Renewable and Sustainable Energy Reviews 161 (2022) 112317

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

# Evolution and reform of UK electricity market

Jinqi Liu [a], Jihong Wang [a,*], Joel Cardinal [b]

[a] School of Engineering, University of Warwick, Coventry, CV4 7AL, UK
[b] Energy Centre, University of Warwick, Coventry, CV4 7AL, UK

ARTICLE INFO

*Keywords:*
Electricity market
United Kingdom
Reform
Decarbonisation
Distribution system operator

ABSTRACT

Electricity Market is structured to fund reliable electricity supply, meet the need of consumers, ensure the affordability of end-users, and support national economic development. In recent years, to meet challenging emission target set by Government, power system in the UK has a rapid increase of integration with various-scale Renewable Energy Sources (RESs) and Energy Storage Systems (ESSs), which pushes the electricity market reform to accommodate the changes, encourage renewable energy integration, adopt new technologies, stimulate consumers participation, and ensure the power system resilience. The paper reviews the history of UK electricity market evolution, driving factors of reform, and the trend of current electricity market reform. In history, the UK electricity wholesale market has experienced three significant reform stages, which are introducing the Electricity Pool of England & Wales (the Pool) in the 1980s, implementing the New Electricity Trading Arrangements (NETA) in the 2000s, and performing the Electricity Market Reform (EMR) in 2013. To address the new emerging challenges in decarbonising power generation, the paper explains and analyses on-going electricity market changes and the trend for future electricity market reform.

## 1. Introduction

Electricity market serves as an effective mechanism linking generators, transmission enterprises, consumers, regulatory bodies, and government policy together [1–3]. Developed countries, including UK, USA, Norway, Canada, and Chile, have been continuously reforming their electricity sectors in the past 40 years, which are also considered as the first echelon of electricity sector reform [4–9]. In general, electricity reform can be summarised as three phases [10]: Phase 1 integrated regional/isolated grid to a vertical grid (from generation, transmission, and distribution to consumption) driving by the technology development. Phase 2 can be described as the liberalisation of electricity market and promoting competition [11]. The third phase is driven by integrating and encouraging power generation of renewable energy sources for decarbonisation. Electricity market mechanisms cannot be simply copied between countries as the diversity of geographical environments, resource distribution, population density, economic characteristics, and government regulations for each country [9,12].

In the UK's 2008 Climate Change Act, Government sets a goal to slash 80% of greenhouse emissions compared with 1990 level by 2050 [13]. In the past ten years, power generation from renewable energy sources (RES) such as wind, solar energy, biomass energy, and geothermal energy increased rapidly. In 2019, the UK produced a total of 323.7 GWh of electricity, with around 37% of it from RESs [14]. RESs rapid impose a significant impact on grid stability, and it is becoming more challenge in maintaining the balance between load and generation due to the intermittence nature of RESs and the reduction of grid system inertia or spin reserve from rotating machines [15–17]. Therefore, the cost of grid balance has continuously increased in recent years, which costed National Grid over £1.5 billion in 2020 [18]. Balancing cost definitely increased electricity price and deprived potential economic benefit of renewable energy. Moreover, a bulk of high-resolution data has been collected from Advanced Metering Infrastructure (AMI) [19], which provides valuable information for business innovation in power

*Abbreviations:* RESs, Renewable Energy Sources; ESSs, Energy Storage Systems; NETA, New Electricity Trading Arrangements; EMR, Electricity Market Reform; AMI, Advanced Metering Infrastructure; DNO, Distribution Network Operator; DSOs, Distribution System Operators; NMF, Neutral Market Facilitator; CLDS, Customer-Led Distribution System; EFFS, Electricity Flexibility and Forecasting System; ESO, Electricity System Operator; VPPs, Virtual Power Plants; FPPs, Federated Power Plants; CCC, Committee on Climate Change; CEB, Central Electricity Board; AEBs, Area Electricity Boards; BEA, British Electricity Authority; CEA, Central Electricity Authority; CEGB, Central Electricity Generating Board; PSA, Pooling and Settlement Agreement; NP, National Power; PG, PowerGen; NE, Nuclear Electric; RECs, Regional Electricity Companies; PES, Public Electricity Supplier.

* Corresponding author.
*E-mail addresses:* jinqi.liu@warwick.ac.uk (J. Liu), jihong.wang@warwick.ac.uk (J. Wang), j.cardinal@warwick.ac.uk (J. Cardinal).

https://doi.org/10.1016/j.rser.2022.112317
Received 19 December 2020; Received in revised form 9 February 2022; Accepted 22 February 2022
Available online 12 March 2022
1364-0321/

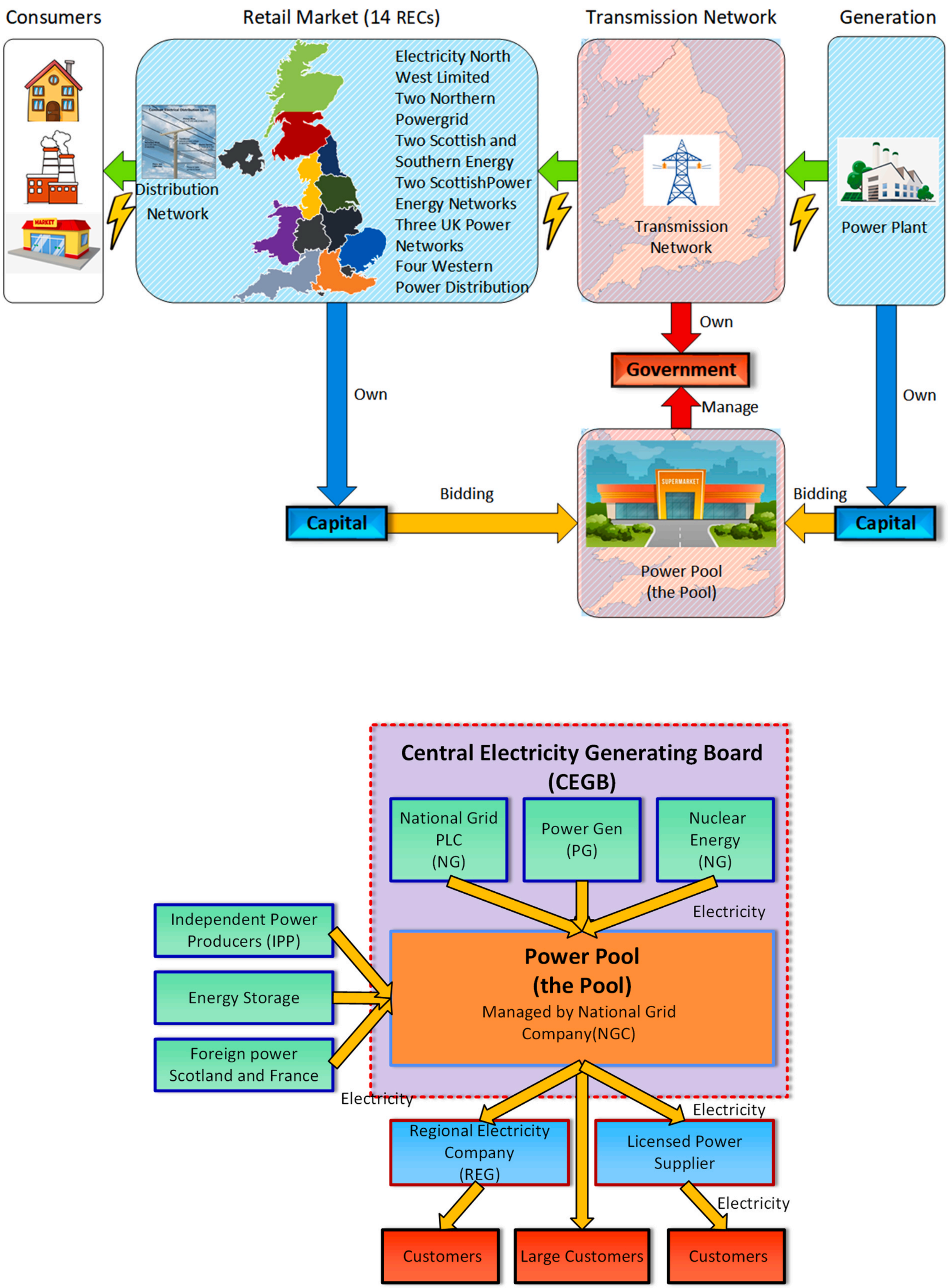


**Fig. 1.** (a) The diagram of the relationship between the structure of the UK electricity industry and electricity trading, and (b) the organisation of the UK electricity market after the first reform.

(2) The Process of Settlement

sectors. Finally, home levelled RES and ESS, which may turn end consumers to potential electricity providers, and needs to have its position in nowadays electricity market. All these issues have challenged the conventional structure of UK electricity market. Indeed, future electricity market is expected to subvert the most basic mode of power operation and will push conventional vertical grid moving towards to smart grid with the capability of accommodating bidirectional energy flows.

The role of current Distribution Network Operator (DNO) is changing and evolving to become Distribution System Operators (DSOs) to meet the demand to managing energy mix and local generation increases in the UK [20]. Four pilot DSOs projects started between 2017 and 2018, aiming to investigate the future roles, functions, and responsibilities of DSO [21–24]. In the project “TRANSITION” [21], the cooperation between DSO, ESO, and the role of Neutral Market Facilitator (NMF) Platform are discussed. Northern PowerGrid formed a project of testing “Customer-Led Distribution System (CLDS)" and aims to identify the most appropriate future structure to accommodate a large volume of DERs at a minimum cost while providing easy access to energy markets for customers [22]. Electricity Flexibility and Forecasting System (EFFS) project, beginning in 2018, explores the requirement of DNO transition to DSO through developing an understanding of forecasting and communication requirements [23]. FUSION project concentrates on managing local distribution network constraints, encouraging DERs, and accelerating utilisation [24]. The relationship between DSO and Electricity System Operator’s (ESO) is investigated as well [25,26]. For the work related to consumer structure, such as much more detailed work of Virtual Power Plants (VPPs) and Federated Power Plants (FPPs) could be found in Refs. [27,28]. Both VPPs and FPPs combine end consumers into a group to participate in electricity trading for profits.

In May 2019, UK Committee on Climate Change (CCC) amended the 2008 Climate Change Act and revealed a more ambitious goal of achieving net-zero carbon emissions by 2050 [29]. The Act has no doubt stimulated more power generation from RESs and consumers’ participation in the UK electricity market. This paper is to give an in-depth analysis of the history and development of UK electricity market and to understand the current under-going electricity market reform.

