonable revenue allocation. Therefore, the market policies implemented in the UK mechanism can be analysed by China to improve DG trading. In addition, both countries are subject to decarbonization targets, with Net Zero to be achieved in the UK by 2050 and carbon peak and carbon neutrality to be achieved by 2030 and 2060, respectively, in China, which accelerates the implementation of DG technologies. Therefore, a comparative study of DG trading mechanisms in the UK and China is worth studying as two representative cases and can be used as a reference for similar regions in the implementation of DG trading mechanisms in the journey of decarbonization.

1.5 | The contributions and structure of the study

In summary, this study yields three main contributions:

- Based on a comprehensive analysis of market structures and DG policies in the UK and China, a comparative review of practical DG trading mechanisms was conducted for the first time with the economic implications of the market players investigated.
- Based on the SWOT-PEST model, DG trading mechanisms were analysed from political, economic, social and technological perspectives to understand their strengths, weaknesses, opportunities and threats. Strategic analysis was provided, along with conclusions on the similarities and differences in DG trading in the two nations.
- Based on quantified comparisons between DG trading arrangements, future improvements for DG trading mechanisms in the UK and China are suggested.

The remainder of this study is organized as follows. Section 2 introduces the DG trading mechanism in the UK. Section 3 discusses the DG trading mechanism in China in detail. Section 4 presents a comparative study. Future research directions and suggestions are presented in Section 5. Finally, this study is concluded in Section 6. The logical connection and organization are shown in detail in Figure 1. The logical arrangement can be unfolded into three main parts: the introduction to the research background (Section 1), the discussions on research contents (Sections 2 to 4), and the conclusions of the research results (Sections 5 and 6). The motivation and research gap are introduced in the research background, along with the development history and reasons for selecting the UK and China. In the research content, the features of DG trading mechanisms in the UK and China are introduced separately, including market structures, policies and pilot projects. Based on this, a comparative analysis is demonstrated to provide a strategic perspective, including discussions on practical issues and SWOT-PEST analysis. Future directions are suggested according to the comparative analysis, including policy improvement advice for the UK and market mechanism advancement for China. Finally, the conclusions are drawn.

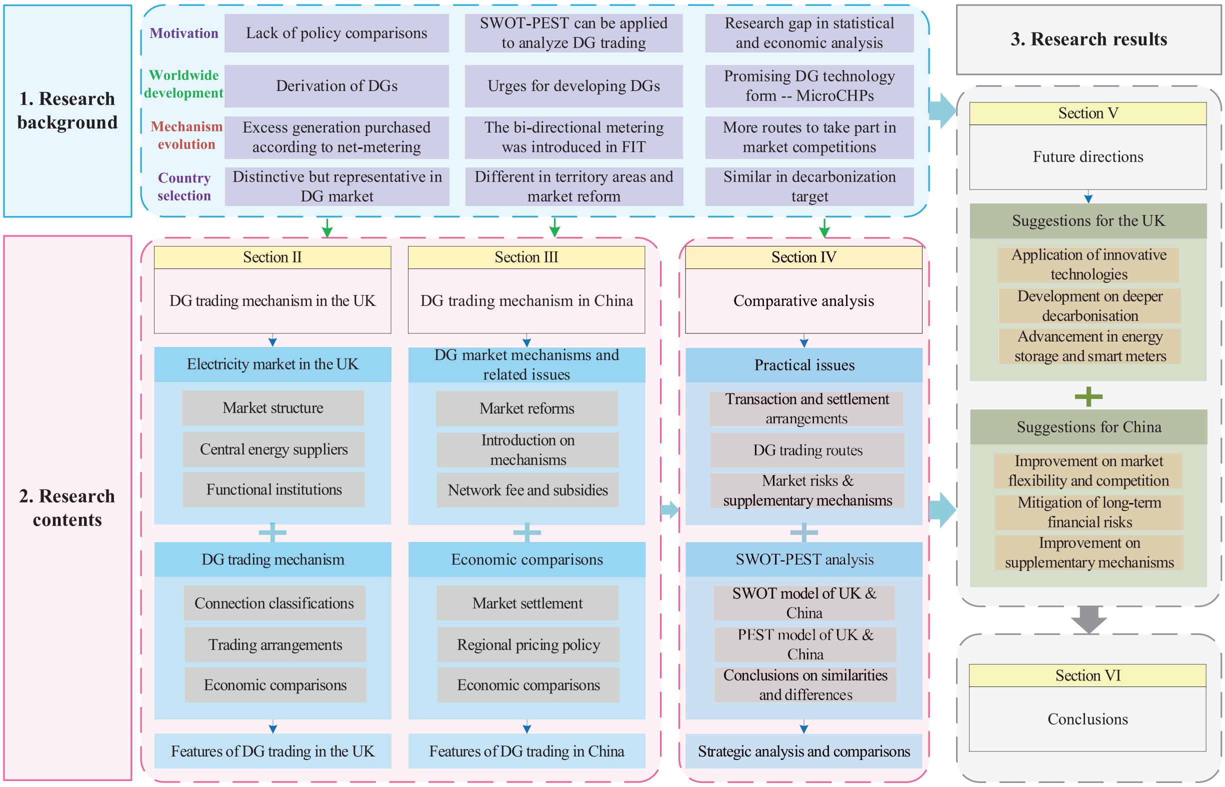

FIGURE 1 Logical connection and organization of this study

2 | DG TRADING MECHANISM IN THE UK

In this section, the power market structure in the UK will be introduced first, including the wholesale and retail markets, and the regulation bodies and main market participants will be described regarding their features and responsibilities. Then, the DG trading mechanism will be introduced based on the network connection classification, trading arrangement types and differences in suppliers. Finally, economic comparisons of different trading arrangements will be discussed.

2.1 | Electricity market in the UK

The electricity market in the UK consists of wholesale and retail markets. Suppliers link the wholesale and retail markets, playing a central role in the electricity market of the UK. Although the market is designed in a fully-competitive manner, there are six big energy companies ("big six") dominating most businesses. The features of the UK electricity market will be discussed in detail as follows.

2.1.1 | Market structure

The electricity market that DG can participate in can be unfolded into two parts, that is, the wholesale market and the retail market [53], as shown in Figure 2.

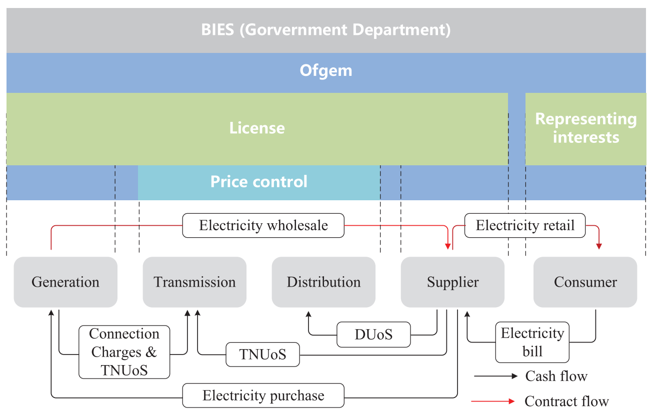

FIGURE 2 The electricity market structure of the UK

The broadly matching process is conducted between suppliers and generators in the wholesale market, where the long-term bilateral contracts are signed, accounting for 77% of the wholesale market transacted volume. The rest is traded through power exchange (PE), which is cleared in day-ahead and intra-day time scales. The PE is conducted through centralized platforms, such as N2EX [54] and EPEX [55] in the UK. Specifically, three forms of electricity transactions take place in the PE platforms, including day-ahead auctions, spot market transactions and prompt market transactions. Although market players bid in different time scales in the three market forms, the transactions are all restricted by the 'Gate Closure,' which is one hour earlier than the settlement period, as shown in Figure 3.

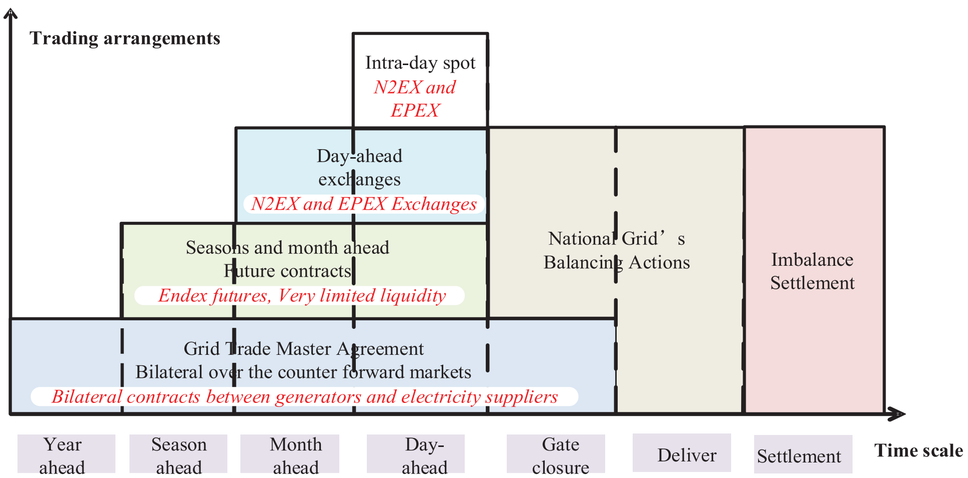

FIGURE 3 Operation of the UK electricity market

FIGURE 4 The market share development of electricity suppliers in the UK (adapted from [56])

2.1.2 | Central energy suppliers

There are six main energy suppliers out of approximately 60 competitors, providing gas and electricity for over 50 million households and commercial utilities across the UK [56], which were formed as private companies since the privatisation in the energy sector after the pass of the 1989 Electricity Act. The electricity market share of main suppliers from 2005 to 2021 is shown in Figure 4.

With the advantage of cheaper market tariffs provided, the market share of small suppliers is growing in recent years, attracting more investment and competition in the wholesale market. As can be seen from Figure 5, net promoters[1] for medium and small suppliers[2] exceed the large ones in the survey conducted by the Office of Gas and Electricity Markets (Ofgem). Further, by comparing Figures 4 and 5, it is clear to see that with the disappearing of SSE, the market share of medium and small suppliers increases to a great extent. This is because of better services, cheaper tariffs and stable energy supply offered by competitive suppliers under market environment.

