# Development of Distributed Energy Market
# (Alternative Format Thesis)

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# Development of Distributed Energy Market

# — Structure, Models and Stakeholders


By

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# Contents

# Abstract

The introduction of decarbonization policies drives the transition of the Great Britain (GB) energy system in both the demand and the supply side, to step into the future of decarbonization, decentralization and digitalization. The appropriate distributed energy market offers consumers the access to the low-cost energies and mobilize the value of flexibility resources in the meantime, transferring end-users from the passive energy receivers to the future active energy market participants.

Preliminary solutions are offered towards the shortages of existing markets, including limited numbers and initiative of market participants, the lack of markets targeting on demand-supply balance, and the undefined responsibilities of regulation institutions.. The innovation and contribution of this research include:

The innovation and contribution of this research include:

- Proposed a multi-layer architecture of distribution-level electricity market, which could illustrate the entire tradable services under the forms of markets. The structure of electricity supply chain and the key information could be represented visually, being convenient to track and explore the distribution-level market transformation tendency.
- Proposed market assessment criteria from the perspectives of economy efficiency and society feasibility. The typical trading methods applied in the wholesale electricity market are assessed under the proposed criteria, offering market feasibility under the future distributed energy communities.
- Proposed a pay-as-clear market settlement which could increase clearing quantity and invest reliability to the system. The published model possesses higher market liquidity and lower market manipulation under the massive introduction of renewable energy resources, with the advantages in risk, simplicity and feasibility
- Proposed automatic trading peer-to-peer market design serving flexible resources transaction, applying a dynamic pricing strategy to provide more sufficient price signals. The market segmentation is explored during the evolution of future energy scenarios. The segmented market gains priority in market value, with the slight advantages in liquidity and preventing manipulation.
- Proposed the development stages of distribution-level electricity market, and explored the roles and functions of DSO under this transition pathway. The diverse engagement levels of DSO is explored, with the responsibility allocation and collaboration between DSO and other regulation institutes.

This work can help policymakers to settle rational rules and regulations of market transactions and operation facing penetrating renewable energy resources and distributed energy resources, further allocating roles and functions of distribution system operators. The market design which could mobilize market value quantitively and quantificationally is explored, with the consideration of boosting the motivation of market participants.

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Last but not least, I must express my love to my parents, without their endless support and encouragement I cannot come so far in this long way.

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# List of Abbreviations

| | |
|---|---|
| EV | Electric vehicle |
| DNO | Distribution network operator |
| DSO | Distribution system operator |
| TSO | Transmission system operator |
| UKPN | UK Power Network |
| WPD | Western Power Distribution |
| Cornwall LEM | Cornwall Local Energy Market |
| FU | Flexible unit |
| FP | Flexibility provider |
| DER | Distributed energy resource |
| DPS | Dynamic purchasing system |
| ITT | Invitation to tender |
| DP | Delivery performance |
| PF | Performance factor |
| BRP | Balance responsible party |
| LFM | Local flexibility market |
| ICT | Information and Communication Technology |
| LP | Linear programming |
| NLP | Neuro-Linguistic programming |
| MILP | Mixed-integer nonlinear programming |
| QP | Quadratic programming |
| MIQP | Mixed-integer quadratic programming |
| KKT | Karush-Kuhn-Tucker |
| GA | Genetic Algorithm |
| DE | Differential evolution |
| SA | Simulated annealing |
| ABC | Artificial bee colony |
| TLBO | Teaching learning-based optimization |

| | |
|---|---|
| PV | Photovoltaics |
| P2P | Peer to peer |
| OCD | Optimality condition decomposition |
| SGAM | Smart grid architecture model |
| NEM | National electricity market |
| EHV | Extreme high voltage |
| HV | High voltage |
| LV | Low voltage |
| IEA | International Energy Agency |
| HHI | Herfindahl-Hirschman index |
| OCT | Over the counter |
| FES | Future Energy Scenario |
| FL | Flexible Load |
| TSL | Time-shiftable Load |
| PSL | Power-shiftable Load |
| OSL | Overall-shiftable Load |
| ENA | Energy Network Association |
| ESO | Electricity System Operator |
| BEIS | Department of business, energy & industrial strategy |

# Chapter 1

# Introduction

# 1.1 Overview

## 1.1.1 Changing landscape of energy resources and electricity system

The ambitious climate change target is proposed by the U.K. Committed by the UK Climate Change Act, the net UK carbon account for the year 2050 is at least 100% lower than the 1990 baseline. The profound changes are undergone in both the demand side and the supply side of the UK energy system. From the supply-side perspective, more renewable energies would participate the system. From the demand-side perspective, more electric power is required to satisfy the demand from transport and heating [1-3] . The introduction of unpredictable and uncontrollable renewable energies would present challenges to manage intermittency, also bring new opportunities to new markets and business models particularly for utilizing flexibility [3-5]. The flexible resources which could coordinate with appropriate market mechanism could both reduce electricity bills and support decarbonization [6, 7]. A sufficient flexibility market could acquire the lowest-cost solutions while respecting the technology limits of market participants and network limits [8]. According to the estimation of Imperial College, the net income brought by a better utilization of flexible resources would achieve 14-24 hundred million pounds annually by 2030 [9, 10]. The figure provided by Committee on Climate Change is 3-38 hundred million pounds, and that coming from Committee on National infrastructure is 2.9-81 hundred million pounds [9, 11, 12]. A sufficient platform for flexibilities is crucial and immediacy because of the considerable economic benefits.

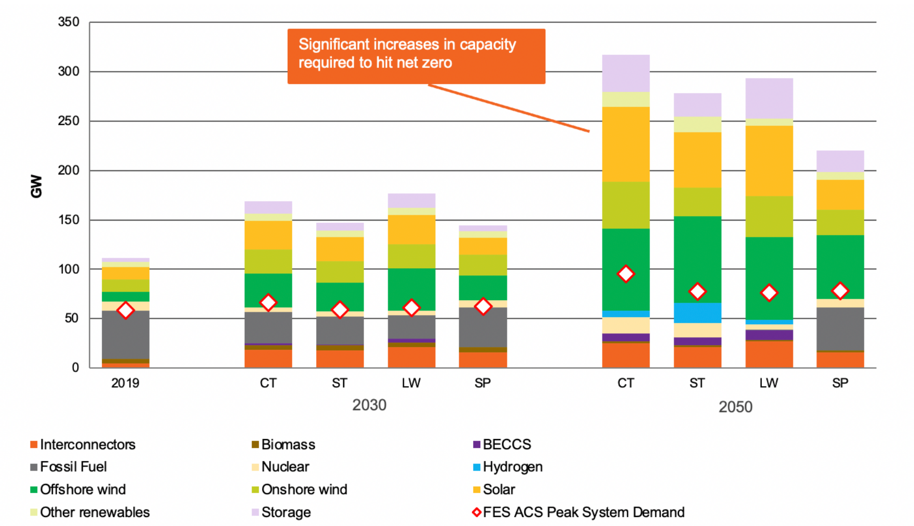



Figure 1- 1 Projected electricity supply in 2019, 2030 and 2050 [13]

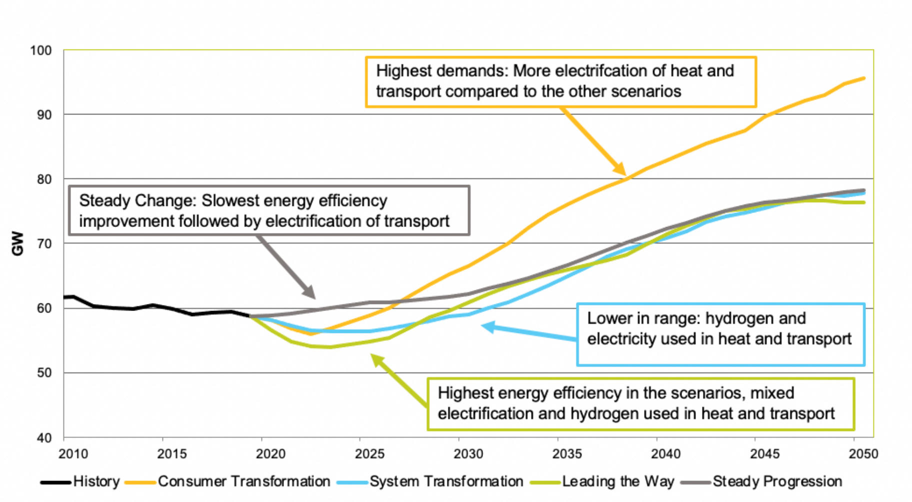



Figure 1- 2 Projected electricity peak demand [13]