## 2. The first reform: the pool

### 2.1. Background

The UK electrical system has a history of approximately 140 years [30]. In 1881, UK operated its first community electricity generator in Godalming. In 1900, power companies were authorised by Electric Lighting (Clauses) Act 1899 to supply electricity to authorised users, which is considered as the birth of UK electricity industry. In the following decades, power stations were gradually interconnected to provide electricity supply with increased flexibility and security. The rated voltage across the transmission lines was increased from 6.6 kV to 132 kV in the 1930s. Following this development, the Electricity (Supply) Act 1919 and Electricity Acts of 1922 were published, which established Electricity Commission, appointed Electricity Commissioners, and joint electricity authorities to provide central coordination and regional organisation [31]. In 1926, the Electricity Supply Act of 1926 introduced the first significant national coordination: Central Electricity Board (CEB), which managed the generation of electricity in a limited number of power stations that were interconnected by a national grid. Electricity Act 1947 established twelve Area Electricity Boards (AEBs) for the distribution and supply of electricity to consumers, which replace 625 separate organisations in England and Wales. Besides, all generations and 132 kV National Grid were vested with newly established department, called British Electricity Authority (BEA). In 1955, BEA became the Central Electricity Authority (CEA). In 1957, it was further changed to Central Electricity Generating Board (CEGB) to replace CEA. It owned all big generators of National Grid, managing the power generation, transmission, and distribution in England and Wales. CEGB provides electricity to twelve local electricity boards, and local boards sell electricity to consumers within their responsible areas. The Electricity Council was established accordingly to oversee industries and CEGB with responsibility for generation and transmission [32].

In 1979, Mrs. Thatcher and the Conservative Party decided to reduce Government’s direct intervention in economy, sold state-owned enterprises at a low price, and carried out a series of state-owned industry privatisation reforms. In 1989, the UK issued a White Paper on the power industry by proposing the privatisation of power industry and implementation of a free-market economic policy. The new structure was introduced on 31 March. 1990 under the Electricity Act 1989.

### 2.2. Structure of the pool

The privatisation activated the competition of providing electricity through a legal frame of Pooling and Settlement Agreement (PSA). The Pool is a mandatory electricity market and all large generators (with exceptions only for plants under 50 MW); the generators and customers were required to sell and purchase electricity from the Pool. Hence, the Pool provides market trading rules for electricity wholesale market and sets outbidding rules that the generator must follow [33,34]. As shown in Fig. 1(a), PSA legally brings capital to the generation and distribution (local suppliers) sides and becomes owners. Government still owns transmission network and manages trading and operation of the electricity market through the Pool markets. The Pool provides [35]:

(1) The Actual Operation Mechanism

In England and Wales, two fossils fuel (National Power (NP) and PowerGen (PG)) and one nuclear power (Nuclear Electric (NE)) generation companies should sell electricity and compete in the Pool. Also, other sources of electricity were allowed to trade in the Pool as long as they were certificated and allowed electricity importing from Scotland or overseas (France). In Scotland, two vertically integrated companies bundled together sell electricity. In comparison, in Northern Island, three generation companies trade with long-term power purchase agreements, as these regions are not included in the Pool [36].

For supplying electricity to consumers at the distribution level, 14 independent Regional Electricity Companies (RECs), which replace 12 ABES, purchase electricity from electricity generators through the Pool. Each REC was obliged to supply on request all reasonable demands for electricity in its authorised area. On December 11, 1990, RECs were privatised and renamed as Public Electricity Supplier (PES).

With regards to the Pool management, National Grid Company (NGC) operates the Pool and becomes Grid Operator (GO). GO is responsible for scheduling and dispatching all power transactions. NGC also administers the Pool’s settlement system on behalf of the Pool members. Members of the Pool are wholesale buyers and sellers of electricity who decides how the Pool was running, modified, or changed. The organisational structure of the UK electricity market during this period is shown in Fig. 1(b).

The Pool accommodates a day-ahead wholesale market. All generation units will be queued according to the bidding price. Then, based on the load forecasting information and considering reserve demand of systems, a combination of units is selected [37]. All costs paid to generators are shared equally by consumers, which also includes capacity payments. Capacity payments are considered as the payment to units that keep active during the period, even if work is not required during this period. Besides, an economic contract usually accompanies trading in the Pool: the most common one is Contracts for Difference (CfD) [38] to reduce uncertainties caused by fluctuations of electricity prices. CfD works in a way that a generator receives, in addition to the usual pool price for any sales, a sum equal to specified strike price less than the pool price, multiplied by the specified number of units contracted. Moreover, there is a market for Electricity Forward Agreements (EFAs) as a


**Fig. 2.** NETA (a) application times for different sectors and (b) Key elements of each sector.

supplementary mechanism, which allows primary components of electricity price uncertainty to be hedged on a short-term basis.

Contracts would be settled based on actual amount of delivered electricity, its real-time price, and contracts signed before. The settlement date begins at 0:00 every day and ends at 0:00 on the next day. Each operation day is divided into 48 equal settlement periods. Settlement System Administrator (SSR) takes charge of the process of settlement. The initial settlement is established within 4–5 business days from trading day, midterm settlement within 9–10 business days, and final settlement within 5–17 business days [39,40] with consideration of reliable reading data.

(3) Demand Side Response and Ancillary Service

From the perspective of maintaining system development and grid balance, reducing load and increasing power generation have the equivalent effect on grid balance. Therefore, some end consumers agree to change their load with price variation and grid need [41]. Since December 1993, Pool officially launched a demand side bid mechanism, and large users can submit their bid, including their capacity and expected price. Generators can also provide ancillary services for extra revenue. There are four main types of ancillary services in the UK electricity market: frequency control, reserve demand, voltage and reactive power support, and black-start [42]. NGC acts as an Ancillary Services Provider, Settlement System Administrator, and Pool Funds Administrator [38].

### 2.3. Discussion

At the beginning of reform, the price of electricity decreased due to

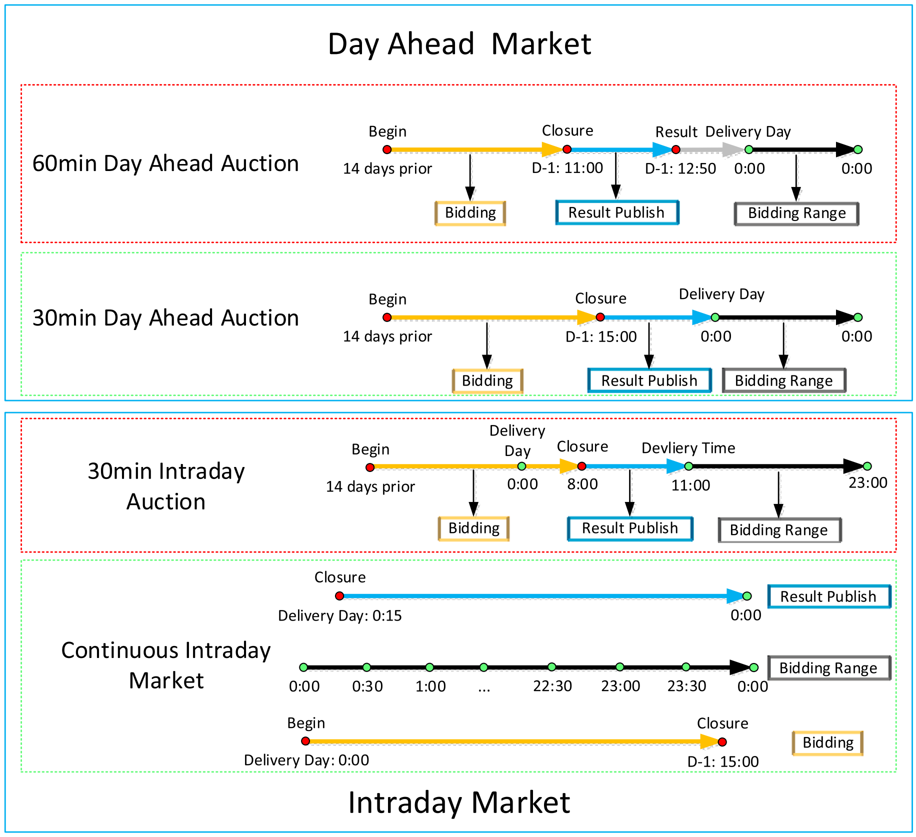


**Fig. 3.** Time line for different services in Spot Market.

the competition introduced, which brought a great benefit to the end consumers. However, the price of electricity has increased since 1995. There are many reasons for soaring electricity prices, such as oil price, gas price, and inflation. Inadequate market mechanisms also have an inescapable responsibility. NGC is responsible for management of the Pool. However, there is no independent body to supervise NGC. Besides, the legal document, PSA, is a commercial contract between participants, and there is no specific mechanism to push them to modify rules unless a consensus can be reached. Moreover, the complicated bidding process of The Pool also increases the operating cost. The biggest flaw in The Pool structure would be the requirement for the mechanism to share the cost of contract equally with all electricity purchasers. In that way, purchaser loses supplier's bargaining power. As a result, electricity prices in The Pool do not reflect the actual cost of electricity and the supply and demand in the electricity market. To hedge their business risks in The Pool, large companies tend to acquire upstream and downstream companies. This move has further exacerbated the monopoly in electricity industry. Potentially, monopoly generators can lead to an overall increase in electricity prices and unusual volatility (e.g., monopoly price-fixing or price wars between oligopolies). These actions often result in a vicious circle of monopolies by forcing small and medium-sized enterprises out of market.

## 3. The second reform: NETA

### *3.1. Background*

After more than ten years of operation, some of drawbacks of the Pool mechanism have gradually emerged, such as soaring electricity prices. Besides, the Pool has only been implemented in specific areas: England and Wales, indicating that the UK still does not have a unified electricity market. Hence, UK began to reform the Pool and hoped to expand the Pool to whole GB range. "New Electricity Trading Arrangement" (NETA) reforms were first proposed by Government in 1998 and implemented in 2001. In 2005, British Electricity Trading and Transmission Arrangements (BETTA) were established, and it expanded NETA from England and Wales to Scotland, establishing a united electricity market in Great Britain.