2.1.3 | Functional institutions

Functional institutions are key components of the UK electricity market for making policies, establishing regulations, and formulating operational requirements, including the Department for Business, Energy & Industrial Strategy (BEIS), Ofgem, Transmission Network Operators (TNOs), System Operators (SOs), Settlement Agent, Power Exchange Operator and Distribution Network Operators (DNOs).

- The BEIS is the government department, and the UK energy policy is set based on government priorities made by BEIS.
- The Ofgem is the independent energy regulator that regulates natural monopolies in transmission and distribution networks as well as promoting market competitions [58].
- TNOs and SOs are responsible for the stable and efficient regional transmission of electricity [59] and balancing energy supply and demand in real-time. TNOs and SOs operate separately.

[1] Net Promoter Score is calculated as the proportion of domestic energy consumers who are promoters of their energy supplier minus those who are detractors. From 0 to 10, promoters score 9–10, passives 7–8 and detractors 0–6.

[2] Large suppliers are the big six companies in the UK. The rest are medium and small suppliers.

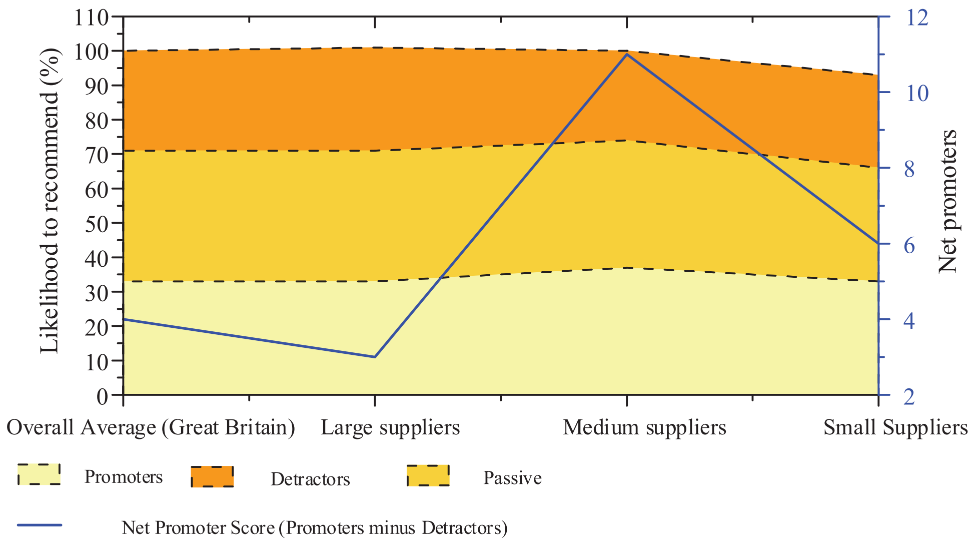

FIGURE 5 Net promoter score for energy suppliers in 2020 in the UK (adapted from [57])

- Elexon is the settlement agent that is responsible for a reasonable allocation of balancing costs between participants as well as the administration of the Balancing and Settlement Code (BSC) [60].
- The Epexspot is the power exchange operator that provides commercial platforms for organised exchanges and mechanisms for physical transactions.
- A DNO is a licenced operator and owner of the public electricity distribution networks, which is also responsible for the maintenance of the networks and the distribution of electricity within the legacy geographic area.

2.2 | DG trading mechanism

DG owners in the UK are offered with ten types of market routes for exporting power based on the network connection status and their market identities.

First, the classifications by electrical connections can be unfolded into three ways, including the onsite supply, the private network and the public network. The main difference between different classifications is the ownership of the networks and the metering arrangements. The corresponding trading arrangements will be further analysed, where the dominant types are elaborated in detail, including the netting off, power purchase agreements and sleeving arrangements.

Second, the market identity of DG depends on whether it chooses to become an authorised supplier because only a supplier can administratively negotiate with large numbers of customers and hedge financial risks by optimizing energy output against the demand portfolio. However, the identity also brings licence obligations and authorization costs.

In the end, the economic comparison between different market routes is conducted to statistically analyse the revenue of DG under specific trading arrangements.

Detailed description and analysis are presented below.

2.2.1 | Connection classifications

The ways in which how the local generation and demand are electrically connected to each other include:

- Onsite supply, where the generation and demand are at the same site and behind the same electricity meter,
- Private network, where the generation and demand are connected by private wires and behind the same electricity meter, and
- Public network, where the generation and demand are connected by public electricity networks and behind different electricity meters,

which are illustrated in Figure 6.

2.2.2 | Trading arrangements

The trading arrangements between local generation and demand vary with the electrical connection modes. For onsite supply, local generation and demand are netted off first, and then the generation surplus or demand deficit will be exported to or supplied by the electricity supplier. The trading arrangement for the private network mode is the same as that of onsite supply. For the public network mode, local generation and demand separately trade with electricity suppliers through standard power purchase agreements (PPAs), or trade with each other through 'sleeving' agreements[3] / peer to peer supply or synthetic PPAs[4] with electricity suppliers as intermediaries. Both sleeving arrangement and peer to peer supply are imple-

[3] With a sleeving agreement, local generation and demand trade with each other with an electricity supplier as an intermediary who will charge a 'tolling fee' to cover network charges, imbalance payments, top-up and spill and a service fee.

[4] Synthetic PPAs are purely financial agreements (typically as contracts for difference) between local generation and demand to reduce the long-term financial risk caused by the fluctuation and uncertainty of electricity prices.

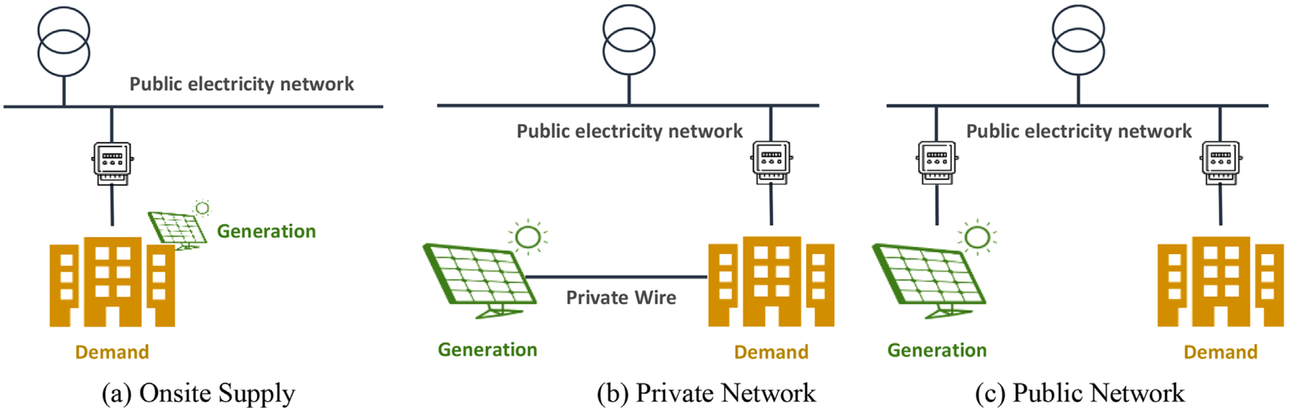

FIGURE 6 Connection modes of local generation and demand

TABLE 1 Trading arrangements between local generation and demand in the UK

Connection mode	Onsite supply	Private network	Public network
Simultaneous generation and demand	- Netted off	- Netted off	- Trading with electricity suppliers separately through standard PPAs - Trading with each other through sleeving arrangements or synthetic PPAs (with an electricity supplier as an intermediary)
Non-simultaneous generation and demand	Exported to/supplied by electricity suppliers		

mented in the same way, but the DGs and users from the latter one are matched through a peer to peer platform. The three arrangements (sleeving, peer to peer and synthetic PPA) are settled at a long-term fixed price for DGs, which has advantages in two aspects: the arrangement provides a long term certainty on revenue, and the contract easily suits DGs because the terms can be agreed directly with users.

The trading arrangements are summarised in Table 1. Although the sleeving agreement encourages transactions in local areas, but the economic benefit is lower than trading through private network or onsite supply. The difference can be well explained through the following example. If a household is built with PV sets on the roof, the most economical way for PV suppliers is to sign contracts with the household. On the other hand, the excess energy can be sold to local demand connected by public wires, but the transaction is conducted with an electricity supplier as an intermediary. In other words, the PV suppliers will be charged with a tolling fee through the sleeving arrangement, and the fee covers multiple costs, including network charges, imbalance payments, top-up and spill and a service fee. Therefore, with the same energy volume transacted, the PV suppliers can make 32–46% savings through onsite supply compared to 0.4–1.1% in sleeving arrangement. Transactions in private networks can achieve the same level of saving as that of onsite supply, because the DG owners can save costs that generated from interacting with an electricity supplier and utilizing public wires.

Practical implementations of DG trading mechanisms have been conducted for years in the UK, which have attracted huge investments and facilitated the optimal distribution of energy sources. For example, the Pimlico District Heating Undertaking [61], which is a combined heat and power project with 3.2 MW in electrical capacity, exports its excess energy through a PPA. Since a large number of offtakers are willing to sign a contract, the annual PPA with lower costs becomes the optimal choice for the suppliers. Besides, the Gateshead Energy Centre [62], which provides heat and power to neighbourhood areas with 4 MW in electrical capacity, chose a private wire route to market instead of the sleeving arrangement. This is because the sleeving arrangement can only bring higher revenues under the wholesale price, but in retail market the private wire approach captures higher retail prices.

2.2.3 | Economic comparisons

The ownership of local generation and demand affects how the costs/revenues are allocated between the generation and demand. For onsite supply and private network cases, bilateral agreements can be made to decide the prices of the electricity sold from the generators to the demand. For the public network cases, synthetic PPAs make no difference if the generation and demand belong to the same entity.