### 1.1.2 Important roles of distributed energy resources in the electricity system

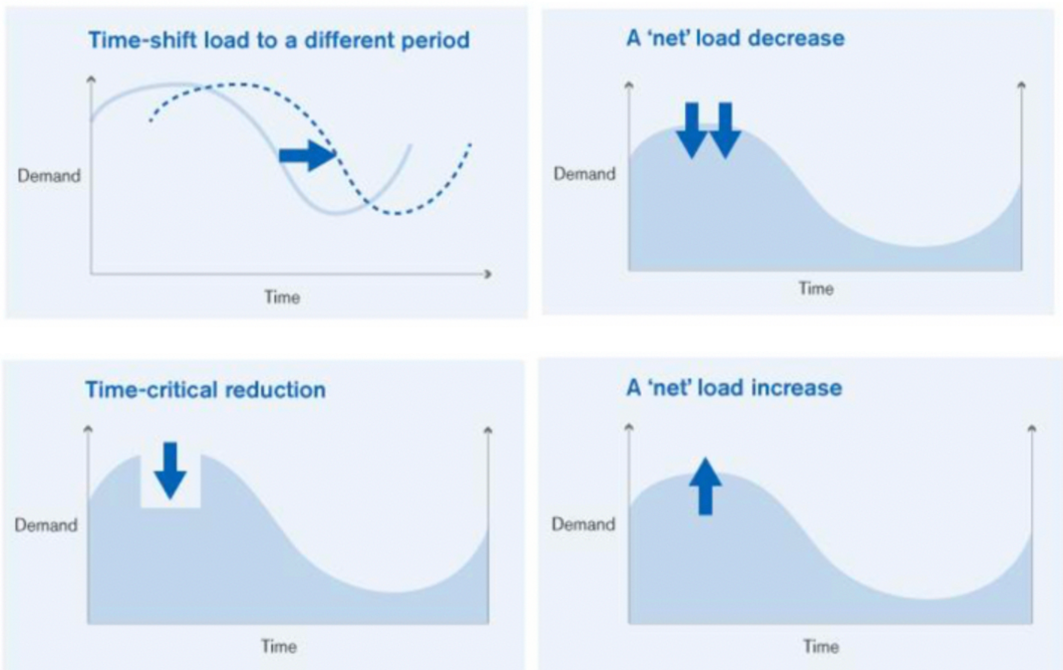
The definition of flexibility is that the mode of power generation and consumption that can be changed according to the external signals such as price changes to provide services and promote the possibility of diverse services [3]. The current major source of flexibilities in the market are the generations from the supply-side, and the demand-side flexibilities would increase with the coming services like demand-side responses. The distributed energy resources contribute massive flexibility to the system. The participants of multiple links in the energy supply chain would proceed with flexibility service procurement to complete management and operation.

Based on the passive network, the traditional network design aims at satisfying peak demand with the minimal intervention of a specific level of redundancy. However, the demands of system and consumers would change facing the carbon emission target and the projected increasing total electricity demand [6, 14, 15]. The introduction of renewable energy resources and distributed energy resources would bring excess generation, generation inadequacy and network congestion to the system. Due to the volatility and intermittent nature of renewable energy sources, there is often insufficient power generation within a certain period of time to meet the load demand. However, The excess generation would occur when simply constructing power plants to satisfy the intermittency of the renewable energies, leading to over-generation in most of the day and long periods of the year [4, 16], further causing network congestion.

Considering of the efficiency and sustainability, the traditional network reinforcement and power plant investment possess tremendous cost and are not economically applicable.

Some low-carbon generators may be restricted for use if the consumption is not modified to a mode that the energy could only be used or stored in the specific available times. Similarly, the connection of renewable energies to the network is also confined without adequate network capacity [17]. The flexibility market is thus required by the supply and demand sides to respond to the consumers' requirements and provide flexible and affordable electricity systems. A more efficient system is expected to benefit all customers. The core drivers of flexibility procurement are to delay network reinforcement and defer asset investments so to avoid asset overloading and investment redundancy [9, 15, 16, 18].

To summarise, network capacity increase could be provided by the flexibilities, so as to better reflect the annual demands of users. The flexibilities could manage the under-capacities in economy efficient ways until the conventional reinforcements are sure to be needed. The long-term investment plans could be launched under the assists of long-period flexibilities. The flexibilities in the system could be realized via: 1. Consumption shifting to diverse time periods 2. Demand reduction in specific times 3. Consumption increases in necessary periods. How flexibility contributes to the power system is shown in figure 1-3 [4].



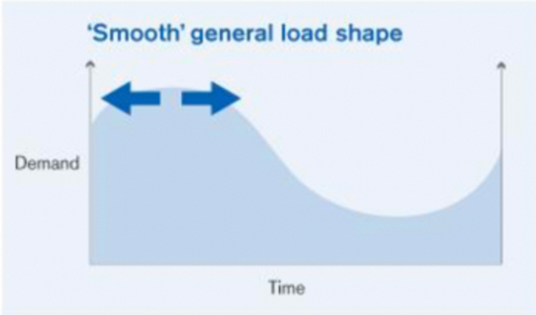



Figure 1- 3 Flexibility helps to manage the electricity system

Those flexibilities could reduce the need for expensive and carbon-intensive variable load plants, which the cheaper and prompter connections could realize through reinforcement deferral and circumvent. The more effective solutions to network issues could also decline network costs. An efficient and sustainable generation portfolio is expected in both the transmission and local levels in the future electricity system, with the deployment of increased demand-side responses. Consumers should be capable to change their consumption patterns responding to market signals and saving bills. New business models operating flexibilities are expected, being easy to provide more sufficient flexibilities.

There are values from three perspectives for flexibility resources, including the time-specific value, the time-coupling operational characteristic value and the location-specific value.

***Time-specific value***

System operators are the largest percentage contractors of balancing services, whose prices are settled by cost forecasting and are fixed months to years in advance [8]. However, the economic value of flexibility services (for example frequency responses) largely depends on system conditions including demand levels, renewable energy outputs and system inertia. Those conditions change in faster timescales compared to the foreseen time periods. The inefficiency in prediction would lead to over-purchasing or under-purchasing, leading to negative impacts on costs. Thus, those services are expected to be procured in faster timescale to better reflect the time-specific value of flexibilities in the system. The dynamic price singles could incentive the availability of flexibilities in demanding times [19, 20].

***Time-coupling operation value***

Demand-side responses and the storages are two typical resources possessing time-coupling operation value. Being fundamentally different to the participants of traditional energy markets, the two resources are equipped with fixed energy constraints, load recovery effects and storage losses. The complex and time-coupling operational attributes integrated the requirements for providing balanced services towards platforms across diverse timescales, which is a characteristic that should be included in the market design [21]. The costs are difficult to fairly reflect by the market if the feature is ignored in energy and balancing segmented markets.

***Location-specific value***

The generation and demand conditions are different in diverse regions, so the location parameter is more and more crucial for energy services. The locational marginal price is introduced to capture the location-specific value of market to allocate network expenses correctly to the parties being in charge of network reinforcement [21]. The adequate reward could gain through the reinforcement deferral and network cost reduction brought by flexibilities [22-26].

## 1.2 Research motivation

The penetration of renewable energies and distributed energy resources are also the drivers of this energy revolution from the resource and technology perspective, that more flexibilities are introduced to the energy system. To adapt the resources effectively and to apply them widespread, the construction of distribution-level markets is always under consideration. There have been network-related local market trials launched in the U.K. which are stably operating for a long time and cover a wide range of regions, settling network issues (such as congestion management and network deferral) through flexibility services. However, there is no mature local energy market dealing with the energy supply-demand balance. This is also the major direction of this research.

### 1.2.1 Market demand analysis from the top-down

The demand towards renewable energies and distributed energy resources could be considered from two perspectives. The needs of the local energy market are analyzed from the perspectives of resource and policy transitions when discussed from the top-down to bottom-up. Globally speaking, the energy system is transferring from the fossil-based centralized generation structure to a renewable-based decentralized one [27-30] . The power delivers from high-rating generators to consumers remotely in the conventional power delivery. The future energy is under a scenario of high infiltration of renewable energies and distributed energy resources. The intermittent energy resources make it possible for prosumers to store, shift and resell their surplus [30-33]. However, a great attention is arisen around the criticism towards the current electricity system as it has leaks in costs, environmental impacts, transmission losses and security flaws facing the introduction of new energies [34, 35]. The energy system is also under the decentralized tendency that the continuous development of both renewable energy technologies and the communication infrastructures at the distribution system level speeds up the system decentralization progress [30, 34, 35]. The local energy market is thus required to serve the transaction of those bilateral energy resources, developing from the markets dealing with network issues only to the ones that guarantee energy demand-supply balance [28, 36, 37].

### 1.2.2 Market Demand Analysis from the Bottom-up

Speaking from the bottom-level to the top-level, that the needs of the local energy market are discussed from the perspective of market participants' consciousness. The original consumers in the energy market are transferring to the prosumers in the local electricity market, who could not only purchase electricity but also sell energies through the market. The small-scale individual suppliers and the renewable energy generators, who are excluded from the current mainstream market, are emerging and participating local energy market, calling it the end of the energy monopoly [38]. Being public utilities, the grid companies are becoming consumer-oriented, while the energy retailers are realizing the self-consciousness awakening of the end-users. On the one hand, the consumers are aware of their expectations towards affordable, clean and reliable energies. On the other hand, the consumers holding more options of retail energy resources are willing to penetrate the energy transactions [38]. The owners of DERs expect the controllability of their assets, including the liberty of electricity generation and the compensation for their services provided to the utility grid [38]. Expecting to gain monetary incentives by load control, prosumers are chasing the win-win results entering local energy markets. Even the prosumers who are not DER holders are gradually becoming interested to the power sources and electricity market participation [39]. The technology development also accelerates the same trend, that the conventional electricity power loads are transforming to the initiative and flexible loads with the development of technology like ICT and smart meters [30, 40, 41]. The prosumers' understanding of the electricity is stimulated through the management, consumption, production, and storage progresses, rising up the appeals towards local energy markets.