### *3.2. Structure of the NETA*

NETA is a self-dispatched energy-only market (abolishing capacity payments), which replaced the central dispatch mechanism of the Pool, aiming to encourage competition. The fundamental principle for NETA was bilateral trading [33]. All output of generators is required to be contracted, thus removing incentives to manipulate spot market [33]. Free bilateral contracts would encourage sellers to increase spot price to above marginal cost when under-contracting while reducing price below the marginal cost when over-contracting [43]. NETA accommodates four electricity market products with different functions: Forward Market, Power Exchange (spot market), Balance Mechanism, and Imbalance Settlement. The structure of NETA and service for each sector are demonstrated in Fig. 2(a) and (b), respectively.

Both in Forward Market and Spot Market, bilateral contracts are signed by traders through free negotiation. Contracts are allowed to be signed several years ahead of fulfilling contract in Forward Market (also known as Futures Market), including Forward Contract, Future Contract, and options shown in Fig. 2(b). Forward Contract is a kind of contract-specific tariffs and delivery time, while Future Contract is similar to Forward Contract but allows to trade their contract. Options are right to buy and sell electricity during a specific period at a specified tariff, while trading in options is also permitted. Spot Market is used to fine-tune contractual electricity for contracts signed in the Forward Market [44]. At present, NORD POOL and Epexspot are the two markets to operate Spot trading. The day ahead auction, intraday trading are primary contract types in Spot Market. The day ahead auction will hold a day before delivery and intraday trading happened on delivery day. A more detailed timeline for different services is plotted in Fig. 3. Not both Forward Market and Spot Market traders are able to sign bilateral contracts as parties to the contract, although these traders do not generate or consume electricity [45,46].

The demarcation point between spot market and the balance mechanism is called “Gate Closure” time [47]. At this time, all trading activities in spot market exchange stopped. After “closed gate”, NETA would conduct the settlement of balanced market. The “Balancing and Settlement Code (BSC)", a rule for settlement mechanism, was launched as part of NETA as well. The settlement mechanism can be divided into two phases: the balance settlement and imbalance settlement. The balance settlement applied for actively managing and controlling the grid power flow. In contrast, the imbalance settlement used flow of funds to punish market participants who fail to fulfil contracts. That is, settlement mechanism focused on power, while imbalance settlement operated with funds. National Grid (NGC and Lattice Group merged to form National Grid Transco in 2002), working as the system operator, will carry out system control through the balance settlement to ensure the balance between generators and load, and maintain system safety and power quality [44]. As for the imbalance settlement, ELEXON, a wholly-owned subsidiary of NGC, is established and administers BSC on behalf of the UK electricity industry [48].

The auxiliary services under the UK electricity market balance mechanism are divided into mandatory and commercial. There are two types of mandatory auxiliary services: one is required for all generators with operating licenses, such as reactive power and frequency response; the other is provided by some generators according to bilateral agreements, such as black start and quick start. Generators voluntarily provide commercial auxiliary services under bilateral agreements [49]. The balance mechanism is a market for commercial auxiliary services that National Grid purchases different types of contracts such as frequency response, reactive power compensation, and reserve services to solve transmission constraints and maintain balance between supply and demand [50].

To avoid monopoly, an independent organisation, Office of Gas and Electricity Markets (Ofgem), was established to regulate both natural gas and electricity markets within UK in 1999. The primary legal basis for supervision of power industry by regulatory authorities is Authorisation of Electricity legislation to issue licenses for various types of businesses such as power generation, transmission, distribution, and power supply. It also supervises the implementation of conditions related to these licenses and has right to impose penalties for violations.

The role of Distribution Network Operators (DNOs) is modified as well. The Utilities Act 2000 introduced legislation of separating electricity distribution and supply, removing the concept of PES [51]. Following this change, the responsibility for supplying electricity to all consumers is replaced by a licensed distribution network operator with a statutory responsibility. Each geographic area of DNO is also divided in a statutory form, which ensures that each area has a specific DNO to serve the consumers. The statutory duties assigned to DNOs are similar to those assigned to transmission network operators. Besides, DNO is required by law to promote a level playing field and be able to provide consumers with an efficient and stable electricity network.

### 3.3. Improvement and expansion: BETTA

In December 2003, UK government and independent regulator Ofgem put the reform of the Scottish electricity market on the agenda [48]. New electricity market mechanism set in the UK is the “British Electricity Trading and Transmission Arrangements” (BETTA). The UK’s Energy Act 2004 established a unified power trading, balancing, and settlement system. This Act legally redefined transmission business activities previously uncommercialised and split transmission function into two parts: System Operator (SO) and Transmission Operators (TO). The former is responsible for coordinating and managing power transmission within full UK range. The latter, TO, plays the role of assets of UK grid within a specified range. In general, the main functions of Great British System Operator (GBSO) include the purchase and use of balancing services in all periods, the real-time operation of transmission system and commercial contract for running grid and network. GBSO will also design a grid-connected and network-based charging mechanism for charging fees to grid-connected and network customers. Finally, GBSO pays revenue toTO. TO will continue to own original and new transmission assets within its designated areas, be responsible for asset maintenance and optimisation, plan, invest, and construct its network.

Government is no longer the owner of electricity assets following this reform. The entire electricity sector, including generation, transmission, and distribution, is fully capitalised. Government became a regulator to electricity industry, with its primary responsibility being to oversee and regulate the industry.

### 3.4. Discussion

NETA/BETTA uses bilateral contracts to replace complex trading mechanisms of the Pool. As a result, it increases efficiency. Bilateral contracts also bring consumers (such as DNO and large factories) into electricity market, avoiding unilateral market manipulation by Generators. In contrast to the Pool, NETA/BETTA gives consumers ability to bargain in electricity market. Through bilateral contracts, consumers can effectively use price competition to undermine “tacit price” between oligopolies, thus effectively reducing electricity bills. NETA/BETTA abolishes the capacity market and converts the UK electricity market to a pure energy market. By using Forward Market and Spot Market, electricity price reflects short-term and long-term capacity needs. Besides, the generator and suppliers are encouraged to participate in electricity market through long-term contracts to reduce investment risks by locking in long-term returns. After NETA/BETTA reform, Government has completely removed itself from being the owner of assets, retaining only the management and regulatory role, which also avoids structural defect of the Government acting as both owner and manager of assets.

Balancing load and generation through purchase and sale of electricity by market entity in electricity market. The balancing and imbalance mechanisms are used to execute the final physical balance and to penalise market participants who fail to achieve a net contract volume of zero. However, the imbalance penalty price is not perfectly designed and the imbalance penalty price may be lower than the electricity market price. On this occasion, market entity has avoided financial losses or increased its revenues (called Net Imbalance Volume (NIV) chasing) by exploiting the price gap between imbalance penalty price and market price. NIV defeats the purpose for which NETA/BETTA was designed, reducing the electricity market’s efficiency.

At the beginning (from 2000 to 2004) of NETA/BETTA, electricity price was reduced significantly due to fierce competition in electricity market. On the positive side, end-consumers can use electricity at a lower price. On the negative side, the electricity market failed to effectively attract investment due to limited profits, resulting in a decline in system backup reserves. In 2006, UK reserve factor of power generation capacity dropped from 35% at the beginning of the reform to 22% [52]. The proportion of research and development investment in sales revenue of UK power grid companies has dropped from 2% before the reform to 0.1% in 2011 [53]. More seriously, limited profits refuse new participants as it is challenging to meet the cost of investment, and push players who have already invested in fighting for more market share. This trend leads to market evolving towards current “The Big Six” [33], that is, British Gas, EDF Energy, E.ON, Npower, Scottish Power, and Scottish Southern Electricity (Ovo Energy has acquired SSE’s retail customers at the beginning of 2020). The Big Six held a combined market share of 70% for electricity supply in Great Britain [54]. With BETTA mechanism, generation companies can sell electricity to

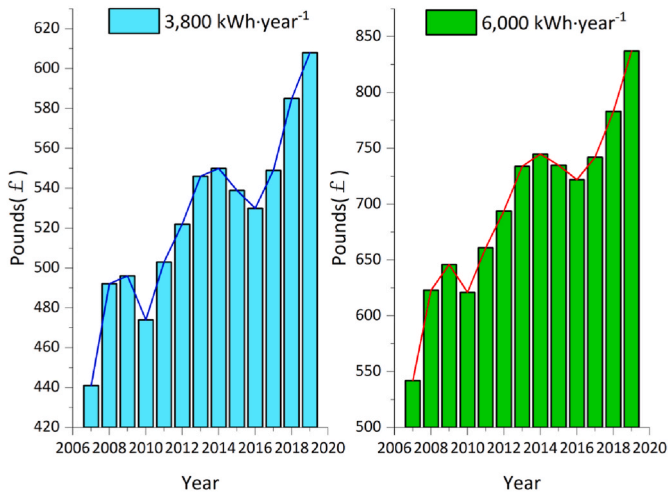


**Fig. 4.** UK average annual domestic electricity bill from 2007 to 2019.

themselves and automatically hedge against electricity price uncertainties. This incentive pushes the UK electricity market to withstand the risk changed from market manipulation in the Pool, to monopoly enterprises in NETA. The UK average annual domestic electricity bill has continued to rise as shown in Fig. 4 [55], and there is no doubt that monopoly resulted from BETTA.

## 4. The third reform: EMR

### 4.1. Background

In 2010, the UK National Grid estimated that the gap between demand and generation in electricity would reach 20 GW in 2020 with a current peak demand around 60 GW [56]. The coal and oil power plants with a capacity of about 12 GW and the 7.5 GW nuclear power all will be shut down [57]. It is expected that total investment in UK power sector will reach £110 billion from 2010 to 2020 to upgrade the facility and compensate for the gap [58].

Besides, to ensure the target of emission reduction, British Government reiterated its intention of developing renewable energy in 2009 [59]. New regulations to attract more investors to participate in UK's electricity market are needed. On July 12, 2011, the white paper "Planning our electric future: a White Paper for secure, affordable, and low-carbon electricity" was published, which is regarded as official preparation for Electricity Market Reform (EMR) [60].

### 4.2. Structure of EMR

Contracts for Difference (CfD) and Capacity Market (CM) are two central policies and other policies include Emission Performance Standard (EPS) and Carbon Floor Price (CPF). Fig. 5 indicates how EMR mechanisms and institutions fit together. Government will set an overall policy direction and critical parameters within the delivery plan. National Grid works as SO to provide analysis to ministers of Department of Energy & Climate Change (DECC) on crucial parameters and run generic CfD and CM allocation processes. DECC was responsible for providing budgets for CfD and CM. In July 2016, DECC and Department for Business, Innovation, and Skills were merged as the Department for Business, Energy and Industrial Strategy (BEIS) [61]. The Low Carbon Contracts Company (LCCC) and the Electricity Settlements Company (ESC) are both private limited companies owned by Secretary of State for BEIS. LCCC would contract with qualified electricity generators by using provided budget and take charge of financial transactions related to CfD, while ESC is responsible for financial transactions related to CM, including making capacity payments to capacity providers, controlling collateral, and managing auction credit cover.