The economic benefits of the aggregation of local generation and demand also vary with the connection modes. For onsite supply, the simultaneous generation and demand are netted off with each other and thus are not exposed to most network charges and levies, resulting in the highest economic benefits. The private network mode has the same level of benefits, but the high upfront investment and operational complexity have to be

TABLE 2 Economic benefits of existing trading arrangements in the UK [63]

Mode index	Connection mode	Independent supplier	Trading arrangement	Economic benefits(As saving compared to Standard PPA)
A	Public network	Required	Standard PPA	0%
B			Synthetic PPA	0%*
C			Sleeving arrangement/peer to peer	0.4–1.1%
D		No	Full supply licence/licence lite	5–10%
E	Private network	Required	Netting off plus topping up by the electricity supplier	8–30%
F	Onsite supply			32–46%

*Compared to a standard PPA, a synthetic PPA will not bring direct economic benefits, but reduce the long-term financial risk if local generation and demand belong to different owners.

taken into consideration. All of the trading arrangements in the public network mode involve full network charges and levies, thus having the least economic benefits. If there is flexibility at the generation or demand side (e.g. the installation of batteries and the capability of conducting demand side response), the economic benefits in all the modes can be further improved. By better matching local generation and demand utilising flexibility, more network charges and levies can be avoided in the onsite supply and private network modes, while the costs to deal with the imbalance between local generation and demand can be reduced in the public network mode.

Quantitative estimation of economic benefits with various existing trading arrangements is summarised in Table 2, based on the calculation presented in [63]. The economic benefits are quantified in the form of the saving in percentage compared with the reference case, where local generation and demand trade separately with suppliers through standard PPAs.

Based on the economic benefits shown in Table 2, more saving can be achieved for the trading arrangements in the public network mode if a new supplier is set up for the local generation and demand. Depending on which type of supplier is chosen (White Label, License Lite or Full License), a further 2–10% saving can be achieved compared to the reference Standard PPA case. Nevertheless, a large customer base (equivalent to annual volume of 6–107 GWh) is required for making it profitable to become a supplier.

3 | DG TRADING MECHANISM IN CHINA

The DG trading mechanism in China is quite different from that in the UK due to gaps in the national policy and development process. In this section, the electricity market and the DG trading mechanism in China will be analysed. First, the market structure, the time scale of trading arrangements and the market members are introduced. Second, the traditional matched trading mode for DG owners will be discussed, where DG owners were not allowed to enter the market unless matched with a particular transaction partner. Then, three existing DG trading modes will be discussed, including: (i) the direct trading mode; (ii) the agent mode and (iii) the grid acquisition mode. Moreover, issues regarding the network fee charged by the grid and subsidies on DG will be described. Further, economic comparisons of different trading arrangements on DGs will be analysed in combination with the market settlement process and regional pricing policy in China. The revenue of DG will be demonstrated through statistical analysis based on practical data from Beijing.

3.1 | Electricity market in China

China conducted a series of power market reform from March 2015 [64], after which the market mechanism was partially liberalized and multiple buyers/sellers are allowed to participate in market competitions. At present, the long-term transaction is the dominant power trading mechanism in China, accounting for 80.5% of the total national transacted volume in 2021 [65]. Besides, 14 pilot regions are running the spot market to better integrate the penetration of renewable energy generation.

3.1.1 | Market structure

The electricity market with DGs' participation consists of wholesale and retail markets. The wholesale market is a platform for transactions between generation and retailers, where the energy and ancillary service markets are incorporated. On the other hand, the retail market is designed for transactions between retailers and small users, where the total trading volume is under the government's guidance. The structure of the wholesale and retail markets are demonstrated in Figure 7.

The transactions can be further divided according to the time scale and trading arrangements, as shown in Figure 8. Specifically, in the mid-to-long term market, participants can trade through listed/centralized/bilateral transactions. As a transition to the liberalized market, traditional generators are identified with generation rights, which can be sold to renewable generation companies through the base contract trading in the mid-to-long term market. In the spot market, participants can trade in day-ahead/real-time market and the ancillary service market. Specifically, the frequency regulation is the main trading product in ancillary service market, whereas peak shaving

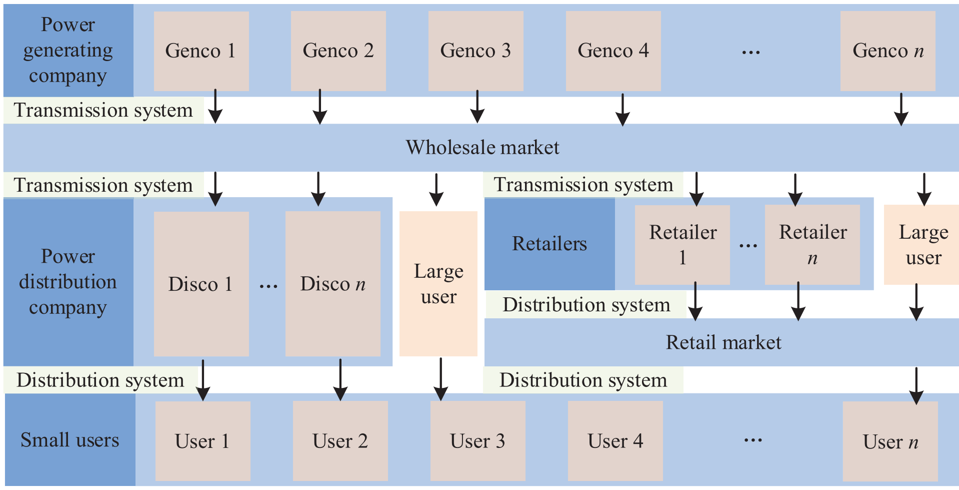

FIGURE 7 The electricity wholesale and retail markets in China

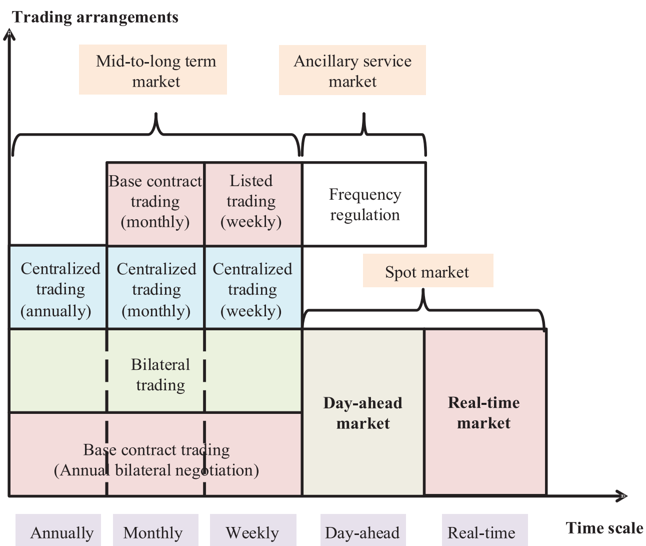

FIGURE 8 Time scales of market transactions in the electricity market of China

is settled through equal sharing mechanism[5] in most provincial electricity markets.

3.1.2 | Market members

The market members include three categories, that is, the trading entities, power grid companies and operational institutions. First, the trading entities refer to electricity users, retailers and generation companies. Their market behaviours are under the management of regulation institutions, and are dispatched by relative agencies. For example, the spot market in Guangzhou is under the operational guidance of National Energy Administration, managed by the Power Dispatching Control Center Corporation. The mid-to-long term market is managed by Guangdong Electric Power Trading Center Co. Second, the grid companies are in charge of the transmission and distribution networks, which are also responsible for the stable energy supply of designated areas and the metering data management. Third, the operational institutions generally include the provincial trading centres and the dispatch centres.

3.2 | DG market mechanisms and related issues

In this part, three existing DG trading mechanisms will be introduced, along with the policy implementation history and detailed trading arrangements. Then, issues on network fees and cross-subsidies regarding the practical implementation of DG trading policies will be analysed, where the reason for adopting network fees and the corresponding calculation method will be discussed.

After that, economic comparisons and practical analysis are conducted based on the market settlement and regional pricing policies, where Beijing is taken as an example to demonstrate the detailed comparisons of economic benefits with different trading arrangements.

3.2.1 | DG trading mechanisms in China

The initial DG trading mechanism in China can date back to 2002, when the Project of Delivering Electricity to Every Village was officially launched to enhance the power supply rate in western China by utilizing local enriched natural resources [66]. Specifically, the project encouraged the self-consumption mode for DG, and the surplus energy could be transmitted to the grid at a negotiated price. However, due to the limit in the trading mechanism and in the transmission lines connected to DG, a DG unit could only trade with a specified

[5] The cost is equally distributed among all renewable energy generators according to the generation volume during the deep peak shaving period.

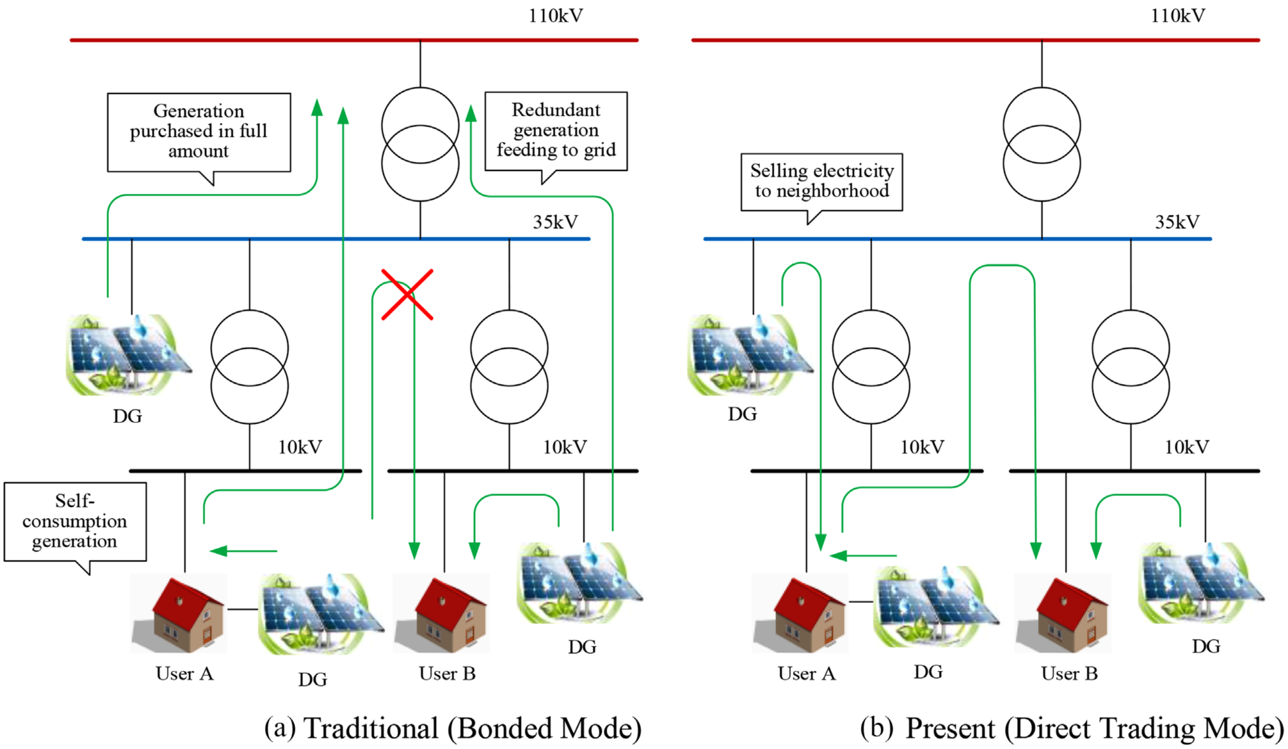

FIGURE 9 Trading mechanisms of DG under the traditional and present policies in China (adapted from [70])

customer. Moreover, if the bonded customer went bust, the installation of DG became useless until the customer was taken over by a new one. This bonded mode is demonstrated in Figure 9a.