### 1.2.3 Requirements towards Local Energy Market Restructing

Based on the demand analysis towards the local energy market from double views above, the electricity market restructuring is inevitable based on the principle of decentralized management and coordination to procure the capability of prosumers. The energy interchange has proceeded in the decentralized market environment under the new market structure. With the prosumers being new participants of the market, the conventional electricity market is transferring to the customer-oriented electricity market. The energies could be managed and traded locally through the platform. A bulk of fluctuant RES could be concentrated upon local energy market platforms, offering more effective incentives compared to the current centralized energy market [34, 42]. The local energy market could construct a local energy balance, making it possible for the localized energy and flexibility interchange. A more balanced energy delivery system could be brought by the local equilibrium distribution, declining the transmission congestions further to the cutting down of renewable energies [9]. The close-to-real-time supply and demand balance is aimed to be constructed by the local energy market. The multi-LEM system could achieve the self-sufficiency of flexibility resourcing, reducing the renewable energy redispatch and delivery in long run [10]. The design of local energy market thus should give consideration to flexibility encouragement, reduce residual demand for peak power, mobilize local energy balance and reduce energy supply costs. The necessity of elextricity market restructure is thus highlighted. On the one hand, the energy transaction are developing from the main current centralized participation to the P2P trading on local platorms. On the other hand, dynamic flexibility cost reflection and market participants' motivation mobilization are expected to be achieved in the developed market structure.

The successful local energy market in the real world is very limited, due to the challenges faced by market taken P2P trading method including technological complexity, fundamental infrastructural availability, detailed market design, user behaviours and acceptance, data privacy, potential business models and regulatory barriers [27]. One shortage of the implemented LEM projects is the limited number of market participants and transaction volumes, leading to low market liquidity [34, 43]. The motivation of participants thus should be considered to mobilize. Besides, the pricing mechanism is also important in the market design. The two P2P local energy market, Cornwall Local Energy Market and Quartierstrom Market, are discussed here as examples [27]. Consumers in the Cornwall Local Energy Market are the passive receivers of the prices, who can only accept the instructions from local energy retailers [39]. Although satisfied with the free equipment, consumers still feel depressed because of the indeterminacy on how to contribute to the future energy system [39]. Consumers in the Quartierstrom market could bid in the user interface, who can affect the local electricity prices directly. However, consistent high praises towards Quartierstrom market are not appeared as predicted, the market participants show preferences on high automation trading system [27, 39]. It is still worthy to be further discussed about the market pricing method. Apart from pricing, the management of the distribution system is also changing with the development of the distribution system structure. Huge pressure is faced by the system including rapidly increasing demand, network limitations, and the absence of investment. The operators of conventional distribution networks are also seeking new roles in the process of transferring from the traditional system to the smart decentralized system.

In conclusion, the local energy construction should consider topics including structure design, pricing mechanism and the roles and functions of operators.

## 1.3 Problem statement

The local energy market refers to energy transaction places targeting at communities and specific areas. The local energy trading market is predicted to develop to a decentralized future, as the energy traded in the local electricity market is mostly the renewable and distributed energy resources possessing small-scale, high variability and low predictivity. There are three major considerations in market construction: 1). Breaking down technical barriers, including energy technology barriers, connecting hardware barriers and arithmetic barriers 2). Settling market design, including operation rules and pricing mechanism 3). Exploring market management-related issues, including market laws and regulations, and the roles and functions of stakeholders.

### 1.3.1 Technical barriers

The technological barriers of the local energy market include the immaturity of traded energy technologies, the immaturity of hardware technologies, and the computing complexity brought by the special P2P clearing. The unmature products traded in the energy market include ES systems including metal-air batteries, solar fuel cryogenic, synthetic natural gas and thermal systems, and diverse fuel cells. The target of greenhouse emission facilitates the development of distributed energies as the fundamental stimulus [18, 44-46].

Being the technologies realizing market transparency and information communication, ICT technologies are the central component of the local energy market. The controllability and observability of the physical process are realized by the ICT through ensuring communication signals, contributing in the integration, delivery, processing, and storage progresses [4, 47-50]. As the introduction about typical flexibility markets in Chapter 2, each market design possesses its own transaction platform such as Piclo. ICT technologies are applied on these platforms, undertaking responsibilities including communication and information settlement. However, the network vulnerability risks themselves may be brought by ICTs, leading to issues like ineffective operational decisions and the instability of voltages and frequencies [47, 49, 51-53].

The computing complexity facing the demand-side responses is triggered by two reasons, including the missing accuracy and its following problems brought by the error prediction, and the nonlinear modelling serving the massively introduced local energy market [29, 47, 54-56]. The design of clearing engine settling large-scale distributed energy resources of Cornwall Local Energy Market is discussed in Chapter 2. The appropriate algorithm is required after the introduction of demand-side responses to balance the local market operation speed and the objective conflicts in linear modelling. The highly tricky computing complexity would be brought by the target to achieve both high economy efficiency and sufficient market matching results [29, 47, 54, 55].

### Market modelling

Considering the smooth running and the sustainability of the market, the design of the local energy market expects to possess enough attractiveness to potential market participants. For the factors that are respected by the participants, the costs play the most important role that the economic effect is the primary motivation for the energy exchange. The mechanism of competition and settlement of the current typical flexibility markets are explained in detail in the literature review chapter. The core of market modelling in academy is also discussed in chapter 2. The pricing settlement mechanism thus is important in market modelling. Apart from cost factors, other elements affecting the initiation of market participants include the convenience of market participation, the trust of participants towards the market platform and their counterparties, and the participants' knowledge of energy markets.

Transformed from the traditional consumers, the prosumers in the local energy market prefer simple transaction process. The operation results of Quartierstrom Market Trail show the market participants preferences in a simple transaction system even when they can directly bid and affect the market prices [27]. The bilateral market interactions are expected because prosumers are no longer limited to the negative price takers. The operation performances of Cornwall Local Energy Market in Chapter 2 also indicate similar results.

The participants' trusts towards the market are composed of trusts towards the transaction platform itself and that towards the other participants of market. The market participants need to realize the platform would guarantee the security and privacy of consumers meanwhile avoiding individual discrimination [57]. The trust of participants towards counterparties evolves from their trust towards energy suppliers in the current stage. The research from Cambridge University exposes the trust prejudice of consumers that the actual horizontal comparison among suppliers could only be reached through the information publication and overlap, which again relies on transparency namely the ICT technologies [4, 47-50, 58-61]. Market transparency should be considered in the operation rules, including the disclosure process and the technically competent market.

There is a positive correlation between the market participation initiation and the policy familiarity they gain about the energy market. The involvement degree towards the market would especially be triggered by the understanding of energy expenditure components [62]. On average, the individual participant would be attracted by the immediate benefit and the perceived tangible things, indicating the importance of information disclosure in the market operation [57]. Other unquantifiable benefits are not easy to be perceived by the consumers, like the reduction of carbon commission and the facilitation of energy transition [44].

### 1.3.2 Roles and functions of future DSO

The market regulation and management issues are composed by internal factors and external factors. The internal factors are mainly the roles and functions that should be taken by the market operators, while the external factors consider the policy support operating the market.

The transition from the DNO to the DSO is the maximum driving force to settle the roles and functions of market operators [63]. The leaders of typical flexibility market projects in UK are DNOs, such as UKPN and WPD. Being the market targeting at distribution system, flexibility markets are majorly operated locally. Being the core of market devolution, sufficient coordination between TSO and the DSO is crucial for grid stability. The measure and prediction under emergencies are always challenges of the market, that the appropriate functions of market operators are required in reducing unnecessary information sharing based on the problem settlement [47, 49, 64].

The systematic revolution brought by the decarbonization of the electricity system is promoted to the generation and transaction of electricity, offering development potentials to local flexibility resources and markets. Focused on the conventional centralized configuration, the on-going market regulation kind of impede the development of local flexibility markets, requiring changes of the existing regulatory environment [44, 65-67]. The decline subsidies of wind and PV brings indeterminacy of the future local energy market, especially the energy community markets, making their final target to construct a sufficient business model to earn profit without depending on subsidies [47, 66-68]. Meanwhile, the vulnerable and price-sensitive groups are specially protected in the market design [68]. The guarantee of energy democratization asks for tighter ties among energy market participants, preventing discrimination towards participants.