CfD is a kind of contract signed between an electricity generator and LCCC. CfD would ensure revenue of generators is stabilised at a pre-agreed level (Strike Price) during contract period. CfD is an economic contract that locks in revenue of parties, and the payment or charge in CfD is based on the difference between actual market price and contract price (normally the price is an estimated price needed to bring forward investment in a given technology): as shown in Fig. 6, CfD compensates generators to get it to a predetermined return (blue area) when market price is lower than agreed price (day 1–20 and day 24–32). Once market price exceeds the contract price (day 21–23), generators must repay a part of revenue that exceeds predetermined price (red zone).

CM is a mechanism to ensure sufficient reliable capacity by providing payments to encourage investment in new capacity or for existing capacity to remain open [62,63]. CM participants can bid for contracts in auctions (called T-4 auction) held four years ahead of delivery date. Supplementary auctions (called T-1 auction) will be held a year ahead of delivery. T-1 auctions will allow bidders of demand-side response capacity to participate in Capacity Auctions. The auctions will follow a descending clock format, starting with offers for a specific price and gradually reducing until minimum price is reached, at which the supply of capacity offered by the bidders is equal to the volume required. If successful at auction, existing generators and demand-side responders will be offered one-year capacity agreements at clearing price. A completer delivery year starts on 1 October and ends on 30 September next year. In the delivery year, contract capacity must be available to grid from 16.00 to 19.00 every day. Providers are expected to be available to respond with their agreed generation volumes or load reductions when called on by National Grid at times of system stress, and its mechanism is shown in Fig. 7. National grid also provides some long-term contract for some particular occasions, such as a 15-year contract are available for new plants and three-year agreements are available for refurbished plants to encourage investment in new generation assets.

EPS came into force on February 18, 2014 under the Energy Act 2013 [60]. EPS is a regulatory limit on the amount of carbon emission from a fossil fuel plant, while carbon pricing and other incentives will encourage switching to cleaner forms of electricity generation. CPF was introduced in 2013 and aims to provide a stable and sufficiently high minimum carbon price to encourage investment in low carbon electricity generation in the UK [64].

### 4.3. Discussion

In the EMR, CfD encourages more RESs such as wind and solar. There are approximately 37% of electricity generated by RESs in UK in 2019 [14]. Different pots were established with different budgets to prioritise different types of renewable energy sources. UK government puts more money into pot two (offshore wind and biomass CHP) compared with pot one (such as onshore wind and solar) and three (biomass conversion). However, does an offshore wind and biomass CHP represent the future of renewable energy in the UK? Is it reasonable to pour more funds into above two technical class and ignore other types of renewable sources?

The objective of CM is to provide a reliable supply of electricity. To achieve the target, CM has brought back capacity market to the UK electricity market, a kind of market that was abandoned in the previous NETA/BETTA reform. EMR restructure the UK electricity market as shown in Fig. 8. The method of capacity stacking does ensure a reliable supply of electricity to consumers, but this will inevitably increase electricity bills of end consumers. CM is somewhat at odds with EMR's objective of providing affordable electricity. Moreover, CM requires parties to provide needed capacity consistently over contract years, which is a considerable challenge for renewable energy plants, as it is challenging to guarantee stable capacity in a given future year. In contrast, conventional fossil power plants are not affected by weather

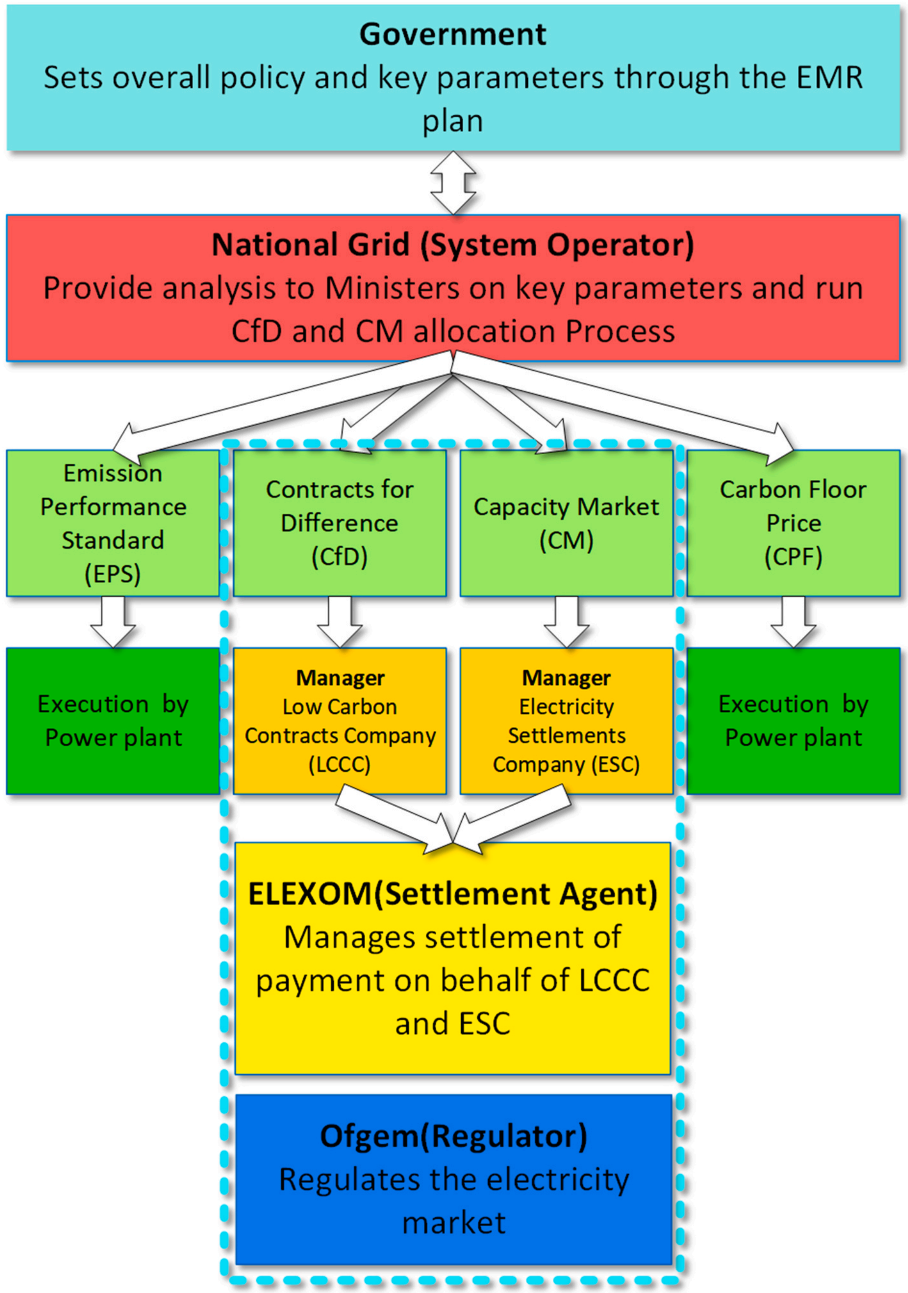


**Fig. 5.** The mechanism of EMR.

conditions and can guarantee capacity. CM has therefore been accused of not supporting RESs because traditional power plants are more competitive in bidding.

Moreover, CfD and CM both use long-term contracts (15 years or more) to provide stable electricity prices and encourage enough investment. However, the history of electricity market reforms in UK tells us that reforms have been increasingly frequent: the first reform (The Pool) last for ten years, the second reform for nine years, and the ongoing reform now are only for seven years. It is still debatable whether this long-term concordance of incentives will actually stimulate more RESs. Should the growth of RESs in the UK be attributed more to scientific and technological developments or government policies? The problems of the Big Six still exist, and since its inception, the Big Six has been actively involved in reform. Interestingly, the result of reform is that UK government will work with the Big Six to optimise the UK electricity market, rather than solving the problems of the Big Six. Finally, dominant participants in the market can gradually reduce their total cost by rebuilding power plants or retrofitting older units, which may make electricity market difficult for other new investors to survive.

## 5. Lessons-learned from three reform

In the Pool reform, electricity prices dropped as the electricity market joined the competition at the beginning, but after several years of development, the electricity price rose again. This change reveals the fact that no policy is perfect. In fact, any policy changes over time will have different effects. Therefore, policymakers need to be reminded that they should not try to solve problems once and for all through laws and regulations. At the beginning of the Pool reform, only the competition on the generation side is considered, and its specific form is that power buyers equally share the power auction expenses. This is because electricity consumers were homogenised in 1980s, so the NGC conducted

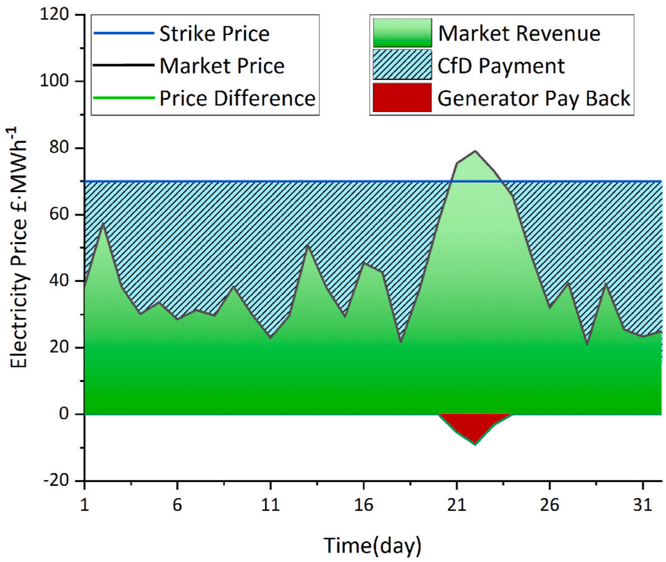


**Fig. 6.** The mechanism of CfD.

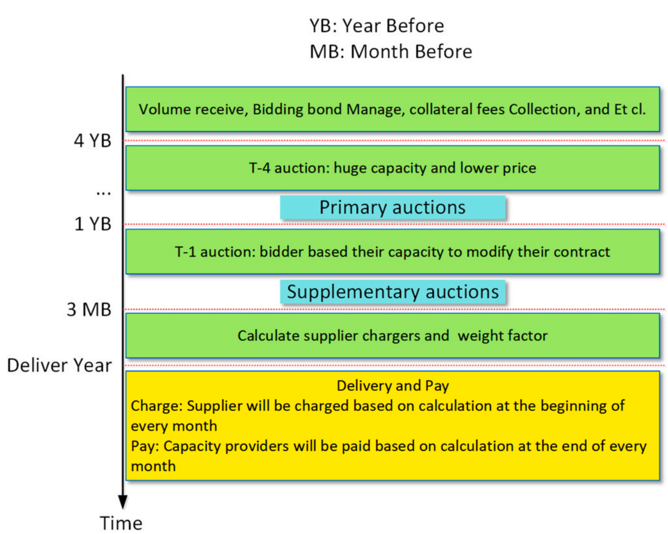


**Fig. 7.** Mechanism and key factors of the CM.

auctions on behalf of consumers. However, with the diversification of electricity demand, this auction method cannot truly reflect the supply and demand situation in the electricity market. Another experience that can be drawn from first reform is the mutual restriction of rights that should always be considered. Once an institution or organisation is both the maker of rules of game and the player of game, it is difficult to avoid the institution or organisation being able to participate in competition fairly. In the Pool reform, NGC members both participate in bidding and determine rules of auction, and there is no independent body to oversee the NGC.