To further enhance the utilisation of renewable energy under a market environment, the Interim Measures for the Administration of Distributed Generation [67] was launched in 2013 by National Energy Administration (NEA) to standardise the market access of DG. However, the debate lasted over the restricted DG capacity since the qualified small DG can add up to an illegal capacity volume over certain periods. Therefore, a supplementary revision has been made and the Circular on the Pilot Market Trading of Distributed Power Generation was launched in 2017 [68], in which the market access regarding generation capacity is distinguished by the voltage level of the accessed grid. The allowable transaction region for DG is restricted within the same voltage level under the direct trading mode, which is demonstrated in Figure 9b. Moreover, DG can also earn revenue in two other ways according to [68]. The first is the agent mode, where the generated power can be sold to potential customers under the proxy of the grid company. The second is the grid acquisition mode, where the generated power is purchased by the grid at the benchmark price. The three DG trading arrangements can be further divided into seven sub-modes according to the connection status and the user classifications, which is demonstrated in Table 3.

Practical implementations of DG trading mechanisms in China have been conducted since 2019, with 26 pilot projects conducted all over the country. The implementations have attracted great investment in exporting excess energy through market routes, being beneficial for the development of renewable energy and the progress of decarbonisation. For example, the Zhenglu industrial park [69], which is located in Jiangsu Province and expected to generate 6.8 GWh electricity annually, can export up to 50 MWh a year through the direct trading mode (modes 6–7 in Table 3). Since the project is invested by the local government for developing indoor agriculture while promoting the utilisation of solar energy, the direct trading mode is chosen for the project operators to recover the upfront costs. Besides, Suzhou industrial park, which is also one of the first pilot DG trading areas, built PV sets on spare roofs for 15 houses and added up to 20 MW in capacity. The excess energy can be exported through the agent trading mode (modes 2–3 in Table 3), which brings more revenue compared with the grid acquisition mode (Mode1 in Table 3) since the latter one is settled at the lower benchmark price.

3.2.2 | Issues on network fee and cross-subsidies

For the three DG trading arrangements mentioned above, issues have been raised regarding the network fee and subsidies. First, the network fee is a specialized distribution fee charged for the power network utilisation engaged in DG transactions. Specifically, the network fee includes the recovery of power distribution asset investment and operation and maintenance costs within the transaction area, which is less than

TABLE 3 DG trading arrangements and detailed modes in China

Mode index	DG connection status	Detailed modes	Trading arrangements
1	Connected to users	Self-consumption + surplus energy sold to the grid	Grid acquisition
2		Self-consumption + Trading with large industrial users (LIU)	Agent trading
3		Self-consumption + Trading with general industrial and commercial users (GICU)	
4	Connected to the grid	Generation sold to the grid (settled at benchmark fee)	Grid acquisition
5		Generation sold to the grid (settled with subsidy)	
6		Direct trading with LIUs	Direct trading
7		Direct trading with GICUs	

the transmission and distribution fee[6] as the latter one charges for cost recovery of the whole system. However, the practical application of the network fee causes trouble for the grid company which tries to meet the expected revenue. This is because most of the existing power grid facilities were initially planned and constructed according to the conventional business model where the electricity is mainly imported from the transmission grid and distributed down across multiple voltage levels to end users. However, the market-oriented transaction of DGs will reconstruct the power flow of the entire distribution network. If the network fee does not include the costs associated with higher-voltage grid facilities that have been constructed but sees a reduction in the utilisation, it will result in grid companies' potential failure in cost recovery, further inducing economic issues in constructing the DG trading market.

Second, the existence of cross-subsidization in the distribution system can cause an imbalance of cost and revenue for the grid company. Specifically, the main form of cross subsidy that relates to DG trading is the voltage level subsidy. The low voltage level is subsidized by the high voltage level. Theoretically, power transmissions for low-voltage level users require more grid levels and power assets with higher losses to receive electricity, and the electricity load rate[7] is relatively lower. Therefore, the transmission and distribution fee should be significantly higher than that of high-voltage level users. However, the electricity price of high-voltage level users is relatively higher compared to its actual cost. This is because the cost of low-voltage level users has been transferred to high-voltage level ones. Therefore, the cross-subsidy for low-voltage level users is formed.

Since the network fee is not standardised in China, the regulations in [68] have defined a temporary calculation method for DG. Specifically, the network fee equals the transmission and distribution fee of the highest voltage level involved in the DG market trading minus the transmission and distribution fee corresponding to the accessed voltage level. This temporary scheme for network fees is in accordance with the marginal price principle, which is reasonable for market members. However, in combination with the cross-subsidy, when transmission and distribution fees of two levels are directly subtracted, the cross-subsidy will be completely offset and DGs pay less compared to the scheme without cross subsidies. This is because the cross-subsidy borne by the high-voltage level is higher. As a result, the DG market turns into a controversial trading scheme because of the unfair calculation method of the network fee regarding the existence of the cross-subsidy.

To further illustrate the effect of cross subsidy, Cases 1–4 is designed in Table 4 to compare the calculation of network fee C^N under different situations. In Cases 1–2, the cross subsidy is considered, and the DG is connected to 110 kV and 35 kV level in Case 1 and Case 2, respectively. In Case 3–4, the cross subsidy is not considered when calculating C^N. According to the definition of cross subsidy, the cost of low-voltage level users is transferred to high-voltage level ones, $C^N_{110kV-Sub} > C^N_{110kV-Sub}$. In combination with the calculation principle of network fee in DG trading [68], DGs in Case 1 pays less network fee than those in Case 2. On the other hand, without cross subsidy, more C^N is charged if the DG is connected to 110 kV level while it is the opposite case if the DG is connected to 35 kV level. This is because the transmission cost is fully demonstrated without cross subsidy. Therefore, DGs in Case 2 are supposed to earn more in the trading mechanism without cross subsidy; more C^N is supposed to be charged in Case 1 to ensure the cost recovery of the grid company. As a result, the cross subsidy can cause a decrease in revenue of DGs and the grid company under certain circumstances, which further affects market competition and the investment on DGs.

3.3 | Economic comparisons

The three DG trading modes, which are the direct trading, the agent mode and the grid acquisition mode, are settled in different ways. Besides, the network fee and subsidies on DG are set at non-uniform values in different provinces over China. Therefore, to conduct the economic comparisons of the DG trading modes, the settlement of each mode and the regional pricing policy need to be introduced in the first place, which is elaborated as follows.

[6] Transmission and distribution fee = income cap for transmission and distribution ÷ electricity selling volume. Income cap includes cost cap, revenue cap and tax.
[7] Electricity load rate = average grid load ÷ peak load.

TABLE 4 Cross subsidy illustration

Case index	Cross subsidy	Network fee C^N per voltage level	110 kV	35 kV	C^N in DG trading
Case 1	Considered	$C^N_{110kV-Sub}$(110 kV), $C^N_{35kV-Sub}$(35 kV)	DG	User	$C^N_{35kV-Sub}$-$C^N_{110kV-Sub} < 0$
Case 2			User	DG	$C^N_{110kV-Sub}$-$C^N_{35kV-Sub} > 0$
Case 3	Not considered	$C^N_{110kV-NoSub}$(110 kV), $C^N_{35kV-NoSub}$(35 kV)	DG	User	$C^N_{35kV-NoSub}$-$C^N_{110kV-NoSub} \geq 0$
Case 4			User	DG	$C^N_{110kV-NoSub}$-$C^N_{35kV-NoSub} \leq 0$

3.3.1 | Market settlement

The market settlement in the three modes is demonstrated as follows:

- The direct trading mode

$$P^{SD} = P^D - C^N \tag{1}$$

- The agent mode

$$P^{SA} = P^R - C^N \tag{2}$$

$$P^R = \frac{\sum_{i \in \Omega_1} P_i^U T_i^U}{\sum_{i \in \Omega_1} T_i^U} \tag{3}$$

- The grid acquisition mode

$$P^{SG} = P^B \quad \text{with reduced subsidy} \tag{4}$$

where the P^{SD}, P^{SA} and P^{SG} refers to the settlement price of the electricity sold by DG in the direct trading, agent trading and grid acquisition modes, respectively. P^D, P^R and P^B refer to the direct trading price, general retailing price and local benchmark price (FIT), respectively. P^R is calculated by the average value of retailing price under the agent mode. P_i^U and T_i^U refers to trading price and traded volume of electricity of user i under the agent mode. C^N refers to network fee. In order to promote the integration of renewable generations, the transacted volume generated by renewable sources will be offered an extra subsidy by the government in the mentioned three DG trading modes. However, it will decrease by 10% if the DG chooses grid acquisition mode instead of direct trading or the agent mode, as shown in (4). Moreover, the network fee will be neglected in the grid acquisition mode because the trading partner for DGs is no longer a user.

3.3.2 | Regional pricing policy

The policies on network fees and subsidies for DG in each province will be introduced. First, the network fee is calculated in relation to the voltage level of where the DG accesses and the classification of the users, as shown in Figure 10.

Voltage level classification
In China, DG tradings are mostly implemented in three voltage levels, that is, 10 kV, 35 kV and 110 kV. The network fee is charged according to the voltage level ranges, which is well explained in Section 3.3-2.

User classification
Power users participating in the DG market are classified into GICUs and LIUs according to the scale of power consumption capacity. Generally, under the same voltage level, GICUs will be charged a higher network fee compared with LIUs.