## 1.4 Objectives and contributions

The complete market-related issues are discussed comprehensively in this research from the macro to the detail, constructing a more rational and effective distributed energy market under the future trend of energy. The structure could reflect the commercial components in the distribution system visually, building a foundation to understand, construct and operate future distributed energy market. The non-technical market assessment criteria are then proposed, being the estimation benchmark of the general energy market and energy business models. Followed are market designs aiming at diverse development phases of energy infiltration. The market design to maximize clearing quantity is firstly presented for the massive introduction of renewable energy resources. The P2P market design which could offer automatic transactions to the individual end-users is then published, complying with the small-scale and privately-owned characters of distributed energy resources. Finally, considering the function changes when market transferring from the transmission level to the distribution level, the roles and functions of market stakeholders under distributed energy market is explored.

- To define the future market structure in the distribution system and key market components, a multi-level distribution system market structure is proposed, reflecting all the commercial elements in the distribution electricity supply chain.

The proposed electricity system could demonstrate all the market layers and components visually, leading to a clearer and more direct logic conducting research. The foundation of understanding the future distributed energy market is laid by proposing the architecture. The key information of each market, including detailed market components, market functions and the market participants is provided in the market structure. The development tendency of the distribution market is then could be explored under diverse future energy scenarios and industrial structures, applying the proposed distribution market structure.

- To estimate the efficiency of community energies applying diverse trading methods, the market assessment criteria is proposed to estimate market efficiency, being the general assessment benchmark of the energy markets.

The non-technology market assessment criteria estimating markets from the perspectives of economy efficiency and society feasibility is proposed in the research. The typical trading methods applied in the running real-world electricity market is estimated under proposed criteria, being judged their feasibilities in the future business models for community energies. Possessing generality, the proposed market assessment could be used as a benchmark to estimate all energy markets.

- To reflect the costs and flexibilities of diverse resources and offer a wide range of energy products, a pay-as-bid market model is proposed aiming at increasing clearing quantity, being suitable for the massive introduction of distributed energy resources in the future.

Taking the market equilibrium point as the clearing point, the traditional market clearing model could guarantee the maximum social welfare of the matching result. However, the system reliability of the conventional clearing may bereft because of the increasing clearing quantity required by the massively introduced renewable energies and distributed energy resources. The market model focusing on increasing clearing quantity is proposed in the research, with the specific detailed transaction rules facing different situation. The market clearing results of the traditional models and the optimized one are compared from the perspectives of system reliability, economy efficiency and market attractiveness. The proposed market assessment criteria is also applied in the following market estimation.

- To provide a fair and attractive energy transaction platform for individual owners of distributed energy resources, an automatic P2P flexibility market applying dynamic pricing strategy is proposed in the research, with a following exploration on when and how to proceed market segmentation.

The Uber-Airbnb Mixture Model proposed in this chapter takes reference from mature P2P business models, combining the matching strategy from Uber business model and the pricing strategy from Airbnb business model. The flexibilities are considered as pure commodity under the P2P Market design, and the automatic trading could be completed. Adapting dynamic pricing strategy, the prices are quantized according to the characteristics of market participants. The relatively fair price signals could be released, and the enthusiasm of participation could be mobilized by the dynamic strategy. The diverse scenatios illustrating different DSO independent degrees are represented, with the exploration towards the necessity of market segmentation. The feasibility of market participation is also discussed under the scenatios, conforming to the economy characteristics and transaction ideas in the real business world.

- To introduce the high-proportion distributed energy resources into the distributed energy market and mobilize their values, the manage-related responsibilities for distribution system operators in the emerging distribution markets are proposed under the development progress of emerging markets. The roles and functions of distribution system operators are discussed considering the transition process as dynamic.

The transition pathway of distribution electricity market is proposed in this chapter complying with the three typical stages of distribution system evolution. The four operation-related roles that should be undertaken by future distribution system is summarized, with diverse functions being responsible for different engagement levels. The responsibility distinction and collaboration implantation between DSO and other management institutes are also explored.

## 1.5 Thesis layout

A comprehensive exploration towards distributed energy market is launched in this thesis from the macro level to the micro level. For macroscopic perspective, the structure of future distribution-level market and the detailed market components are discussed in Chapter 3, laying a fundamental understanding of the topic. Universal market assessment criteria are proposed as a benchmark in Chapter 4, answering to the question of how to estimate the market efficiency. For microscopic perspective, two distributed market models are published in Chapter 5 and Chapter 6, conforming to the initial and mature penetration levels of renewable energy resources connecting to the system as Chapter 3 discussed. The market operation results and performances are evaluated under the criteria proposed in Chapter 4. Apart from the market competition mechanism, the benefits of stakeholders are also explored in Chapter 6. The transition pathway of regulation institutes and their responsibility allocation and collaboration is analyzed. The detailed of the thesis is organized as followed:

Chapter 2 reviews the distributed energy market systematically from both the industrial and academic perspectives. From the aspect of the industry, the certain-scale flexibility market trails which are stably operated for a period are emphasized, focusing on the design of market operation rules and transaction methods. From the aspect of the academic, the definition and structure of flexibility market are combed, concerning the flexibility market model construction and clearing algorithm options. The challenges of the existing distributed energy market including technological barriers, sufficient market design pursuing and supporting rules and regulations are also reviewed and summarized in this chapter.

Chapter 3 proposes an electricity market structure that could illustrate the entire commercial elements in the electricity system supply chain. The current market structure for the distribution-level market and the projected future distribution electricity market under the massive penetration of renewable energy resources are published in the research. The crucial information including market components, market functions and participants are represented through the structure, showing changes at a clear glance.

Chapter 4 proposes benchmark non-technical market assessment criteria. The market valuation mechanism jumps outside of the traditional framework which emphasizes the technical-related assessment criteria, publishing the assessment criteria considering economy efficiency and society feasibility. The typical trading methods applied in the transmission-level wholesale market are estimated for applicability in the future energy communities.

Chapter 5 proposes increased quantity market design to guarantee the system security and reliability facing penetration of renewable energy resources and distributed energy resources. The published market design goes through the stages from increasing to maximizing clearing quantity. Both the market-clearing performances and the market real-world simulated operation are discussed, applying the market assessment criteria proposed in chapter 4.

Chapter 6 proposes a P2P automatic trading market design to mobilize the value of distributed energy resources, considering of the energy characteristics including small-scale, individually owned and easy to start-stop. The P2P market design takes the reference of the mature P2P business model, and applies the dynamic pricing strategy published in this research which could sufficiently provide market signals reflecting features on market participants. The necessity of market segmentation is explored on the premise of considering energy products as pure commodities. The market operation applicability is discussed under the chapter 4 assessment criteria.

Chapter 7 proposed roles and functions of Distribution System Operator in the transition from Distribution Network Operator. The responsibilities of stakeholders are changing along with the gradually mature of distributed energy market. The roles and functions of the DSOs and their coordination with other management entities in the emerging distribution electricity market are explored in the chapter.

Chapter 8 summarizes the major contributes and findings of the research.

Chapter 9 presents the potential future work to construct more sufficient distributed energy market.

# Chapter 2

# Review of Distributed Energy Market in the Industry and the Academy

This chapter reviews the flexibility market from both the perspectives of UK electricity industry and the academy. The emerging challenges of distribution-level energy market construction under infiltrating renewable and distributed energy resources are introduced.

The construction of a flexibility market is required facing the future infiltration trend of the flexibility energy resources to release the network pressure. Composed by renewable energies, EV, and demand-side response which is majorly located on the distribution sector, the flexibility market discussed proceeds on the distribution level as well. That is, the exploration towards the local market or the distribution-level market is equivalent to analyzing most features of flexibility market.

Two main perspectives are concerned when launching market construction research, including market mechanism design and the market stakeholder interactions. For market mechanism design, the operation rules and transaction rules are discussed. The market products, the timeline of market stages, the detailed trading rules such as pricing strategies and clearing rules are the typical aspects discussed in the market mechanism design. As for the stakeholders, the attention is paid on both the market internal stakeholders like participants, and the external ones such as regulation and supervision. Being the trading platform of small-scale energy products, a distinctive concern of the distribution-level market is the existence of aggregators. The local energy resources are explored whether to be integrated before launching transactions.

Being a crucial development direction, the research toward local market is always proceeding. The achievements of local market nowadays are summarized from the aspects of industry and academy in this literature review. As there are flexibility market trails in application in the U.K., the industrial perspective research is proceeding to the research of real-world local markets. As for the academic perspective, the flexibility market definition is illustrated in this research. The basic concepts of market, including the market participants and general operation rules, are introduced. The major body of the academic summary locates on the model construction of flexibility market. The optimization and algorithm chose to simulate the local flexibility market are presented in the research.

## 2.1 Typical distributed energy market applied in the industry

Three typical real-world flexibility markets belonging to different distribution network operators (DNOs) are discussed in this literature review, including the flexibility market from UK Power Network (UKPN), Western Power Distribution (WPD) and Cornwall Local Electricity Market (LEM). Diverse pricing methods are taken by the three flexibility markets with various operation strategies. The classic tender mode and the performance-based pricing strategy is taken by the UKPN market. The WPD market launches a three-stage pricing strategy, which settles the products prices under different rules according to the various market maturity. The energy auction is adapted by Cornwall LEM, whose trading strategy is familiar with the auction launched in the transmission-level market.