NETA/BETTA, the second reform, uses bilateral contracts to introduce consumers (such as DNOs and large factories) to electricity market. The price of electricity therefore reflects the relationship between the generation and demand in the electricity market. The fundamental reason for this change is that the way of sharing electricity bills with consumers makes electricity prices dominated by generators. Consumers simply cannot enjoy reasonable electricity prices. Bilateral trading and commodity attributes are considered to be the greatest successes of NETA/BETTA. So it can be observed that the development of regulations and policies is not necessarily as innovative as technology in order to be successful. For the policy, it is more like a summary and reflection on past patterns. Advanced technology is forward-looking, and the forward-looking nature of regulations is sometimes dangerous. There is a need to be more cautious in the development of policy towards new technologies, and an extensive post-reform or cautious strategy may give more opportunities for more potential science and technology. NETA/BETTA also abolished the capacity market and converted the UK's electricity market into a pure energy market. The debate on capacity markets and energy markets has never ended. Capacity markets were initially designed to ensure that the system had sufficient spare capacity to generate electricity at any given time, while proponents of energy markets argue that a well-functioning energy market naturally has sufficient spare capacity. However, to author's knowledge, there is no example of a well-functioning electricity market that would justify the redundancy of a capacity market. As a basic source of energy to ensure livelihood of citizens, the power sector is necessary to ensure sufficient capacity reserves with capacity markets. The elimination of capacity market was therefore a major failure of the second reform. Supporting this conclusion is the fact that in the third reform the capacity market was reintroduced into the electricity sector. Balancing load and generation through the purchase and sale of electricity by market players in the electricity market gives electricity the attributes of a commodity, allowing it to be sold as an ordinary commodity. Interestingly, NETA/BETTA was also the period when "The Big Six" was formed, which means that NETA/BETTA facilitated the conditions. Policymaking may also need to consider factors beyond technology. The advancement of science and technology has promoted policy reform, but the designation of policies may also require more factors other than science and technology, such as game theory and consumer psychology.

In third reform, different types of renewable energy sources have been classified into different pots. However, the pot with offshore wind and biomass CHP has the most financial support. This means that offshore wind and biomass CHP will attract more capital, while other types of renewable energy sources will be put at a disadvantageous stage in the UK. Putting more money into the above two technology categories and ignoring rest kinds of renewable energy is one that should be carefully discussed. In EMR, the capacity market was reintroduced into electricity market, which was implemented to ensure the stability and reliability of the UK electricity system. The reintroduction of the capacity market has also aroused some controversy. Some scholars believe that the capacity market puts renewable energy sources at a disadvantage, as participants need to be able to provide the promised capacity at any time if participants want to bid in capacity market. However, electricity generation of renewable energy sources is unstable to a certain extent, relating to the installed capacity and environmental factors such as weather or wind speed. Capacity market is a typical policy compromise, with the Government choosing the former between stability of the power system and its low-carbon goals. Capacity market does not indicate Government is giving up on low-carbon target: CfD is designed to continue to support renewable energy sources. CfD uses long-term contracts to pre-lock the revenue during the contracted period to encourage adequate investment in terms of renewable energy sources. It can be seen that in the third reform, both the stability of power system and target of low carbon are taken into account.

The core of the reform of the UK electricity market is marketisation of electricity. The fundamental driving force for this reform is the development of electricity technology to enable electricity to form interconnection and flow between areas. Technological progress making electricity to be sold and bought freely in a market like a standard product is the key to reform of UK electricity market. Electricity has not been entirely a commodity until now, so the reform of UK electricity market is a brave attempt. British Government wants to create a market where electricity, an energy source that is not entirely a commodity, can be freely traded. Therefore, a more forgiving attitude is the key to encouraging Government continuous exploration as a pioneer. Another point worth discussing in the reform of UK electricity market is the issue of monopoly. Before the first reform, electricity sector was actually

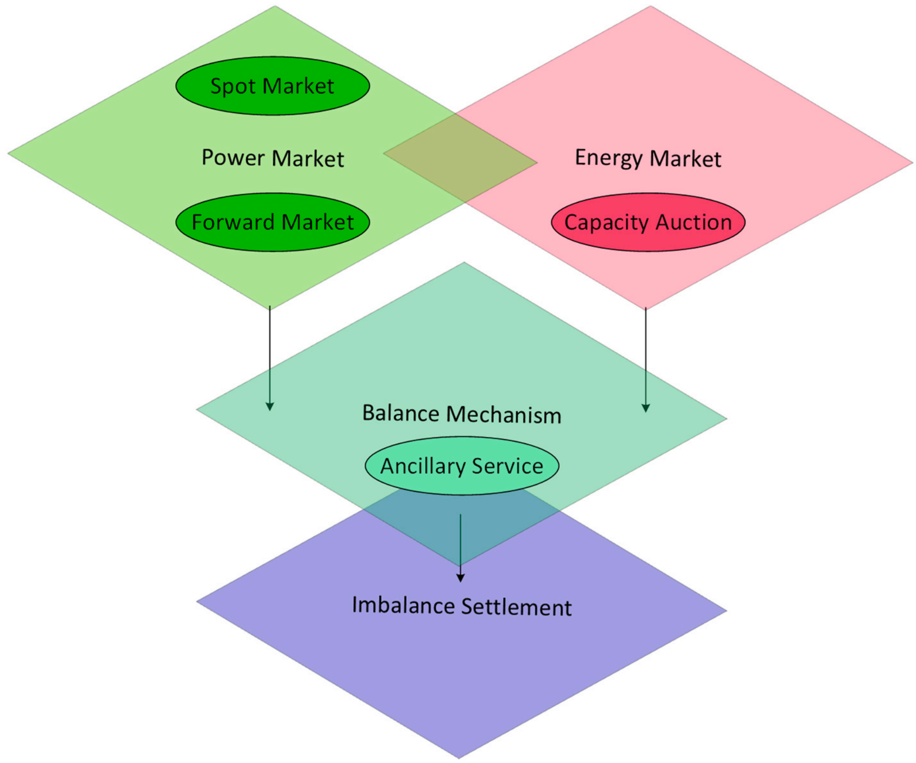


**Fig. 8.** EMR based UK electricity market.

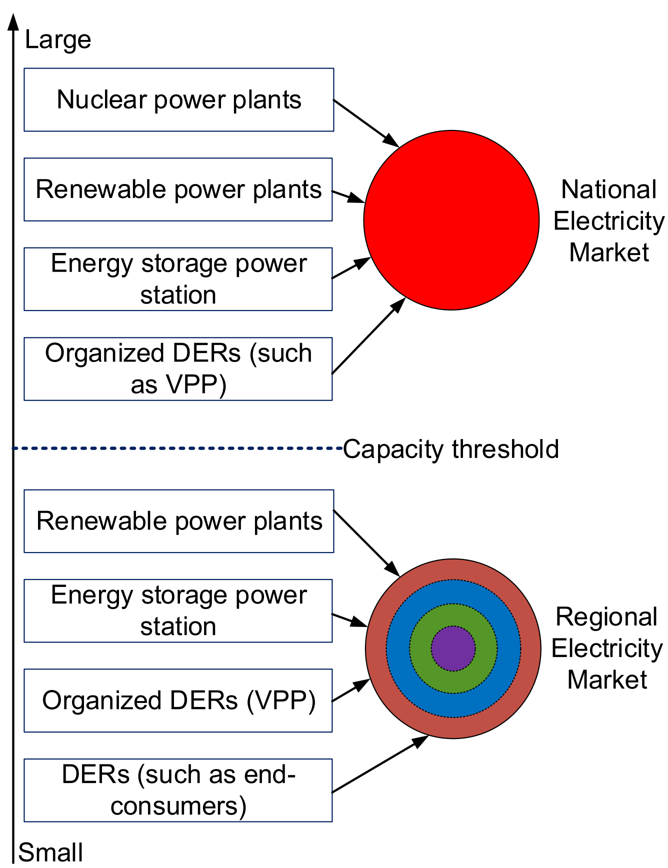


**Fig. 9.** The possible future of the UK electricity market.

dominated by the Government. The first reform introduces electricity market and bring capital in, while in second reform, a large amount of capital poured into electricity market forming the Big Six. The wealthier capitalists quickly occupied the electricity market with their advantages. The reasons for this phenomenon are the objective laws of capital market and the inappropriate design of the electricity market (potentially encourages entrepreneurs to merge to hedge risks). Therefore, both the nature of electricity and the characteristics of market should be considered during the electricity market design.

For current UK electricity market, it seems inevitable to change the established fact of monopoly, so the next reform should focus on regulating these monopoly enterprises in terms of their profits. Moreover, electricity was not considered storable in previous electricity market designs, which meant that electricity produced in real time had to be consumed in real time. The balance of power grid in current electricity market is to punish each generator, trader or consumption unit based on the difference between real-time electricity consumption/generation and purchase/sell. But with the rapid development of energy storage technology, electricity may be stored in large quantities in the near future. Through energy storage, intermediaries may compete to some extent with generating units. Therefore, the position of energy storage in future electricity market should be carefully considered. Appropriate application of energy storage can achieve positive results such as shaving peaks and filling valleys and stabilising electricity prices. Conversely, inappropriate use of energy storage may result in generation units not making a reasonable profit, even withdrawing from the market.