Second, the subsidies on DGs, especially renewable energy sources, are set at different values according to the power exporting modes and regional policies. For example, at a national level, PV generation is subsidized at 0.37 RMB/kWh under the self-consumption mode [71], while it will decrease by 10% when the PVs choose to participate in the DG trading market [68]. Besides, to promote the generation of renewable energy, each province adds its own subsidy according to the generation volume. For example, PV are subsidized with 0.3, 0.25 and 0.15 RMB/kWh for 5–10 years in Beijing, Anhui and Shanxi, respectively. Moreover, with the rapid development in DG technology, subsidies on distributed renewable generations are reducing at both central and local governments' levels. Therefore, DG is more encouraged to participate in the trading to earn revenue through market competitions instead of relying on subsidies.

3.3.3 | Economic comparisons

In combination with the market settlement rules and regional pricing policies, economic comparisons of existing DG trading mechanisms are conducted. Considering the differences in regional policies, Beijing is taken as an example to conduct the economic comparisons, which is both the political capital and a major northern city of China urging to promote environmentally friendly DG technologies to relieve the haze issues and improve local energy utilisation. Moreover, as the most installed DG technology, PV is taken as an example to illustrate the pricing policy and economic revenue calculation process. The

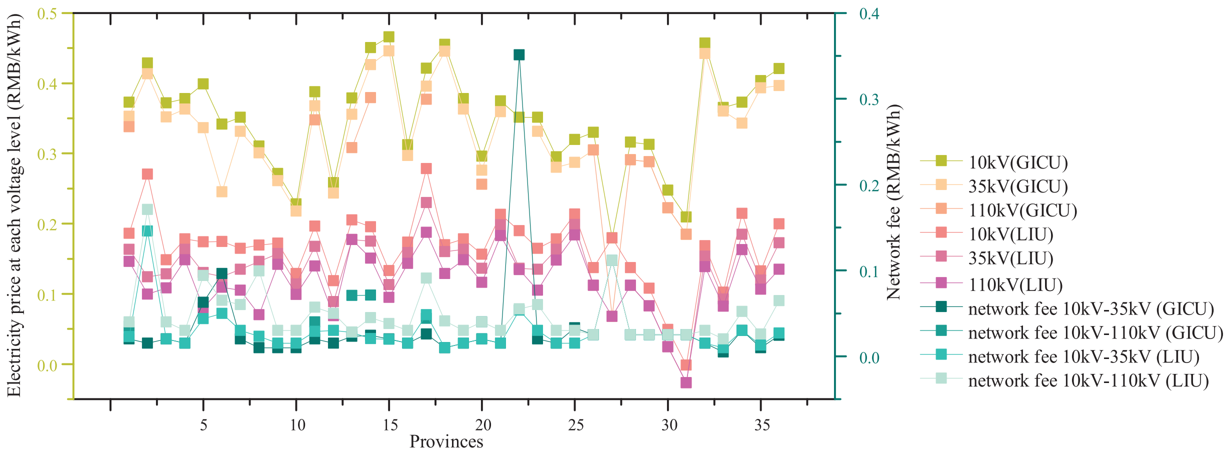

FIGURE 10 Network fees in different provinces of China (sorted by the alphabetical order of provinces)

TABLE 5 Economic comparisons of different trading mode in Beijing

Mode index	Trading modes	Subsidy (RMB/kWh)	FIT (RMB/kWh)	Average traded price (RMB/kWh)	Economic benefits (Compared to Mode 1)
1	Self-consumption + Grid acquisition	0.37	0.3598	1.02	0%
2	Agent trading–LIUs	0.41		1.14	8.03–11.76%
3	Agent trading–GICUs			1.35	26.87–32.35%
4	Grid acquisition-benchmark fee	–	0.75	0.75	0%
5	Grid acquisition-subsidy	0.37	0.3598	0.78	
6	Direct trading-LIUs	0.41		1.06	1.27–3.92%
7	Direct trading-GICUs			1.2	9.44–17.98%

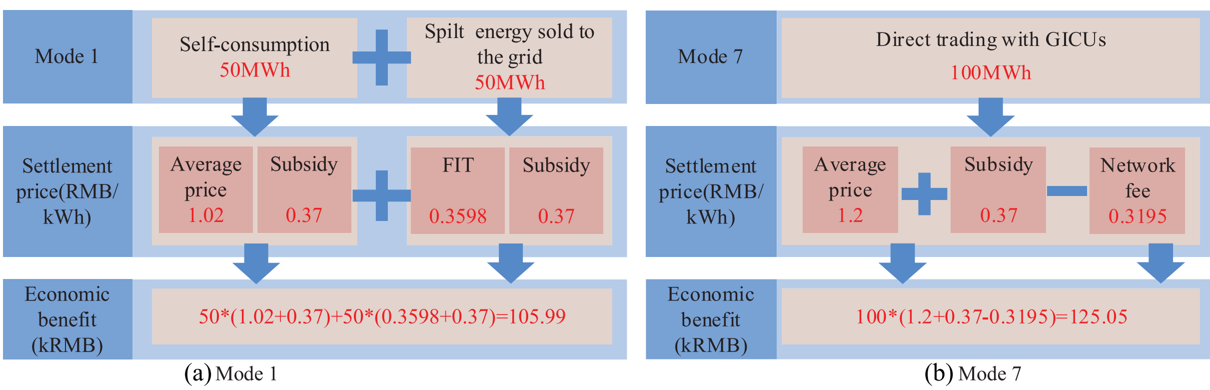

FIGURE 11 The process of calculating economic benefits for DG in Modes 1 and 7 in China

economic benefits of DG in existing trading arrangements are demonstrated in Table 5, where the trading modes are in accordance with those in Table 3. Specifically, the self-consumption volume in Mode 1 is assumed to be 50% of the generated energy. In Mode 2/3, the ratio is assumed to be within 30–70%.

Here, the Mode 1 and Mode 7 are taken as an example to show the calculation process, as shown in Figure 11. It is assumed that in both modes the tradable energy is 100 MWh. The user and DG are connected to the 110 kV level and the DG is assumed to be PV. First, in the Mode 1, half capacity is self-consumed, and the rest is treated as surplus energy sold to the grid. According to (4), the settlement price of the grid acquisition mode should be the sum of benchmark FIT P^B and reduced subsidy. By contrast, the economic benefits of the self-consumed volume is estimated by adding the average saved costs and reduced subsidy, where the average saved cost is calculated as average electricity price times consumed energy. Therefore, the economic benefits can be deduced as 105.99 kRMB.

In Mode 7, the DG is assumed to trade 100 MWh generation directly with LIUs. According to (1), the settlement price is calculated as direct trading price P^{SD} minus network fee C^N. Since the DG will be subsidized if it is a renewable generation technology, the trading price will include average trading price and the subsidy. Because the user is GICU and is connected to the 110 kV level, the network fee and average price will be 0.3195 and 1.2 RMB/kWh. Therefore, the final economic benefit can be deduced as 125.05 kRMB, which saves 17.98% compared with that of the Mode 1. In conclusion, the calculation verifies the model and the economic results which are demonstrated in Table 5. Here, P^D, P^R and $P^B$are represented by average traded price for simplification.

As seen from Table 5, the economic benefits of DG can be promoted by 1.27–32.35% when participating in market transactions and can increase by 8.03–32.35% in agent trading mode compared to grid acquisition when connected to users. Therefore, DGs are encouraged to take part in direct transactions or sign contracts with agencies under present pricing policies for more economic benefits, especially when DG trades under the agent mode.

4 | COMPARATIVE ANALYSIS

The DG trading mechanisms in the UK and China share some similarities regarding trading arrangements and market structures. Meanwhile, due to the differences in electricity market reform between the two countries, there are also many differences in DG market trading mechanisms, including the market roles, network ownership (private / public networks) and options for confronting risks. In this section, the comparisons are conducted from three aspects.

First, similarities and differences are analysed and discussed in detail from four perspectives, including general electricity transaction and settlement arrangements, DG trading arrangements, market risks hedging and supplementary mechanisms. Second, the SWOT-PEST model is adopted to demonstrate and compare the characteristics of DG trading and development in both countries. Third, a quantitative comparison is conducted to further investigate the differences and similarities of DG trading arrangements in the UK and China.

4.1 | Practical issues

4.1.1 | Transaction and settlement arrangements

DG trading mechanisms in the UK and China both develop under the policy guidance of the government department, but with different arrangements for transaction and settlement. Specifically, the power exchange and settlement are conducted in two independent platforms in the UK, the Epexspot and the Elexon, while all the transaction-related activities are monitored by the provincial transaction institutions and the government in China. The UK has a developed power market with competition among multiple parties, which enhances the service quality and efficiency. Further, the separation of settlement and transaction can provide the buyers with flexible access towards competitive market products including financial contracts (e.g. future and forward contracts). On the other hand, the vertical management manner in China's power market can also operate in high efficiency, especially for the implementation of new policies.

4.1.2 | DG trading routes

DG owners in both countries are provided with various trading routes, such as direct trading with users, self-supply, and long-term contracts with a third party. However, there are also many differences. In the UK, linking DG and consumers through private wires can create more economic benefits, because the transmission and distribution fees (TNUoS and DUoS) can be saved compared to using the public electricity network. In China, all power transactions flow through public networks, but the DG is charged with reduced network fees instead of all the transmission and distribution fees, as a result of the limited geographical range of DG transactions and the initiatives of the government for incentivising local consumption of renewable energy.

Moreover, DG in China is defined as a simple identity in the market, which has three trading routes. In the UK, DG can choose to trade as a generator or to become a licensed supplier. In the latter case, the trading routes will increase from six to ten, providing DG with competitive access for being a profitable market role.

4.1.3 | Dealing with market risks

There are multiple ways in the UK for DG owners to mitigate financial risks. First, DG can settle a long-term fixed price through signing a standard PPA with a supplier. Second, the synthetic PPA between DG and consumers, usually in the form of CfD, is able to smooth volatilities in electricity prices for both parties. On the other hand, DG in China is offered a 20-year-long contract option by the power utility at a fixed price, plus a stable subsidy on renewable generation. However, this stable income can induce unnecessary energy exported to the power grid because more generation can bring more subsidies, but not all the power can be transmitted by the grid or consumed by the demand. Therefore, the subsidy policy in China needs further reform, so that the stable development of DG in the near future can be ensured while the market competitiveness can be improved in the far future.