## 2.1.1 UKPN flexibility market

UKPN declares to be a ‘flexibility first’ operator in their Flexibility Roadmap published in 2018 [69]. The flexible energy services are considered as the default procurements rather than reinforcing or upgrading assets in relieving network pressures [70]. The first UKPN flexibility tender was launched in the first quarter of 2019, which was the beginning of UKPN flexibility market.

### 2.1.1.1 Market product

Three flexibility services are procured in the UKPN flexibility market, including Secure product, Sustain product and Dynamic product. The UKPN local market here is the network market rather than energy market, which provides services to settle network-related issues but not pays attention to the system demand-supply balance. The procured services are categorized into the high-voltage ones and the low-voltage ones. The Secure services belong to the high-voltage working category, and the Sustain services are sufficient under low voltages. The Dynamic services are provided under both situations [69, 71-73].

The increased generation or decreased demand is adapted by Secure services to reduce the peak load of high-voltage substations. Secure services are paid with the availability payment and the utilization payment. The Flexible Units (FUs) are required in procuring Secure services as the existence of the minimum threshold of the UKPN market. The FUs here are functioned as aggregators. A delivery commitment is given six months before the contract. The Secure services obey real-time dispatch [69, 73].

Sustain services offer peak load reduction of low voltage substations by increasing generation or decreasing demand. Being different from the secure services who receive availability fee and utilization fee, the Sustain services only require fixed service fee. FUs are essential to the Sustain services as well since the minimum engagement threshold limitation. The delivery commitment for Sustain services is required one month before contracted delivery time. Advanced notifications should be sent to Sustain services when asking for their delivery, as those services adapt scheduled dispatch [69, 73].

Dynamic services are procured to satisfy many network needs in their definition. As the network issues settled by dynamic services are mostly unpredicted, only the utilization fee is asked by Dynamic services without the availability fee paying for the preparation. The Dynamic-related network issues possess abruptness, which means the dynamic services should only follow real-time dispatch. There are no service windows for Dynamic services because of their unpredictability [69, 73].

Other than the service objects, the biggest difference among those products are the diverse payments. The Secure services are paid by availability fee and the utilization fee, the Sustain services are charged for the fixed service fee, and the Dynamic services collect only the utilization fee. The predictability of diverse demanding situations is distinctive, leading to differences in service charging strategies.

There are services windows for Secure products, which are the projected demand peak periods. Most Secure service windows are diurnal periods [73, 74]. The very exact prediction for Secure products is difficult while requiring real-time dispatch, so both the availability fee and the utilization fee are charged awarding the possible preparation and service provision [71].

The Dynamic products, including high-voltage targeted and low-voltage targeted ones, are offering services closing to the real time to facilitate the flexibility market transition towards real-time market. The unpredictability of dynamic products leads to the absence of their availability fee. Higher premium dynamic utilization fee is charged by Dynamic products according to the application condition [71, 72].

Sustain services could be considered as the low-voltage version of Secure services, whose contracts are signed to ask for energy during service windows [72]. The peak demands for Sustain services happen in winter nights [75]. The Sustain services are under scheduled dispatch. As the planned delivery time is known at the commitment moment, only the fixed service fee would be charged by Sustain services without any awarding payments [69, 71, 72]. The service fee here could be understood as less-expensive utilization fee, that no extra utilization fee is required because of the advanced planning.

#### 2.1.1.2 Market Operation

The UKPN flexibility procurement is composed by 5 stages, including visibility, tender initiation, pre-qualification, competition, and pre-delivery [70, 71]. The competition stage is the market clearing traditionally discussed. The pre-delivery stage is the solution testing of flexibility providers before the actual delivery. The crucial stages from the perspective of operation are the visibility, tender initiation, and pre-qualification. Although being named differently, those stages are contained in general flexibility market operation. The qualified assets are expected to screen out before market competition.

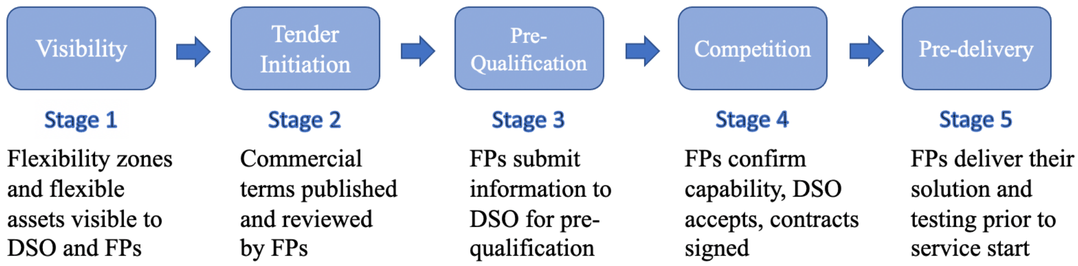



Figure 2- 1 The stages and dates of Flexibility Services Tender.

The timing sequence is important when talking about market operation. Market participants pay attention to the availability and nomination declaration period to follow the arrangements better. The asset dispatch schedules are published three weeks before the start of delivery. The asset availability is sent one week later by flexibility providers, followed by the nomination results in another week [75].

The participants are decided whether to be nominated according to their technical parameters submitted in the asset registration and pre-qualification processes. The comparable rate is constructed to proceed with quantitative comparison to flexible providers. The comparable rate is the general estimation indicator of flexible loads. The performance factor would also be introduced if the flexible load is under poor performance persistently.

The dispatch is the core sector of operation related to the final service delivery, possessing a similar necessity to the timing sequence. The projected happening times for network faults and limits are reflected in the flexibility dispatch arrangements. The dispatches are classified according to the timing of faults as pre-fault dispatch and post-fault dispatch. The nominated flexibility providers should provide delivery under schedule, and no extra on-off instructions would be offered by UKPN [69, 75]. The individual flexible load would receive their own start-stop arrangement in the nomination process.

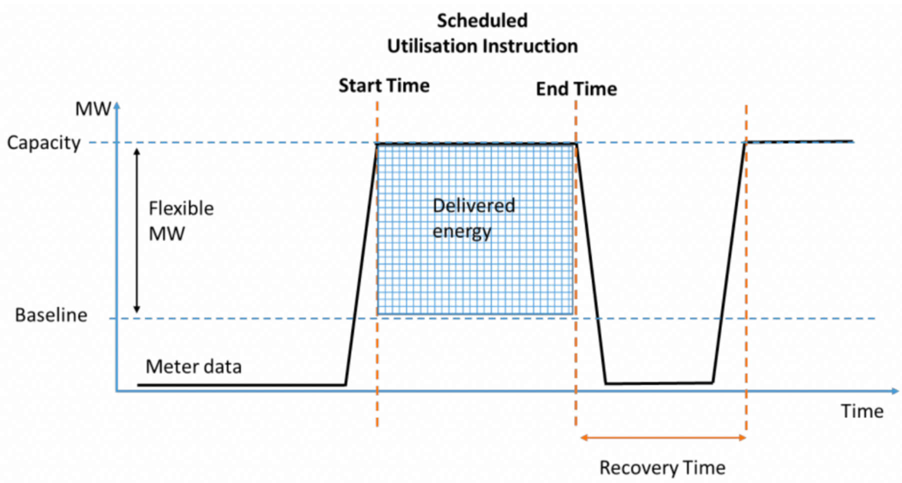



Figure 2- 2 Operational parameters during a scheduled utilisation event [71, 72]

The entire operational parameters participating in a scheduled utilization event is illustrated in the figure 2-2. The energy output of flexibility is displayed by the meter data curve. To deliver flexibility in the utilization instruction section, the flexibility would climb at a time before the instruction start time and contribute at the value of capacity. The statistic of the delivered energy is the output section between the baseline and the output capacity. The flexibility output would fall after the end time of one instruction and proceed a recovery time till the next instruction period.

#### 2.1.1.3 Market competition

***COMPETITION RULES***

The flexible loads entering the competition should have gone through two stages including the qualifying stage and the pre-qualified stage. Some competition rules should be satisfied by flexibility providers [74]:

1. Service Window: There are many service windows in one delivery season. The flexibility provider participants should be applicable in the one entire window period. They are not required to suit all the service windows.

2. Delivery Season: The intended flexibility providers must be available in the entire delivery season.
3. Service Period: The length of the service period could strike from 1 to 7 years.
4. Additional parameters: The additional parameters which do not meet the technical limitations are not permitted to submit during the competition period. All the technical limitations should declare to the UKPN in the asset register.

***PAYMENT CALCULATION***

The performance-based pricing strategy is adapted in the UKPN market during the flexibility procurement. The attention towards market competition then would transfer from the clearing process to the price and payment settlement.

The payments that could be received by nominated services include service payment, availability payment, and utilization payment. All the nominated Sustain products would receive fixed service fee. The utilization fee is paid to Secure services and Dynamic services, the specific amount of which is settled according to the individual service performance.