## 6. Challenges and trend of electricity market reform

The movement towards low-carbon energy has pushed transformation of generation and consumption, which imposes changes to power transmission, distribution, and system operation. The primary changes in generation include more power from intermittent RESs and smaller-scale distributed power generation connected to the grid.

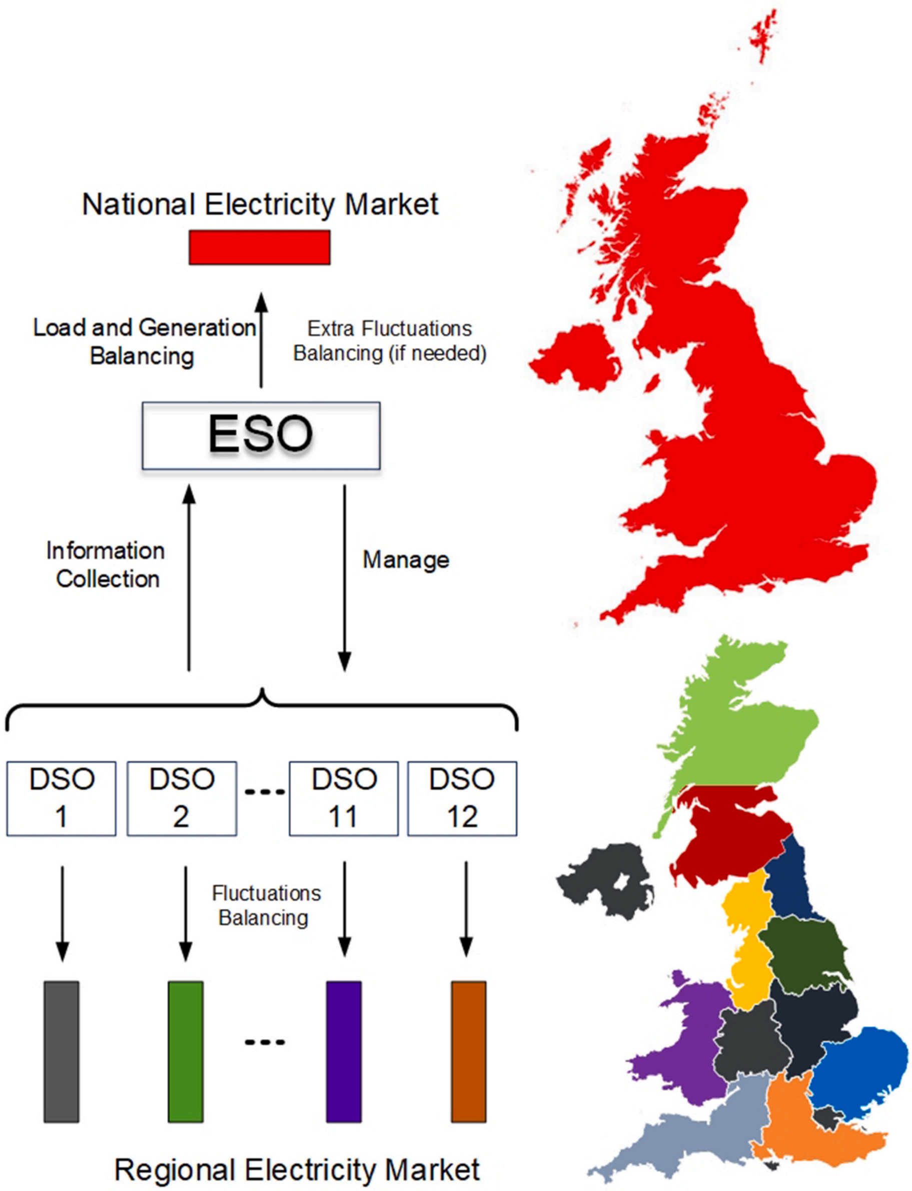


**Fig. 10.** The relationship between ESO, DSOs, national electricity market and regional electricity market.

Intermittence and unpredicted nature of renewable energy increase challenge of maintaining load balance and spin reserve reduction made grids have less network inertia. On the other hand, with the development of local generation, end consumers are becoming prosumers as they use and also generate electricity [65]. More and more end consumers will start using self-generated electricity to promote green agenda. This trend weakens the connection between grid and end consumers and challenges existing structure of power systems. Meanwhile, as the cost of ESSs drops, more ESSs will be installed on grid, which will make load demand more complex than before. Producers combined with ESS can flexibly change their energy usage patterns: they can freely dispatch their own electricity to a certain extent, so demand to grid without following their real consumption curve. Hence, the conventional way of load and generation forecasting and management is no longer suitable.

Another significant change anticipated is the electrification of road transportation and heating [66–68]. The electrification would increase electricity load massively in one aspect, and also presents an excellent opportunity for power systems to manage load and generation balance by regulating onboard ESS of electric vehicles and using thermal energy storage as a buffer to regulate electrical load.

It is inevitable for those conventional large-scale fossil fuel power plants to be replaced by relatively small-scale RES. National Grid estimated that up to 58% of all generations (around 136 GW) could potentially be decentralised by 2050, while it was only 29% in 2018 [69]. Decentralised generation, to some extent, drives for changes in power system management.

The future UK power system is expected to move towards to:

1) a few large-capacity centralised power plants (nuclear) mixed with many power generators from renewable energy sources;
2) bilateral power flow grid (mainly on distribution level);
3) growing number of prosumers;
4) a more efficient and better-serving power system based on AMI.

The current on-going change is to move DNO structure to DSO, which will independently operate the distribution network in their responsible areas and run a regional power market [21–26]. Participants for different mechanisms of electricity market are shown in Fig. 9. It will have large-scale power plants such as nuclear power plants and other

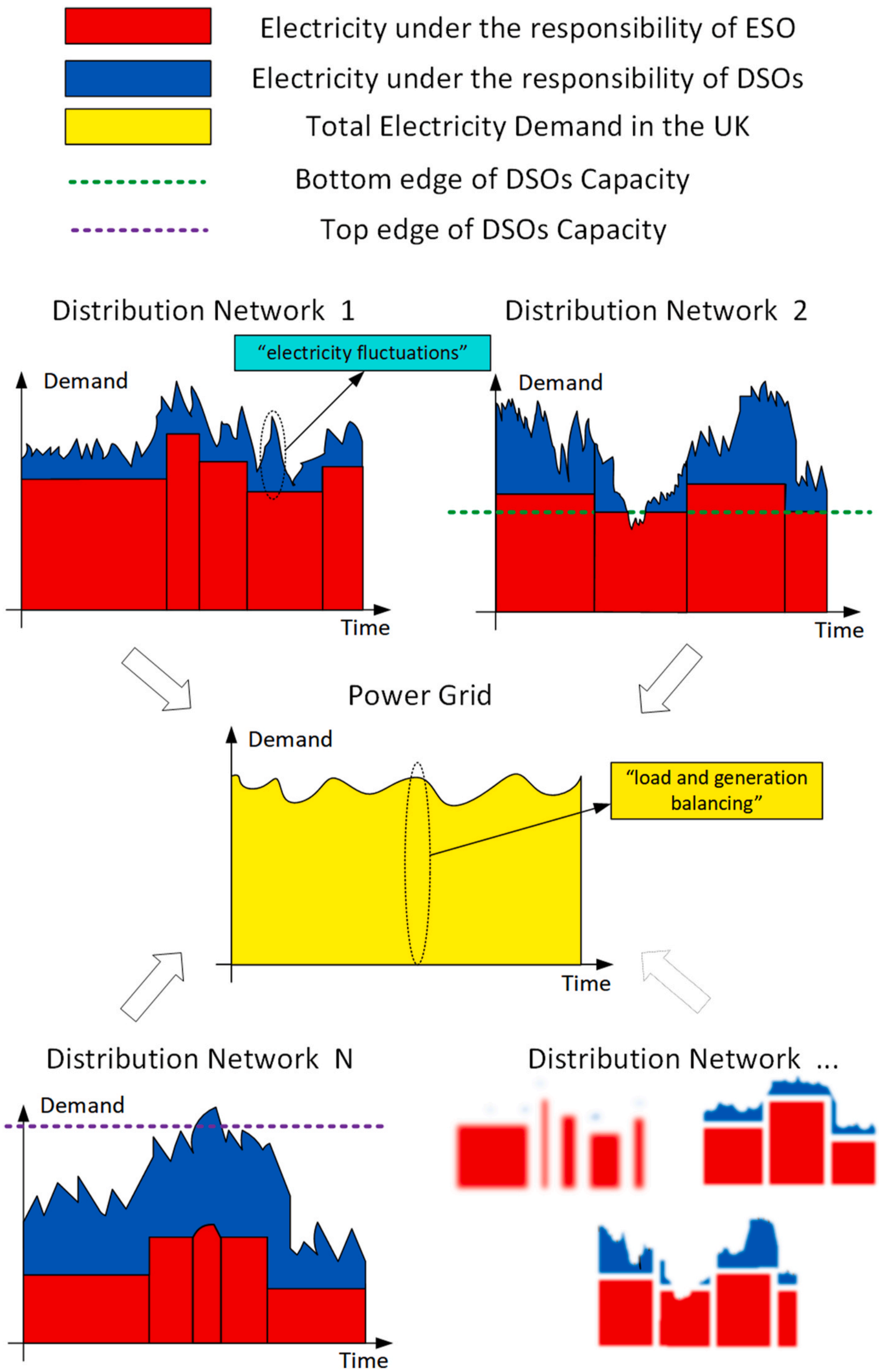


**Fig. 11.** Diagram of electricity management on grid level and distribution level.

organisations formed by integrated end-consumers with aggregated capacity over the threshold for electricity trading through national electricity market. Small-scale power generators (may be prosumers) and other organisations such as VPP can directly participate in regional electricity market. Nevertheless, all participants in regional electricity market should locate in their regions. Participants can enter any electricity market, but they can no longer compete in two electricity markets at the same time. The existing bilateral contracts should be adopted by all electricity trading to encourage competition.