4.1.4 | Supplementary mechanisms

The adoption of DG technologies, especially renewable energy sources, will induce uncertainties in the power supply. Regarding this, the UK and China have implemented supplementary mechanisms to deal with the stochastic generation and ensure the supply-demand balance. In the UK, balancing services are implemented by the power system operator to ensure the balance in transmission systems based on the monitoring results of power frequency and voltage [72]. The balancing cost of DG is included in the Balancing Services Use of System (BSUoS) charge to compensate for the units that provide the balancing services. In China, the supply and demand are also balanced by the bulk power grid, but the balancing cost is not explicitly reflected in the DG transaction price. This is feasible for now when the DG penetration is still small, but in the long term, this cost needs to be calculated and reasonably transferred to DG through a reasonable mechanism to provide correct incentivising signals to DG.

4.2 | SWOT-PEST analysis of DG trading mechanisms in the UK and China

The SWOT-PEST model is a typical analysis tool for enterprise planning and strategic management [73], which can be applied to the assessment and comparison analysis of DG trading mechanisms in the UK and China. Specifically, both SWOT and PEST can be unfolded into four aspects: strength, weakness, opportunity and threat (SWOT); and policy, economy, society and technology (PEST). In combination with the analysis on practical issues, the SWOT-PEST matrix of DG trading mechanisms in the UK and China is demonstrated in Table 6, based on which the similarities and differences of developing DGs in two countries are concluded.

4.3 | Quantitative comparisons

In order to further investigate the differences between DG trading mechanisms between China and the UK, a quantitative comparison is made for evaluating the economic benefits of different trading arrangements, with the results shown in Table 7. Because of the policy and arrangement differences, an approximate analogy is made for easier comparisons. First, the self-consumption mode in China is in accordance with the onsite supply arrangement in the UK, because they are both behind the same meter. Second, the grid acquisition and agent trading modes are similar to synthetic PPA/sleeving arrangement, because all these arrangements are settled at a fixed price, and are transmitted through public wires. Besides, a service fee is required by the agency/supplier/grid in these arrangements. The difference is that the service fee is charged at different levels and thus the economic benefits will vary greatly. Specifically, Mode 3 creates 26.87–32.35% in savings compared to 1.1% in Mode C. This is mainly because of the higher subsidy on renewable energy generation and increased average traded price compared to the grid acquisition mode. Third, the direct trading mode is in analogy with full supply licence/licence lite, because both are traded without an independent supplier, and transmitted through public wires.

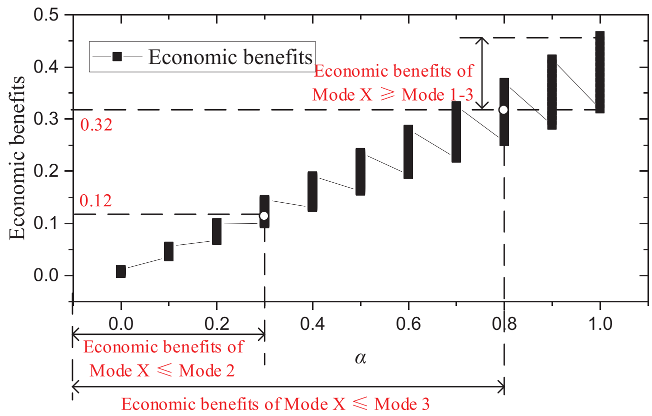

FIGURE 12 The economic benefits of Mode X with the variation in α (Alpha ranges from 0 to 1 at the step of 0.1. A black bar represents the range of economic benefits of Mode X with the variation in the economic benefits of Mode F/B/C for each alpha)

Based on the analogy, the arrangements in the UK are grouped into three modes in accordance with trading modes in China, and the economic benefits are further calculated. For example, the economic benefits of Mode X is the sum of benefits in Mode F and B/C. Therefore, by changing the ratio α of Mode F and ratio (1-α) of B/C in Mode X, the benefit range is calculated as [0%, 46%]. Detailed discussions are presented as follows. Note that the economic benefits are calculated as savings compared to Mode 1/Mode A in China/UK, and therefore the base Mode 1/Mode A is not discussed in the cross comparison between China and UK.

Mode X and Modes 2–3

In order to study the gaps between Mode X and Mode 2/3, the economic benefits of Mode X is demonstrated with the variation in α, as shown in Figure 12. Here, Mode F/B iterates within the range according to Table 2. As α grows, the economic benefits of Mode X increases. This is because onsite supply brings more savings in the combination. Therefore, if the DG chooses more proportion on Mode F, its overall benefits will increase. Specifically, when $\alpha < 0.4$, the economic benefits of Mode X is less than Mode 2; when $\alpha < 0.9$, the economic benefits of Mode X is less than Mode 3. This is because Mode B/C is transacted with a fee charged by the supplier. Therefore, the decrease in proportion of Mode B/C can increase the overall benefits in Mode X. In conclusion, Mode X brings more revenue in DG trading compared to Mode 1–3. In other words, DGs in the UK can earn more benefits than that in China if the proportion in onsite supply exceeds 80%.

Mode Y and Modes 4–5

As can be seen from Table 7, the benefit of Mode Y is relatively lower compared to Mode X/Z, and the Modes

TABLE 6 SWOT-PEST matrix of DG trading

		Policy	Economy	Society	Technology
UK	Strength	Developed under the government's support and guidance	Private wires brings more revenue than public ones	Satisfying users' energy demand with options that suit their situations	Research on DG trading platforms combined with information and big data is emerging
	Weakness	New policies proceeds slower faced with independent market players and agencies	High construction costs and maintenance fee on private wires	The public generally understand few DG technologies and is unconcerned about new ones	The practical application costs are non-negligible
	Opportunity	Decarbonisation policies and the Net Zero target will encourage DG development	Expensive energy prices will bring more investment	Enormous potential development exists in social benefits of DG with high environmental revenue	Smart local energy systems and peer-to-peer trading platforms contribute to DG trading
	Threat	Longer decarbonisation process induces higher construction costs and less secure DG generation	Economic effect that public wires require more transmission cost will cause reduced public network demand [74]	The quantification of environmental benefits brought by DGs is difficult	Operations, maintenance and dispatching problems brought by new equipment and platforms will increase
China	Strength	Apart from national supportive policies, provinces and cities are encouraging and subsidizing DGs	Local consumption of renewable energy bears less network fees	Large population generates great demand for DG	Research on improving energy conversion efficiency is emerging
	Weakness	Regulation variations on subsidies brings uncertainties to DG installations; The vertical management manner causes less competition	Highly dependent on public wires, therefore the network fees can affect and limit long-term installation and development of DG	Investment on new DG technologies (micro-CHP) is greater than the short-term payback	Research and development on gas turbines lag behind market demand
	Opportunity	Carbon neutrality target will encourage DG development	Decarbonised energy is favoured for its environmental revenues, and attracts investment on DG	In the long run, potential market for DG is enormous considering the environmental-friendly public perspectives	DG projects are launched to further improve the generator performances, such as those in Tongli Industrial Park
	Threat	Market players are vulnerable faced with unpredicted situations under fewer trading routes, such as bankruptcy of trading partners	DGs in remote area lack development due to high installation and energy transmission costs Subsidies on different types of DG vary greatly, causing imbalanced development	Market share for traditional generators is squeezed with more DG installed, therefore reducing backup capacities for tackling stochastic generation and affecting the stable energy supply to the public	Innovations on energy storage are in need for implementing DG in larger scales
Similarities		Both are developed under the government's support. The decarbonisation background urges the promotion of DGs	Local consumption of DG is encouraged because it decreases transmission cost	DG development sees great potential in both countries for the environmental friendly perspectives of the public	Innovative research regarding the combination of DG trading with blockchain and big data is emerging, but the application costs of new technologies should be taken into consideration

(Continues)

4–5 in China show the same trends. This is because in the UK, Mode B/C captures the lowest revenue in all trading modes, whereas in China, Mode 4/5 creates little trading revenue after most generation being purchased by the grid at a low price. On the other hand, since the above mentioned modes are settled at a long-term fixed price, the financial risks that DGs bear are very low in the market. Therefore, for securing a stable return for investing DG trading, Mode

TABLE 6 (Continued)

	Policy	Economy	Society	Technology
Differences	Different market managements cause diversified policy weakness and threats in the UK and China. For the UK, the separation of settlement and transaction requires more efforts in coordination among departments. For China, lack of market competition and weak risk resistance of DG market players are main policy weaknesses	Different transmission routes cause diversified economic effects in the UK and China. For the UK, private wires require high construction and maintenance fee, and it reduces the demand for public wires. For China, high network fee in long distance transmissions and high construction costs in remote areas are the main economic weaknesses and threats for developing DG	Different social backgrounds cause diversified effects. For the UK, DG is provided with ten characterized trading options, but the public hardly focus on new DG technologies. For China, the demographic dividend provides DG with an enormous potential market, but the replacement of traditional generators can be the issue for providing stable energy in the long term	The technology development determines the differences in DG trading in the UK and China. For the UK, more new technologies have been put into use, such as new trading platforms with smart metering devices. Therefore, practical issues such as maintenance and investment costs are the main issues. For China, gas turbine and energy storage are in need of further development

TABLE 7 Economic benefits comparisons of trading arrangements in the UK and China

	China	Economic benefits(As savings compared to Mode 1)	The UK	Economic benefits(As savings compared to Standard PPA)
Self-consumption+	Grid acquisition (Mode 1)	0%	Mode X: α*Onsite supply (Mode F) + (1-α)*[Synthetic PPA (Mode B) / Sleeving arrangement (Mode C)]	0–46%
	Agent trading-LIUs (Mode 2)	8.03–11.76%		
	Agent trading-GICUs (Mode 3)	26.87–32.35%		
Grid acquisition-benchmark fee (Mode 4)		0%	Mode Y: Synthetic PPA (Mode B) / Sleeving arrangement (Mode C)	0–1.1%
Grid acquisition-subsidy (Mode 5)		0%		
Direct trading-LIUs (Mode 6)		3.92%	Mode Z: Full supply licence/licence lite (Mode D)	5–10%
Direct trading-GICUs (Mode 7)		17.65%		

4/5 and Mode Y are desirable choices in China and UK, respectively.