The minute resolution meter data is provided from flexibility providers to UKPN at the end of each year, which is used to calculate the delivered energy to get the utilization payment amount. The formula of utilization payment is [70-72]:

The energy delivery situation of a flexibility unit or a flexibility provider responding to the utilization instruction is illustrated in figure 2-3 [71, 72].

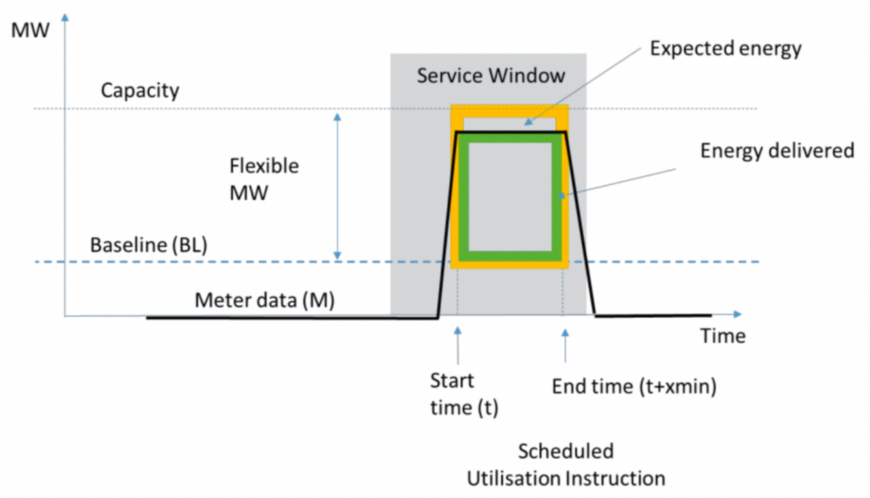



Figure 2- 3 Delivery of a flexible energy

As the figure suggested, the grey shaded area is the service window for a scheduled utilization instruction, during which the contracted flexibilities are committed to being available. The expected capacity provided period in one instruction is illustrated in yellow, and the actual output of the flexibility is displayed in green. Differences are allowed to exist between actual delivered and the scheduled contents that the output capacity is allowed to be less than the scheduled one. However, the output time period is compulsory locating within the service window. The calculation of the delivered energy is the output section between the baseline and the output capacity.

### 2.1.2 WPD flexibility market

Western Power Distribution assumes the responsibilities of both the distribution network operator (DNO) and the distribution system operator (DSO), working on the commercial and residential electricity distribution in West Midlands, East Midlands, the South West and South Wales [76]. WPD performs as the DSO with the penetration of distributed generation and the popularization of electric vehicles (EVs), operating smarter and more efficient distribution systems.

#### 2.1.2.1 Market Product

The three products offered in the WPD flexibility market are the Secure services, Dynamic services and Restore services. Although possessing the same name of the products from the UKPN market, those products are different in definitions, payment strategies and management methods.

The WPD Secure products are defined to manage peak demand loading on the network. The advanced management would be launched by WPD Secure services [16, 77]. Higher availability payment and lower utilization payment are expected to WPD Secure products compared to the UKPN ones. The Secure product of WPD and the Secure and Sustain product of UKPN are under a similar function to deal with the peak loads. The product differentiation of UKPN is more meticulous, that the UKPN Secure and UKPN Sustain work under high and low voltages respectively. Diverse pricing strategies also allocate to various products because of the differences within their procurement timeline and dispatch schedule. The WPD Secure products are stated to work at higher voltage levels. The expectation of future recruitment of all-voltage level services indicates that current services provided in the WPD market are not sufficient under all-voltage scenarios [16, 77].

Another difference between WPD services and UKPN services shows in their minimised engagement threshold. There is no minimum participating capacity limitation for WPD products as they are expecting a wider range of suppliers and flexibilities. More flexibility providers are expected in the WPD market, including ones connected at lower voltages [78].

The demand time of Secure products is predictable in the WPD market, they thus charge aiming fee and the utilization fee. The arming fee is paid to the services regardless of their utilization signed in the schedule period [79, 80]. The utilization fee is a kind of delivery award that is only be charged when the actual utilization happens. The payment amount is relative to the flexibility provision amount [79, 80].

The Dynamic products in the WPD market support network when the specific fault conditions happen, such as maintenance work outages following the network faults [16, 77]. Dynamic products are paid with lower availability payments and higher utilization payment. The Dynamic service providers are expected to respond within 15 mins after utilization calls [81].

The UKPN Dynamic products offer a wider range of services compared to the WPD ones. Only the network fault conditions are mentioned in the WPD Dynamic, while UKPN products settle 'various' network issues in their definition. For pricing strategy, WPD Dynamic services are paid for availability fee and utilization fee, and UKPN Dynamic products only charge for utilization fee. The differences in pricing come from the diverse pre-delivery period. There are no service windows for UKPN Dynamic since they are not predicted in advance, so no preparation fee would be charged. The WPD Dynamic products, which have preparation time, charge the awarded availability fee [79, 80].

The WPD Restore products help power restoration under rare faults situations, relieving the stress of networks. The WPD Restore services obey real-time dispatch because of the unpredictability of the system stress time. Due to the unnecessity of advanced preparation, the aiming fee and availability fee are not charged. The expensive premium utilization fee is the only payment to WPD Restore services [79, 80].

Overall speaking, the UKPN Secure products and Sustain products together possess the same function as WPD Secure products. The UKPN Dynamic services are similar to the integration of WPD Dynamic and Restore services.

#### 2.1.2.2 Market Operation

The WPD market operation is composed of four stages, including DPS registration stage, ITT complete stage, competition stage and deliver stage, which is more concise than the UKPN 5-stage operation [82]. The dynamic management system is applied by WPD in managing pre-qualified participants to participant in published procurement cycles.

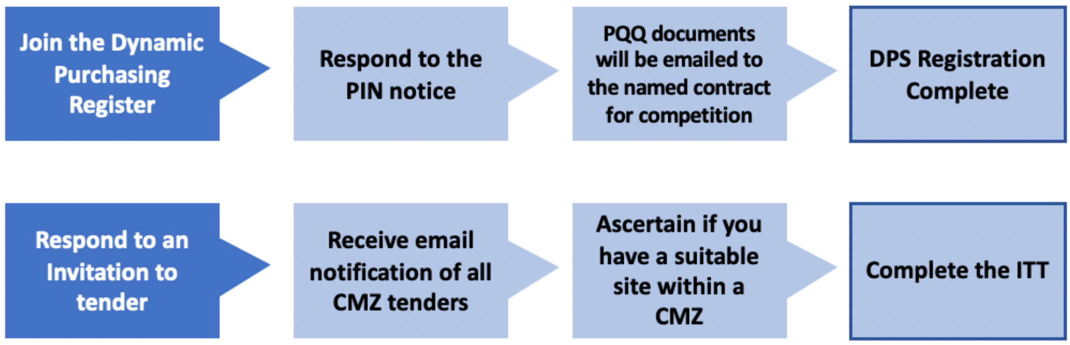



Figure 2- 4 Procurement process overview [82]

The DPS registration stage takes the duties of both visibility and pre-qualification. Being a dynamic procurement system, all the pre-qualification records are saved in the system being easy to launch demand response service tender in any zone [83]. There is no high threshold for the DPS registration, that neither the flexibility technical ability nor the geography location assessments are required in the process. The intentional service providers would receive a simple pre-qualification questionnaire, the completion of which is the finishing registration.

The ITT complete stage in the WPD market is similar to the tender initiation stage in UKPN flexibility market. The successfully registered assets in the DPS would be invited to future tender. Two tender invitations are published every year by WPD, where emphasizes are placed on the geographic locations and asset technical abilities [84]. Although the fixed-price pricing strategy is adopted by the WPD under the current pricing stage, the expected prices of flexibility providers are still asked as pricing preferences.

There are two procurement cycles in WPD market every year, with annual-updated procurement details. The demand prediction of flexibility services launches once a month.

The instruction timing is important in the market operation, where diverse flexibility services possess different instruction times [81]. Secure: All the accepted Secure services are considered to be used by default. The utilisation instructions are sent 15 minutes before the demanding moment to schedule asset operation. Dynamic: The requirement of Dynamic services is triggered by network conditions, that the service delivery time is 15 minutes after utilization instruction. Restore: Restore services are always ready for special network conditions that are only passively triggered. Restore services are expected to respond as soon as possible when receiving instructions.

#### 2.1.2.3 Market Competition

***DYNAMIC PRICING STRATEGY***

The WPD flexibility market is a very typical market that adapts the dynamic pricing strategy. The three-stage pricing strategy is applied in WPD market, settling diverse pricing strategies according to different market maturity [85]. The pricing structure of WPD is decided by the procurement competition level. The numbers and scales of flexibilities are different among zones, being calculated individually.

Phase 1 - Fixed Price: There are not adequate flexibilities in the current market, which could not be considered as completely competitive. Fixed pricing is adapted in this stage. The price taken by WPD flexibility market is around £300/ at present [85].