The prosumers are encouraged to compete in regional electricity market by selling self-generated electricity or storing low price electricity to make profits. VPP is designed for end-consumers or organisations with limited production to compete in regional electricity market. If an electricity generation body is too small for trading through regional electricity market, it can be united via an aggregator or VPP system to be a part of a bigger trade unit. Through VPP systems or similar organisations, electricity market will not exclude any generators from the electricity market. Compared with integrated control of VPP, FPP is developed where participants are free to enter and quit. The relationship between ESO, DSOs, national electricity market and regional electricity market is shown in Fig. 10.

To more accurately distinguish the responsibilities of ESO and DSOs, the terms "electricity fluctuations" and "load and generation balancing" are used here. DSOs take responsibility for the balancing of regional electricity fluctuations and ESO takes responsibility for the balancing of load and generation as shown in Fig. 11. From Fig. 11, national electricity market operated by ESO should sell and purchase bulk electricity called national electricity (blue region). In contrast, regional electricity market would sell and purchase electricity called regional electricity (red region).

As illustrated in Fig. 11, if the fluctuation of demand exceeds the capacity of DSO, DSO would report this gap to ESO and ask for extra electricity to compensate for the gap. ESO is responsible for compensating the gap between load and generation that happened between distribution networks. The demand curve of grid constantly fluctuates as it is the sum of multiple basic demands from different DSOs, as shown in Fig. 11. Note that in a single region, the amount of transmitted national electricity may be greater or less than the amount of regional electricity. It depends on features of local distribution network, such as the number and capacity of DESs and fluctuating demand.

In summary, the responsibility of DSOs is [70–75]:

1) To conduct regional load and generation forecasting using the AMI data.
2) To meet the ripple of load forecasting (blue region in Fig. 11) curve and submit the net demand curve (Red region in Fig. 11) to ESO through regional electricity market. If demand exceeds the top or bottom edge of DSOs capacity (purple or green line in Fig. 11), this information should be forwarded to ESO through DSO.
3) To enable customers to be both producers and consumers.
4) To facilitate the optimal use of DERs on distribution networks to deliver security, sustainability, and affordability in support of whole system optimisation.

While the responsibility of ESO is [70–73,76–78]:

1) Based on information such as weather, temperature, and wind, electricity generated by renewable power plants should be predicted.
2) Based on the sum curve of predicted demand submitted by DSO and generation prediction, ESO plans reasonably the production of electricity between different power plants and power flow on the grid.
3) ESO is responsible for the ultimate balance between load and generation, in case of the gap between load and generation exceeds capability of DSOs.

DSO is an organisation that does not yet exist in the UK, but it is under experiment with some pilot projects [21–24]. DSOs must deal with flexible demand, and operate networks that can accommodate dispatchable resources like DR. They control networks capable of intelligently aggregating many different geographically dispersed inputs and complications. In this way, electricity market will be structured to have two levels: grid level and distribution network level. Large-scale power plants and large-scale energy storage power plants operate at the grid level, while the distributed and small-scale generation units and energy storage equipment operate at the distribution level. National electricity market can be developed from current electricity market. DERs are pretty similar to power plants and energy storage plants on a grid scale at distribution level. Therefore, the existing electricity market can also provide valuable experience and guidance for the future regional electricity market. Separating the large-scale power plant and DERs into two different electricity markets protects large-scale power plants from the low-price electricity generated DERs. It also protects DERs from a large capacity of large-scale power plants. More detailed algorithms between DSO and ESO are discussed in Refs. [79–82].

The main advantage of such a structure of electricity market is that regional electricity markets in different regions can formulate corresponding strategies according to features of their regions, such as encouraging different types of renewable energy. Participants can enter any electricity market as long as they meet requirements, which ensures the competitiveness of market. To maintain security, the grid needs to be kept active by ESO in case DSO fail to manage their networks. Tiered electricity market keeps grid active and enhances the stability of UK grid.

## 7. Concluding remarks

In this paper, the history and three reforms of the UK electricity market are discussed, which helps identify the critical elements required for further electricity market reform. The first reform of the Pool marks UK electricity industry privatisation and the establishment of UK Electricity Market. The second reform of NETA/BETTA uses bilateral contracts to replace complex trading mechanisms (the Pool), so capital can participate in all stages of electricity industry (generation, transmission, and supply). The third reform EMR uses CfD, CM, EPS, and CPF to encourage the growth of renewable energy and provides secure and affordable electricity to end consumers. Then the trend for future electricity market evolution is discussed with clarifying responsibilities of ESO and DSOs in transmission and distribution networks.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Acknowledgement

The authors would like to give their thanks to PENSO Power Ltd, the University of Warwick and Engineering and Physic Sciences Research Council, UK (EP/S032622/1, Supergen Storage Network Plus) for the funding support and the project of West Midlands Regional Energy System Operator (RESO) funded by Innovate UK.

## References

[1] Honglei W, Yiming W. An analysis of game of electricity trade in electricity power market. In: 2007 Chinese control conference; 2007. p. 133–7. Hunan.
[2] Fagiani R, Hakvoort R. Simulating the performance of market-based policies for renewable energy using learning trading agents. In: 11th international conference on the European energy market (EEM14); 2014. p. 1–5. Krakow.
[3] Lytvyn IV, Hewitt N. Barriers to increased electricity interconnection between neighboring markets. In: 2013 10th international conference on the European energy market (EEM); 2013. p. 1–8. Stockholm.
[4] Holburn G, Spiller P. Institutional or structural: lessons from international electricity sector reforms. In: The economics of contracts: theories and applications. Cambridge, UK: Cambridge University Press; 2002. 40pp.
[5] Danielsen A, Gupta N, Klein P. Contracts and the institutional environment for electricity reform. Electr J 1999;12(10):51–60.
[6] Woo C, Lloyd D, Tishler A. Electricity market reform failures: UK, Norway, Alberta and California. Energy Pol 2003;31(11):1103–15.
[7] Janjani A, Zareipour H. An overview of the operation of the Alberta electricity market. In: 23rd Canadian conference on electrical and computer engineering; 2010. p. 1–6. Calgary, AB.
[8] Chwalowski M. How companies fare through deregulation. Electr J 1997;10(1): 32–40.
[9] Joskow P. Lessons learned from electricity market liberalisation. Energy J 2008; 29m. Special Issue# 2.
[10] Coxe M. Competition perspective of electricity sector reforms an overview of electricity sector reforms. In: 2013 10th international conference on the European energy market (EEM); 2013. p. 1–8. Stockholm.
[11] Besant-Jones J, Vagliasindi M, Shumilkina E. Revisiting policy options on the market structure in the power sector. Washington, DC, USA: World Bank; 2011. p. 1–91. Tech. Rep.
[12] Edomah N. Modelling future electricity: Rethinking the organisational model of Nigeria's electricity sector. IEEE Access 2017;5:27074–80.
[13] Act CC. Climate change act 2008. GOV UK. 2008. https://www.legislation.gov.uk/ukpga/2008/27/contents/. [Accessed 3 September 2020]. accessed on.
[14] DBEIS. UK energy statistics, 2019 & Q4 2019. UK: Department for Business, Energy & Industrial Strategy; 2020. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/877047/Press_Notice_March_2020.pdf/. [Accessed 3 September 2020]. accessed on.
[15] Barton JP, Infield DG. Energy storage and its use with intermittent renewable energy. IEEE Trans Energy Convers 2004;19(2):441–8.