Mode Z and Modes 6–7

It can be seen from Table 7 that the benefits can be sorted as Mode 6 < Mode Z < Mode 7. Mode 6/7 ranks medium in all trading modes in China, so is the case with Mode Z in the UK. This is because these modes do not need an independent supplier as the intermediary, which saves DG some service fees. On the other hand, since energy is transmitted through public wires, the transmission cost will decrease the trading revenue. Therefore, if DG is not offered with onsite supply/self consumption choices, direct trading or Mode Z in China and UK are good choices for securing relatively high economic benefits.

5 | FUTURE DIRECTIONS

With the firm target of reducing carbon emissions, the necessity of developing and promoting DG is clear. For both the UK and China, mechanisms that can encourage transactions between DG and consumers are one major direction for future development.

For the UK, with the developed market trading mechanism, more innovative technologies can be implemented to enhance the utilisation of DG for deeper decarbonisation. For example, smart local energy systems can reduce inefficiencies, increase local benefits and reduce carbon emissions, which can be further invested and developed [75]. Besides, technologies that can unlock the benefits of energy storage, smart meters and local grids will also contribute to the efficient utilisation of DG, such as the digital comparison tools of trading costs with data portability and simple switching arrangements for convenient financial savings of DG [76].

For China, the development of DG can be further promoted through the improvement of market mechanisms. For example, transactions and settlement can be monitored and conducted through different agencies to increase the flexibility and competition in the market. Besides, more market options can be offered to DG, such as CfD, to help DG and consumers mitigate financial risks in the long term. Further, supplementary mechanisms can be improved to ensure feasible backup for DG for dealing with its intermittency and randomness in power output, together with further standardisation of network fees and a proper solution to the cross-subsidy problem.

6 | CONCLUSIONS

The DG trading mechanisms were investigated in this study through a comparative analysis between the UK and China. First, by introducing the history of DG trading mechanisms and comparing representative features, the necessity of this study was highlighted. In particular, both the UK and China are under decarbonization pressures, but their national features are distinctive and representative in terms of development level, territory scale, and population. Therefore, the analysis and discussion can be a reference for other countries to promote the DG trading mechanism under their decarbonization targets.

DG trading mechanisms in the UK and China were discussed in detail by investigating the electricity market structure and players, along with issues on network fees and subsidies for DG. In particular, the market operates and settles on separate platforms in the UK, which enhances market competition and further improves service quality. Moreover, the DG and users can be connected through private wires, which reduces the transmission costs and creates more economic benefits. However, in China, the market is under vertical management, which can operate with high efficiency when new policies are implemented. Moreover, DG trading is charged lower transmission fees because the local consumption of renewable energy is incentivized.

Further, a comparative study was conducted through discussion of practical issues, SWOT-PEST analysis, and quantitative comparisons. The main findings were as follows:

- Based on a comparison between Mode X (the combination of onsite supply and synthetic PPA/sleeving arrangement) in the UK and Mode 2–3 (self-consumption + agent trading) in China, it was found that DG in the UK could earn more benefits than that in China if the proportion of onsite supply exceeded 80%.
- To secure a stable and resilient return for the investment in DG, Mode 4/5 (grid acquisition with benchmark fee/subsidy) and Mode Y (synthetic PPA/sleeving arrangement) were desirable choices in China and the UK, respectively.
- If DG was not offered with onsite supply/self-consumption choices, direct trading and Mode Z (Full supply license/license lite) could be chosen in China and the UK, respectively, to ensure a good level of economic benefits.

Finally, in combination with the comparative analysis, future directions and suggestions for improving DG trading in the UK and China were provided. Quantitative comparisons were conducted without electricity transmission loss. Therefore, more discussions are needed to combine practical transmission issues with new policies and implementations for innovative DG technologies. Further research can be conducted to design market mechanisms for developing DG in the UK and China in a practical context.

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CONFLICT OF INTEREST

The author declares no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

NOMENCLATURE

Ω_I	Set of users
P^{SD}	Settlement price in the direct trading mode
P^D	Direct trading price
C^N	Network fee
P^{SA}	Settlement price in the agent trading mode
P^R	General retailing price
P_i^U	Trading price of user i in the agent trading mode
T_i^U	Trading volume of user i in the agent trading mode
P^{SG}	Settlement price in the grid acquisition mode
P^B	Local benchmark price
$C^N_{xkV-Sub}$	Network fee at different voltage levels considering cross subsidy
$C^N_{xkV-NoSub}$	Network fee at different voltage levels without considering cross subsidy
BEIS	Department for Business, Energy & Industrial Strategy
BSC	Balancing and Settlement Code
CfD	Contract for difference
CHP	Combined heat and power system
CT	Combustion turbine
DG	Distributed generation
DNO	Distribution network operator

DUoS	Distribution Use of System
FIT	Feed-in tariff
GICU	General industrial & commercial user
i	Subscript indices of users trading with DG
LIU	Large industrial users
NEA	National Energy Administration
Ofgem	Office of Gas and Electricity Markets
OTC	Over the counter
PE	Power exchange
PPA	Power purchase agreement
PV	Photovoltaic
TNUoS	Transmission Network Use of System
TSO	Transmission system operator
WT	Wind turbine
α	Ratio of onsite supply in the energy traded

REFERENCES

1. Li Z., Wu W., Shahidehpour M., Zhang B.: Adaptive robust tie-line scheduling considering wind power uncertainty for interconnected power systems. IEEE Trans. Power Syst. 31(4), 2701–2713 (2016). https://doi.org/10.1109/TPWRS.2015.2466546
2. He H., et al.: Joint operation mechanism of distributed photovoltaic power generation market and carbon market based on cross-chain trading technology. IEEE Access 8, 66116–66130 (2020). https://doi.org/10.1109/ACCESS.2020.2985577
3. Ochoa L.F., Harrison G.P.: Minimizing energy losses: optimal accommodation and smart operation of renewable distributed generation. IEEE Trans. Power Syst. 26(1), 198–205 (2011). https://doi.org/10.1109/TPWRS.2010.2049036
4. Li H., Lin H., Tan Q., Wu P., Wang C., De G., Huang L.: Research on the policy route of China's distributed photovoltaic power generation. Energy Rep. 6, 254–263 (2020)
5. Samper M., Coria G., Facchini M.: Grid parity analysis of distributed PV generation considering tariff policies in Argentina. Energy Policy 157, 112519 (2021)
6. Andrade J.V., Rodrigues B.N., Santos I.F., Haddad J., Filho G.L.: Constitutional aspects of distributed generation policies for promoting Brazilian economic development. Energy Policy 143, 111555 (2020)
7. Song P., Zhou Y., Yuan J.: Peer-to-peer trade and the economy of distributed PV in China. J. Cleaner Prod. 280(2), 124500 (2021)
8. Uhde H.: Peer-to-peer electricity trading in China and the EU – A comparative evaluation of key policy documents. Res. Globalization 4, 100078 (2022)
9. Ma Z., Li C., Xue Y., Nduneseokwu C.K., Wang X., Harder K.: From pioneer to promotion: How can residential waste diversion nonprofit organizations (NPOs) best co-evolve in modern China? Environ. Challenges 3, 100055 (2021)
10. Elavarasan M., Afridhis S., Vijayaraghavan R., Subramaniam U., Nurunnabi M.: SWOT analysis: A framework for comprehensive evaluation of drivers and barriers for renewable energy development in significant countries. Energy Rep. 6, 1838–1864 (2020)
11. Cox J.: The higher education environment driving academic library strategy: A political, economic, social and technological (PEST) analysis. J. Acad. Librarianship 47(1), 102219 (2021)
12. Tan Z., Tan Q., Rong M.: Analysis on the financing status of PV industry in China and the ways of improvement. Renewable Sustainable Energy Rev. 93, 409–420 (2018)
13. Tan Z., Tan Q., Wang Y.: A critical-analysis on the development of Energy Storage industry in China. J. Energy Storage 18, 538–548 (2018)
14. Zhu L., Hiltunen E., Antila E., Huang F., Song L.: Investigation of China's bio-energy industry development modes based on a SWOT-PEST model. Int. J. Sustainable Energy 34(8), 552–559 (2015).
15. Ackermann T., Andersson G., Söder L.: Distributed generation: A definition. Electr. Power Syst. Res. 57(3), 195–204 (2001)
16. Shahidehpour M., Wang Y.: Integration, control, and operation of distributed generation. In: Communication and Control in Electric Power Systems: Applications of Parallel and Distributed Processing. pp.391–438. John Wiley and Sons, Hoboken, NJ (2019)
17. POWER. The Smart Grid and Distributed Generation: Better Together, https://www.powermag.com/the-smart-grid-and-distributed-generation-better-together/ (2011). Accessed on 1 April, 2011
18. Eia. Net Summer Capacity Using Primarily Renewable Energy Sources and by State. https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_6_02_b (2021). Accessed on 1 Jan 2021
19. Jackson. BOS costs will play an important role in future solar installations. https://www.jakson.com/blog/bos-costs-will-play-an-important-role-in-future-solar-installations/ (2019). Accessed on 25 March 2019
20. IEA. Renewables 2019—analysis and forecast to 2024. https://iea.blob.core.windows.net/assets/a846e5cf-ca7d-4a1f-a81b-ba1499f2cc07/Renewables_2019.pdf (2019). Accessed on 24 March 2019
21. Bhatia S.C.: Advanced Renewable Energy Systems, (Part 1 and 2) pp. 24–56. CRC Press, Boca Raton, FL (2016)
22. GOV.UK. Net Zero Strategy: Build Back Greener. https://www.gov.uk/government/publications/net-zero-strategy (2021). Accessed on 19 Oct 2021
23. Mayor of London. London's response to climate change. https://www.london.gov.uk/what-we-do/planning/london-plan/past-versions-and-alterations-london-plan/london-plan-2016/london-plan-chapter-five-londons-response/pol-22 (2021). Accessed on 31 Jan 2021
24. GOV.UK. Combined heat and power. https://www.gov.uk/guidance/combined-heat-and-power (2013). Accessed on 22 Jan 2013
25. GOV.UK. Decentralised energy and storage. https://www.energy-uk.org.uk/publication.html?task=file.download&id=5716 (2016). Accessed on 4 April 2016
26. GOV.UK. UK CHP Development Map. https://chptools.decc.gov.uk/developmentmap (2018). Accessed on 03 Feb 2018
27. Nicholas Stern. The 14th Five-Year Plan: peaking China's greenhouse gas emissions and paving the way to carbon neutrality. https://www.lse.ac.uk/granthaminstitute/wp-content/uploads/2021/07/The-14th-Five-Year-Plan_Peaking-Chinas-greenhouse-gas-emissions-and-paving-the-way-to-carbon-neutrality.pdf (2021). Accessed on 09 July 2021
28. GOV.CN. Opinions on fully, accurately and comprehensively implementing the new development concept to achieve carbon peak and carbon neutral work. http://www.gov.cn/zhengce/2021-10/24/content_5644613.htm (2021). Accessed on 24 Oct 2021
29. Saad Sayeef. Overview of microgrids in Asia. https://microgrid-symposiums.org/wp-content/uploads/2019/08/Asia-1_Sayeef.pdf (2019). Accessed on 9 Aug 2019
30. SOUHU. Natural gas distributed energy station of Shanghai Tower. https://www.sohu.com/a/153313883_463997 (2017). Accessed on 30 June 2017
31. NDRC. Measures for the administration of Prices and charges for central Heating in Cities and towns. https://www.ndrc.gov.cn/yjzxDownload/gg3czjzgrjghsfgl.pdf (2007). Accessed on 5 March 2007
32. GOV.CN. Notice on the issuance of administrative Measures for Cogeneration of Heat and Power. http://www.gov.cn/gongbao/content/2016/content_5092473.htm (2016). Accessed on 33 March 2016
33. Heideier R., Bajay S.V., Jannuzzi G.M., Gomes R.D.M., Guanais L., Ribeiro I., Paccola A.: Impacts of photovoltaic distributed generation and energy efficiency measures on the electricity market of three representative Brazilian distribution utilities. Energy Sustainable Dev. 54, 60–71 (2020)
34. Gregoratti D., Matamoros J.: Distributed energy trading: the multiple-microgrid case. IEEE Trans. Ind. Electron. 62(4), 2551–2559 (2015)
35. Wan C., Lin J., Guo W., Song Y.: Maximum uncertainty boundary of volatile distributed generation in active distribution network. IEEE Trans. Smart Grid 9(4), 2930–2942 (2018).https://doi.org/10.1109/TSG.2016.2623760
36. Silva P.P., Dantas G., Pereira G., Câmara L., Castro N.J.: Photovoltaic distributed generation – An international review on diffusion, support policies, and electricity sector regulatory adaptation. Renewable Sustainable Energy Rev. 103, 30–39 (2009)