Phase 2 – Pay-as-clear: The clearing strategy here is to find the interaction point of supply and demand curves. All the bidding participants are cumulatively under the price merit order as the supply curve, while offers are allocated under a similar price descending order. The pay-as-clear strategy performances better in price manipulation prevention than pay-as-bid strategies to avoid market participants bid as premium prices on purpose.

Phase 3 – Full market: The market operation mechanism from procurement to settlement grows maturely with the increasing of market liquidity and competitiveness. The market clearing frequency increases and the advance-prediction time decreases in this phase to construct the close-to-real-time market [85].

The current WPD flexibility market is under an early phase due to the technology immaturity and short-term market construction. The increasing flexibility consumption would soon lead the WPD market to phase 2 and phase 3.

***PRODUCT PRICING MECHANISM***

***SECURE SERVICE PRICING***

Secure services in the WPD flexibility market are used to manage the network peak demand. The projected demand times of Secure are weekday evenings. The next-week secure requirements are published on week-advanced Thursday because of the product's strong predictability. The week-advanced requirements and nominations could bring more flexibilities to Secure service providers that unarmed ones could change to find other transaction opportunities.

The armed flexibility providers are considered to be utilizable by default. The flexibility providers are informed when network requirement changing, when they could select whether to proceed delivery. However, the utilization amount would face revocation without compensation when they are under-contracted [79]. This is a safeguard measure for the actual provision capacity.

Two aspects, the aiming fee and the utilization fee, are included in the Secure service payment [79]. The arming fee protects the certain payment of flexibility providers that the arming payments are paid no matter whether the event happens, or the flexibilities are utilized. The calculation of utilization fee is illustrated [79].

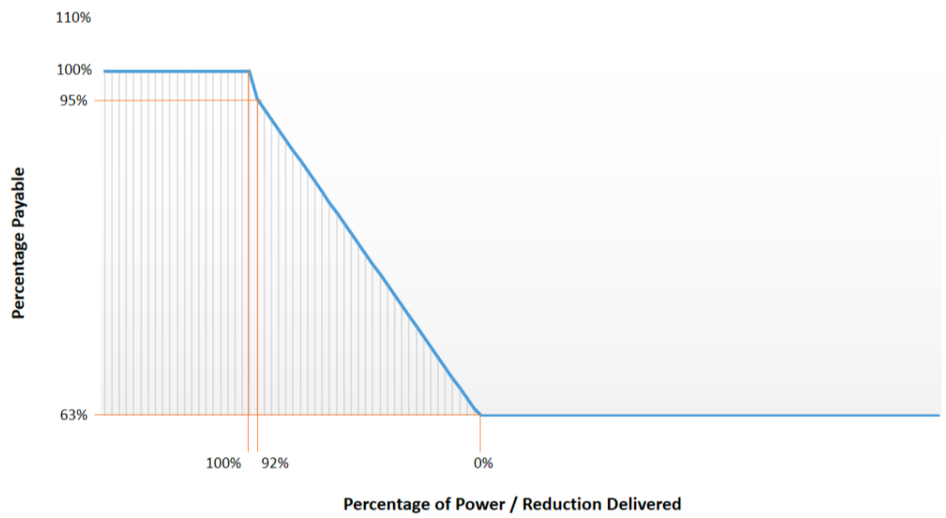



Figure 2- 5 Utilisation payment for Secure service

The value of utilization payment relates to the actual delivered energy in needed times. The power percentage is applied to reflect the proportional relation. The utilization payment would pay as 100% of the contracted amount as long as the percentage of power is higher than a specific value. Otherwise, the payable percentage would decrease correspondingly [79, 84]. ***DYNAMIC SERVICE PRICING***

Being a support of network during maintenance work, the general demanding time of dynamic services happen in British summer [16, 77]. It is a kind of post-fault services.

The availability fee and the utilization fee are included in the Dynamic payment. The availability fee is similar with the mentioned arming fee to award the preparation, when the availability payment reflects less utilization expects. The arming fee is defined as the payment for expected utilization duration, and the availability could be considered as payment for readiness. As the demands of Dynamic services are real-time ones, the responses within 15 minutes are required [81].

The event of default is not mentioned in the payment mechanism, as there is no penalty if delivery doesn't proceed as expected. The absence of punishment could mobilize the participants. However, payments are not paid to the unexpected deliveries. The delivery may face withdraw if the utilization capacity is less than the contractual amount [16, 77, 79].

Being the same with that of Secure Service, the utilization payment of dynamic service follows the same linearity relation between Percentage Payable and the Percentage of Power [79, 84].

***RESTORE SERVICE PRICING***

The requirements towards Restore services possess unpredictability because of the rarity of unalarmed faults. Only the utilization payment is paid to the Restore services then, without the preparation-related payments [79]. The utilization payments are under high premium rate due to the unpredictability. The participants declared restore service availabilities are accepted automatically, expected to response to any utilization requirement within 15 minutes [81].

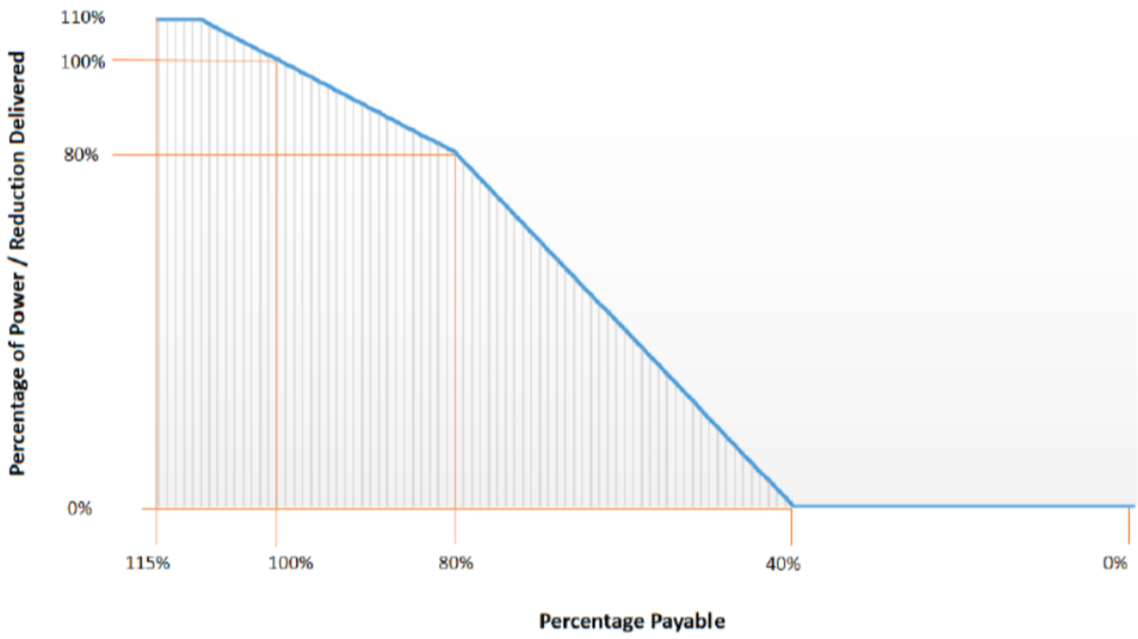



Figure 2- 6 Premium utilisation for Restore service [79]

### 2.1.3 Cornwall local energy market

The DSO flexibility procurement in UKPN and WPD market is under an annual timetable, which has a long tender cycle with contract awarding for many months. The short-term flexibility procurement market is then expected to encourage the engagement of more flexibilities and renewable energies. The short-term flexibility procurement could save expenses for end-users by attracting more participants and reducing demands towards long-term underutilized contracts. The short-term flexibility procurement could be the crucial promoter of a smart energy system.

The Cornwall Local Energy Market (LEM) is a three-year project ranging from 2017 to 2020, funded by European Regional Development Fund and Centrica [86].

#### 2.1.3.1 Market Operation

Most procured flexibilities nowadays are completed applied specific flexibility platforms. The Pico Platform is used by UKPN to register interested participants and collect bids. The Dynamic Purchase System is applied by WPD. And Cornwall LEM proceeds market transactions through Cornwall Local Platform [20, 87]. Being an auction-based flexibility market platform, the close-gate and pay-as-clear auctions are hold on the platform. The entire operation process from the initial registration to the final settlement is implemented on the platform. The detailed Cornwall LEM operation steps are illustrated in figure 2-7 [9].