[16] Qin X, Su L, Jiang Y, Zhou Q, Chen J, Xu X, Chi Y, An N. Study on inertia support capability and its impact in large scale power grid with increasing penetration of renewable energy sources. In: 2018 international conference on power system technology (POWERCON); 2018. p. 1018–24. Guangzhou.
[17] Hossain M, Hossain MA. Future research directions for the wind turbine generator system. Renew Sustain Energy Rev 2015;49:481–9.
[18] ESO. Balancing data. National Grid ESO; 2020. https://www.nationalgrideso.com/balancing-data/. [Accessed 3 September 2020]. accessed on.
[19] Quilumba FL, Lee W, Huang H, Wang DY, Szabados RL. Using smart meter data to improve the accuracy of intraday load forecasting considering customer behavior similarities. IEEE Trans Smart Grid 2015;6(2):911–8.
[20] Barton J, Emmanuel-Yusuf D, Hall S, Johnson V. Distributing Power: a transition to a civic energy future. In: Realising transition pathways research consortium' engine room' report; 2015. Bath, UK, https://researchportal.bath.ac.uk/en/publications/distributing-power-a-transition-to-a-civic-energy-future/. [Accessed 3 September 2020]. accessed on.
[21] Clifton F. TRANSITION. Scottish and southern electricity networks. 2017. Electricity Network Innovation Competition Screening Submission Pro-forma, https://www.ssen.co.uk/SmarterElectricity/. [Accessed 3 September 2020]. accessed on.
[22] Sidebotham L. Customer-led distribution system. Northern powergrid NIA project registration and PEA document. 2017. https://www.northernpowergrid.com/innovation/projects/customer-led-distribution-system-nia-npg-19/. [Accessed 3 September 2020]. accessed on.
[23] WPD. Electricity flexibility and forecasting system in innovation to enable the DSO transition. Western power distribution. Available online: https://www.westernpower.co.uk/projects/effs/. [Accessed 3 September 2020]. accessed on.
[24] SP. FUSION. SP Distribution; 2018. https://www.spenergynetworks.co.uk/pages/fusion.aspx/. [Accessed 3 September 2020]. accessed on.
[25] Migliavacca G, Rossi M, Six D, Džamarija M, Horsmanheimo S, Madina C, Kockar V, Moraleset JM. SmartNet: H2020 project analysing TSO–DSO interaction to enable ancillary services provision from distribution networks. CIRED - Open Access Proc J 2017;1:1998–2002.
[26] Hadush SY, Leonardo M. DSO-TSO cooperation issues and solutions for distribution grid congestion management. Energy Pol 2018;120:610–21.
[27] Bakari KE, Kling WL. Virtual power plants: an answer to increasing distributed generation. In: 2010 IEEE PES innovative smart grid technologies conference europe (ISGT europe); 2010. p. 1–6. Gothenberg.
[28] Morstyn T, Farrell N, Darby SJ, McCulloch MD. Using peer-to-peer energy-trading platforms to incentivise prosumers to form federated power plants. Nat Energy 2018;3(2):94–101.
[29] Carmichael R. Behaviour change, public engagement and net zero. A report for the committee on climate change. 2019. https://www.theccc.org.uk/wp-content/uploads/2019/10/Behaviour-change-public-engagement-and-Net-Zero-Imperial-College-London.pdf/. [Accessed 3 September 2020]. accessed on.
[30] Coxe M. Competition perspective of electricity sector reforms an overview of electricity sector reforms. In: 10th international conference on the European energy market (EEM); 2013. p. 1–8. Stockholm.
[31] Hannah L. Electricity before nationalisation. AG, Switzerland: Springer; 1979. p. 466.
[32] Sheail J. Power in trust: the environmental history of the central electricity generating board. Oxford, UK: Oxford Clarendon Press, Great Clarendon Street; 1991.
[33] Grubb M, Newbery D. UK electricity market reform and the energy transition: emerging lessons. Energy J 2018;39(6):1–24.
[34] Page J. Changing environmental perspectives in the electricity industry. In: IEE colloquium on electricity privatisation - opportunities and constraints; 1993. London, UK, pp. 10/1-10/4.
[35] Lin J, Magnago F. Electricity markets: theories and applications. River Street Hoboken, NJ, USA: John Wiley & Sons; 2017. p. 332.
[36] Simmonds G. Regulation of the UK electricity industry. Bath, UK: School of Management, University of Bath, Claverton Down; 2002. p. 136.
[37] Aijuan W, Ramsay B. The power pool, a competitive electricity market in the UK. Power System Technology - Beijing; 1997. p. 47–51.
[38] Newbery MD. Pool reform and competition in electricity. Cambridge, UK: Department of Applied Economics, University of Cambridge, New Museums Site; 199734pp.
[39] Ruusunen J, Ehtamo H, Hamalainen RP. Dynamic cooperative electricity exchange in a power pool. IEEE Trans Syst Man Cybern 1991;21(4):758–66.
[40] Dettmer R. The UK electricity pool-a leap in the dark? IEE Rev 1991;37(9):309–12.
[41] Caramanis MC, Bohn RE, Schweppe FC. System security control and optimal pricing of electricity. Int J Electr Power Energy Syst 1987;9(4):217–24.
[42] Aijuan W, Ramsay B. The power pool, a competitive electricity market in the UK. Power System Technology-Beijing; 1997. p. 47–51.
[43] Newbery DM. Power markets and market power. Energy J 1995;16(3):39–66.
[44] Dettmer R. Living with NETA [new electricity trading Arrangements]. IEE Rev 2002;48:32–6.
[45] Scott J. Elucidating RETA (reform of electricity trading arrangement) (panel on evolution of electricity market structures). In: 1999 IEEE power engineering society summer meeting. Conference proceedings (Cat. No.99CH36364), vol. 2; 1999. p. 756–9. Edmonton, Alta., Canada.
[46] Lipp J. Policy considerations for a sprouting UK green electricity market. Renew Energy 2001;24(1):31–44.
[47] Xing W, Song YH, Guiguang X. The balancing mechanism of the new electricity trading arrangement in UK. Autom Electr Power Syst 2000;12.
[48] Elexon L. Profiles and their use in electricity settlement (November 2013). ELEXON L; 2013. https://www.elexon.co.uk/documents/training-guidance/bsc-guidance-notes/load-profiles/. [Accessed 3 September 2020]. accessed on.
[49] Pettigrew J. Trading in ancillary services (Ref. No. 2000/038), London, UK. In: IEE seminar on electricity trading; 2000. 3/1-3/6.
[50] Wang X, Song Y, Wang X. Operation experiences of the UK new electricity trading arrangement. Electr power 2003;36(6):1–5.
[51] HoC. Utilities act 2000. House of Commons UK; 2000. https://www.legislation.gov.uk/ukpga/2000/27/contents/. [Accessed 3 September 2020]. accessed on.
[52] Dyer JR, Williams TG, Dunnett RM. Economic dispatch advice for the NETA balancing mechanism. In: Proceedings of international conference on power system management and control; 2002. p. 1–6. London, UK.
[53] BIS. Annual innovation report 2012: innovation, research and growth. Department for Business, Innovation & Skills; 2012. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/34805/12-p188-annual-innovation-report-2012.pdf/. [Accessed 3 September 2020]. accessed on.
[54] Ofgem. Electricity supply market shares by company: domestic (GB). Ofgem UK; 2020. https://www.ofgem.gov.uk/data-portal/electricity-supply-market-shares-company-domestic-gb/. [Accessed 3 September 2020]. accessed on.
[55] Statista. Average annual domestic electricity bill in the United Kingdom (UK) from 2007 to 2019. Statista; 2020. https://www.statista.com/statistics/496661/average-annual-electricity-bill-uk/. [Accessed 3 September 2020]. accessed on.
[56] Grid N. Future energy scenarios. NG UK future energy scenarios. National Grid, https://investors.nationalgrid.com/~/media/Files/N/National-Grid-IR-V2/reports/2016-17/fes-2017-final.pdf/. [Accessed 3 September 2020]. accessed on.
[57] Grid N. Project Discovery seminar – scenarios. National Grid, https://www.ofgem.gov.uk/publications-and-updates/project-discovery-energy-market-scenarios%20/. [Accessed 3 September 2020]. accessed on.
[58] DECC. UK.. Delivering UK energy investment. Department of Energy & Climate Change; 2014. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/331071/DECC_Energy_Investment_Report.pdf/. [Accessed 3 September 2020]. accessed on.
[59] Nreap UK. National renewable energy action plan for the United Kingdom: article 4 of the renewable energy directive 2009/28/EC. UK government. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/47871/25-nat-ren-energy-action-plan.pdf/. [Accessed 3 September 2020]. accessed on.
[60] DECC, UK. Planning our electric future: a white paper for secure, affordable and low-carbon electricity. Department of Energy and Climate Change; 2011. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/48129/2176-emr-white-paper.pdf/. [Accessed 3 September 2020]. accessed on.
[61] May T. Machinery of government changes: written statement. HCWS94. https://www.parliament.uk/business/publications/written-questions-answers-statements/written-statement/Commons/2016-07-18/HCWS94/. [Accessed 3 September 2020]. accessed on.
[62] BIES, UK. Electricity market reform: contracts for difference. Department for Business, Energy & Industrial Strategy; 2015. https://www.gov.uk/government/collections/electricity-market-reform-contracts-for-difference/. [Accessed 3 September 2020]. accessed on.
[63] Yiakoumi D, Rouaix A. Understanding the new capacity market implemented in the UK. University of Aberdeen, Discussion paper; 2016. p. 16.
[64] Ares E, White E, Danby G, Hough D. Energy policy overview. House of Commons; 2016. https://commonslibrary.parliament.uk/research-briefings/cbp-7582/. [Accessed 3 September 2020]. accessed on.
[65] Parag Y, Sovacool KB. Electricity market design for the prosumer era. Nat Energy 2016;1(4):1–6.
[66] Verdicchio A, Ladoux P, Caron H, Sanchez S. Future DC Railway electrification system - go for 9 kV. In: 2018 IEEE international conference on electrical systems for aircraft, railway, ship propulsion and road vehicles & international transportation electrification conference. Nottingham: ESARS-ITEC); 2018. p. 1–5.
[67] Rull-Duran J, Bergas-Jane J, Galceran-Arellano S, Sumper A, Coves-Moreno J. Power electronics improving 3-Wire DC railways electrification. In: 2009 13th European conference on power electronics and applications. Barcelona; 2009. p. 1–7.
[68] Mousavi Gazafrudi SM, Tabakhpour Langerudy A, Fuchs EF, Al-Haddad K. Power quality issues in railway electrification: a comprehensive perspective. IEEE Trans Ind Electron 2015;62(5):3081–90.
[69] Ng UK. Future energy scenarios. National Grid UK; 2019. https://www.nationalgrideso.com/sites/eso/files/documents/fes-2019.pdf%20/. [Accessed 3 September 2020]. accessed on.
[70] Vicente-Pastor A, Nieto-Martin J, Bunn DW, Laur A. Evaluation of flexibility markets for retailer–DSO–TSO coordination. IEEE Trans Power Syst 2019;34(3):2003–12.
[71] Silva J, Sumaili J, Bessa RJ, Seca L, Matos MA, Miranda V, Caujolle M, Goncer B, Viana MS. Estimating the active and reactive power flexibility area at the TSO-DSO interface. IEEE Trans Power Syst 2018;33(5):4741–50.
[72] Edmunds C, Galloway S, Elders I, Bukhsh W, Telford R. Design of a DSO-TSO balancing market coordination scheme for decentralised energy. IET Gener, Transm Distrib 2020;14(5):707–18.
[73] Almeida P, Kane L, Collins M, Breaden C, Davidson E, Ault G. Implementing optimisation functionality on network management platforms for new DSO business models. CIRED - Open Access Proc J 2017;1:2779–82.
[74] Alkandari A, Sami AA, Sami A. Proposed DSO ancillary service processes considering smart grid requirements. CIRED - Open Access Proc J 2017;1:2846–7.

[75] Fonseca J, Verdelho MI, Prata R. Impact for the DSO of integrating storage systems in a low-voltage grid with distributed energy resources. CIRED - Open Access Proc J 2017;1:1795–9.
[76] Wen Y, Chung CY, Liu X. Hierarchical interactive risk hedging of multi-TSO power systems. IEEE Trans Power Syst 2018;33(3):2962–74.
[77] Olmos L, Perez-Arriaga IJ. Evaluation of three methods proposed for the computation of inter-TSO payments in the internal electricity market of the European union. IEEE Trans Power Syst 2007;22(4):1507–22.
[78] Zotti GD, Pourmousavi SA, Morales JM, Madsen H, Poulsen NK. Consumers' flexibility estimation at the TSO level for balancing services. IEEE Trans Power Syst 2018;34(3):1918–30.
[79] Contreras DA, Rudion K. Time-based aggregation of flexibility at the TSO-DSO interconnection point. In: 2019 IEEE power & energy society general meeting (PESGM); 2019. p. 1–5. Atlanta, GA, USA.
[80] Radi M, Taylor G, Uslar M, Köhlke J, Suljanovic N. Bidirectional power and data flow via enhanced portal based TSO-DSO coordination. In: 2019 54th international universities power engineering conference (UPEC); 2019. p. 1–5. Bucharest, Romania.
[81] Reinders J, Morren J, Slootweg H. Comparing probabilistic load flow methods in dealing with uncertainties at TSO/DSO interface. In: 2017 52nd international universities power engineering conference (UPEC); 2017. p. 1–5. Heraklion.
[82] Suljanović N, Souvent A, Taylor G, Radi M, Cantenot J, Lambert E, Morais H. Design of interoperable communication architecture for TSO-DSO data exchange. In: 2019 IEEE Milan PowerTech; 2019. p. 1–6. Milan, Italy.