37. GOV.UK. Energy Policy Act of 1992. https://afdc.energy.gov/files/pdfs/2527.pdf (1992). Accessed on 24 Oct 1992
38. First energy. Bi-directional metering. https://www.firstenergycorp.com/content/dam/feconnect/files/retail/Net-Metering-Primer.pdf (2016). Accessed on 14 Jan 2016
39. Applied materials. Feed-in Tariffs or Net Metering? What's the Difference? https://blog.appliedmaterials.com/feed-tariffs-or-net-metering-what%E2%80%99s-difference (2009). Accessed on 14 Sep 2009
40. Tan H.G., Chow T.L.: A comparative study of feed in tariff and net metering for UCSI university north wing campus with 100 kW solar photovoltaic system. Energy Procedia 100, 86–91 (2016)
41. Obi M., Slay T., Bass R.: Distributed energy resource aggregation using customer-owned equipment: A review of literature and standards. Energy Rep. 6, 2358–2369 (2020)
42. Ghorbanian M., Dolatabadi S.H., Siano P.: Game theory-based energy-management method considering autonomous demand response and distributed generation interactions in smart distribution systems. IEEE Syst. J. 15(1), 905–914 (2021). https://doi.org/10.1109/JSYST.2020.2984730
43. Parag Y., Sovacool B.K.: Electricity market design for the prosumer era. Nat. Energy 1, 16032 (2016)
44. Marqus A., Serrano M., Karnouakos S.: NOBEL—a neighborhood oriented brokerage electricity and monitoring system. In: Energy-Efficient Computing and Networking. pp. 187–196. Springer, Berlin (2011)
45. Mahmud M.A., Islam S.N., Lilley I.: A smart energy hub for smart cities: Enabling peer-to-peer energy sharing and trading. IEEE Consum. Electron. Mag. 10(6), 97–105 (2021)
46. Investopedia. Top 25 Developed and Developing Countries. https://www.investopedia.com/updates/top-developing-countries/ (2021). Accessed on 24 April 2021
47. CEC. Analysis and Forecast of China Power Demand-Supply Situation 2020–2021. https://english.cec.org.cn/detail/index.html?3-1128 (2021). Accessed on 9 Feb 2021
48. Statisca. Annual demand for electricity in the United Kingdom (UK) from 2000 to 2020. https://www.statista.com/statistics/323381/total-demand-for-electricity-in-the-united-kingdom-uk/;2021 (2021). Accessed on 5 July 2021
49. Grubb M., Newbery D.: UK Electricity Market Reform and the Energy Transition: Emerging Lessons. https://www.eprg.group.cam.ac.uk/wp-content/uploads/2018/06/1817-Text.pdf (2018). Accessed on 08 June 2018
50. GOV.UK. Electricity Market Reform: policy overview. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/65634/7090-electricity-market-reform-policy-overview-.pdf (2012). Accessed on 09 Nov 2012
51. The Oxford Institute. UK Electricity Market Reform and the EU. https://www.oxfordenergy.org/publications/uk-electricity-market-reform-and-the-eu/ (2021). Accessed on 22 Jan 2021
52. Yao, Y., C., Gao, H.T., Zhang: Review of mid-to long-term trading mechanism for renewable electricity consumption in Ningxia, China. Renewable Sustainable Energy Rev. 134, 110325 (2020)
53. Karagiannis E.A.: UK power networks' DSO strategy paves the way for flexibility markets, offering new revenue streams for customers and efficient distribution system operation. In: CIRED 2020 Berlin Workshop (CIRED 2020). Berlin, pp. 690–692 (2020)
54. Nordpool. N2EX Day Ahead Auction Prices. https://www.nordpoolgroup.com/Market-data1/GB/Auction-prices/UK/Hourly/?view=table (2021). Accessed on 10 Aug 2021
55. EPEXspot. General conditions. https://www.epexspot.com/en (2020). Accessed on 9 Jan 2020
56. Ofgem. Retail market indicators. https://www.ofgem.gov.uk/retail-market-indicators (2021). Accessed on 15 April 2021
57. Ofgem. Energy Supplier Performance Scorecard-2020. https://www.ofgem.gov.uk/publications/energy-supplier-performance-scorecard-2020 (2020). Accessed on 9 Jan 2020
58. Ofgem. Our roles and responsibilities. https://www.ofgem.gov.uk/about-us/our-role-and-responsibilities (2018). Accessed on 5 March 2018
59. National grid. What we do. https://www.nationalgrid.com/about-us/what-we-do (2021). Accessed on 8 Jan 2021
60. Elexon. Balancing and settlement code. https://www.elexon.co.uk/bsc-and-codes/balancing-settlement-code/ (2021). Accessed on 16 Oct 2021
61. ENERGETIK. Visiting a UK district heating icon. https://energetik.london/2018/04/pdhu-visit-history-of-district-heating/ (2019). Accessed on 05 Sep 2019
62. GOV.UK. Gateshead District Energy Scheme. https://www.gateshead.gov.uk/article/2993/Gateshead-District-Energy-Scheme (2015). Accessed on 18 June 2015
63. GOV.UK. Heat network electricity revenues and licencing. https://www.gov.uk/government/publications/heat-network-electricity-revenues-and-licencing (2018). Accessed on 3 July 2018
64. CCCPC. Opinions on Further Deepening Electricity System Reform. https://chinaenergyportal.org/opinions-of-the-cpc-central-committee-and-the-state-council-on-further-deepening-the-reform-of-the-electric-power-system-zhongfa-2015-no-9/ (2015). Accessed on March 2015
65. YNET. China's electricity trading centers saw a year-on-year increase of more than 19 percent. https://t.ynet.cn/baijia/32098494.html (2022). Accessed on 22 Jan 2022
66. NEA. Connecting villages with the grid. http://www.nea.gov.cn/2012-11/05/c_131951542.htm (2012). Accessed on 5 Nov 2012
67. NEA. Interim Measures for the administration of Distributed Generation. http://zfxxgk.nea.gov.cn/auto87/201308/P020130814363503053455.pdf (2013). Accessed on 14 Aug 2013
68. GOV.CN. Supplementary Notice on the Pilot market trading of distributed Power Generation. http://www.gov.cn/xinwen/2018-01/03/content_5252800.htm (2018). Accessed on 3 Jan 2018
69. NEA. Notice on the announcement of the whole county (city, district) rooftop distributed photovoltaic development pilot list. http://zfxxgk.nea.gov.cn/2021-09/08/c_1310186582.htm (2021). Accessed on 8 Sep 2021
70. Liu S., Bie Z., Liu F., Li Z., Li G., Wang X.: Policy implication on distributed generation PV trading in China. Energy Procedia 159, 436–441 (2019)
71. NEA. The subsidy per kilowatt hour of distributed generation will be reduced by 0.05 yuan. http://www.nea.gov.cn/2018-01/02/c_136866746.htm (2018). Accessed on 2 Jan 2018
72. Nationalgrid ESO. What is Frequency? https://www.nationalgrideso.com/electricity-explained/how-do-we-balance-grid/what-frequency (2018). Accessed on 7 March 2018
73. Chen Z., Dong J., Ren R.: Urban underground logistics system in China: Opportunities or challenges? Underground Space 2(3), 195–208 (2017)
74. Ade. Risks to energy intensive industries and local generation? https://chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/viewer.html?pdfurl=https%3A%2F%2Fwww.theade.co.uk%2Fassets%2Fdocs%2Fresources%2FEmbedded_Benefit_Report_final.pdf&clen=795750&chunk=true (2018). Accessed on 22 July 2018
75. Rebecca Ford. A framework for understanding and conceptualising smart local energy systems. https://www.energyrev.org.uk/media/1298/energyrev-sles-frameworkv4.pdf (2019). Accessed on 16 Oct 2019
76. Carmichael R., Gross R., Hanna R., Rhodes A., Green T.: The demand response technology cluster: Accelerating UK residential consumer engagement with time-of-use tariffs, electric vehicles and smart meters via digital comparison tools. Renewable Sustainable Energy Rev. 139, 110701 (2021)

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