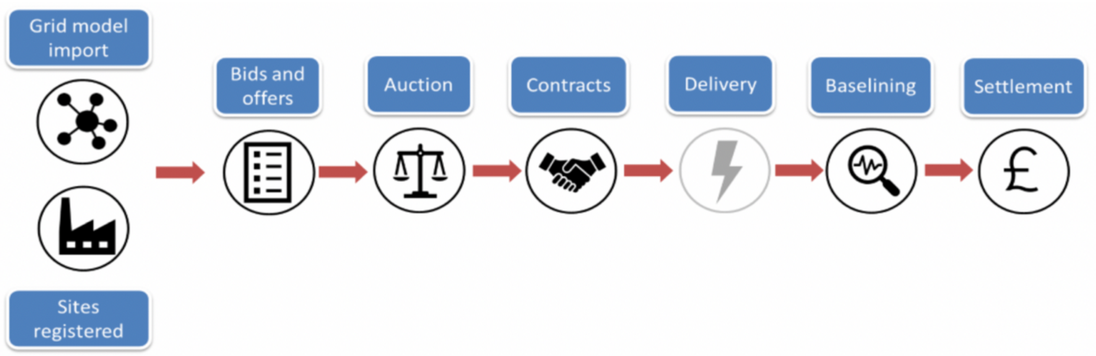



Figure 2- 7 End-to end flexibility procurement process

Many stages could be summarized from the market operation steps. The first stage includes grid model import and site registration. This stage promotes understanding to the network condition and requires visibility to resources. The grid model import is the submission of network topological structure and the demand and constraints of each substation. The site registration is the resource reporting process that the flexibility providers could prepare for demands. This stage is similar with the UKPN visibility stage and WPD registration stage.

The second stage includes bids and offers step, auction step, and contract step. This is the core market clearing phase completing transaction. Both the UKPN market and the WPD market procure flexibility resources through tender process, although they are under slightly different pricing strategy. The auction clearing is adapted in the Cornwall LEM, being the most competitive market. The auction-based clearing is also feasible to the local market trend facing penetration of flexibility resources.

The auction in Cornwall LEM is composed by the reserve auction and the utilization auction, both auctions are close-gate and scheduled. Reserve auctions are launched three-month, one-month and one-week ahead the delivery, the participants of which are required to be available on the following utilization auction in both time and volume [9, 21]. The utilization auction is closer to the delivery time, that they are launched day-ahead or intraday until 2 hours before delivery [9, 21]. The orders in the utilization auction could be the activated reserve capacity or the utilization-only capacity. The maximum social welfare is expected to reach while caring the technical limits of assets and networks, so the N-side clearing engine is developed to match auction bids and offers [87]. The specific cases of auctions are introduced later. The timeline of the whole auction process is presented in figure 2-8 [9].

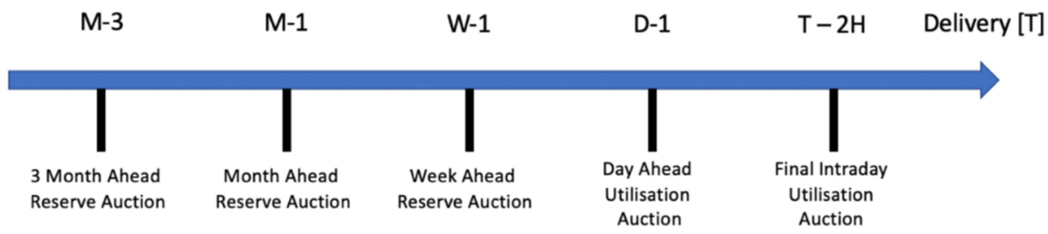



Figure 2- 8 Timeline of the auction process

The third stage includes delivery, baseline, and settlement steps, reflecting the dispatch and payment processes. The successful utilization contract holders are asked to provide flexibilities as the contract instructions, and there is no following control to the assets. The whole delivery process is completed automatically. The half-hourly site-level metering data is provided by sellers to proceed the event performance evaluation [88]. The sellers receive payment through monthly settlement process.

#### 2.1.3.2 Market competition

Being an auction-based flexibility market, Cornwall LEM launches transactions through regular closed pay-as-clear auctions. The platform covers the whole process through asset registration, market clearing, service delivery to settlement [20].

The buyer is limited with many sellers in the Cornwall LEM, so a complicated optimization problem is faced by buyers. All the bids could be considered at the same time in the auction-based clearing to output the lowest-cost combination giving consideration of social welfare and technical constraints. The outcome would be the economically optimal choice among available flexibilities for buyers. The cleared flexibilities thus won't violate any network restrictions.

The reserve procurement and the utilization procurement are separated since the Electricity Balancing Guideline indicates that the prices of balancing energies should not be pre-settled in the balancing capacity contracts [89]. The reserve auctions are launched three-month, one-month and one-week before the delivery. The reserve capacity procurements are long-term in the LEM market so that they could be utilized in the following utilization. The reserve capacity contract holders are required to be available in the utilization auction period. The contracted reserve capacity is not mandatorily used by buyers.

The utilization auction is day-ahead or intra-day until 2 hours before delivery. The buyers are in authority to active reserve capacity or set up utilization-only orders. Both reserved and unreserved capacities are included in the utilization auction, so the reserved assets are not promised to win the utilization contracts [21]. The utilization prices are not considered during reserve auction settlement because the clearing prices are set to reflect real-time situations. The buyers and sellers both could adjust their utilization quotes before auction clearing.

The time, location, volume, and price information of flexibilities are required in the auction quotes. The requirements of time and location are gathered to match the network demand, and the volume and prices are the decisive factor of clearing decisions. There is minimum engagement threshold of 50kWh in the Cornwall LEM, so the aggregators are required to integrate small-scale energy resources in the market [90]. Two methods are taken to participate market for flexibility providers, including creating offer directly on platform or aggregation into the flexibility pool [9]. The aggregated participant could bid at a unique price rather than individual ones. Participants could gather flexibilities at any network level.

#### 2.1.3.3 Market clearing

The Cornwall LEM model would consider comprehensive conditions and variables in optimization, thus facing complex problems. The N-side engine taken by the market could guarantee the scale expansion.

The information including bids and offers, network topological structure, available node capacity and historical contract lists would be sent to the clearing engine when auction is proceeded [87]. The bids and offers are matched by the optimization algorithm. The largest surplus of sellers and buyers are expected to achieve the maximum social welfare.

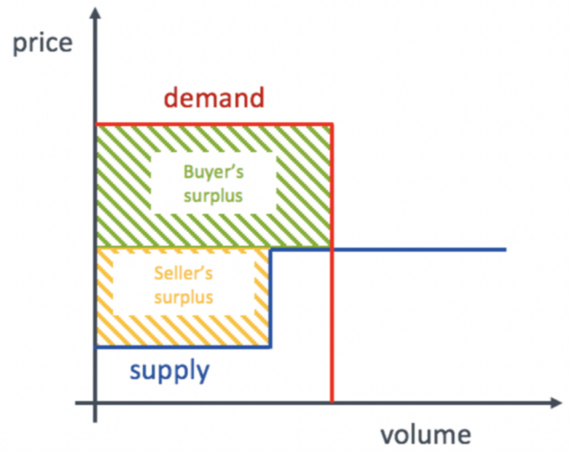



Figure 2- 9 Optimisation algorithm supply and demand curves [9]

The separation of reserve procurement and utilization procurement is adapted. The potential risk of this allocation is that some participants would hold the reserve contract as secure and then raise price in the utilization auction to avoid the utilization clearing. Those speculators could receive the reserve payment without providing flexibilities [21]. The easiest method to settle the problem is to introduce the price cap that sellers are not allowed to quote higher than the cap. The flexibility contracts can only be held by the sellers bid less than or equal to the price cap [19].

## 2.2 Flexibility market research in academy

### 2.2.1 Local flexibility market schematic overview

Flexibility market is defined as the trading flatform of electricity flexibilities, whose transactions always happen within communities and towns [62, 91]. The flexibility market in the future is expected to extend to the entire distribution level. Without considering the situation that more than one role could be undertaken by one institution, the general composes of a local flexibility market is illustrated in Figure 2-10 [92].

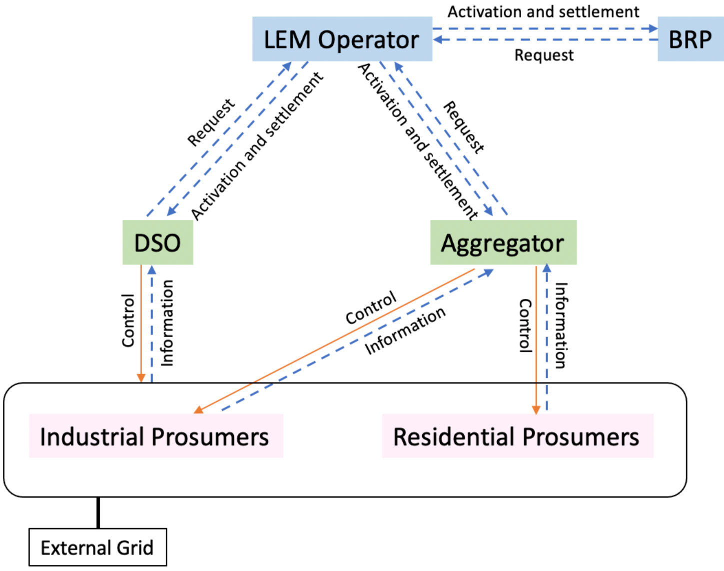



Figure 2- 10 Schematic overview of a local flexibility market

The residential prosumers and industrial prosumers are the suppliers of flexibilities, who are integrated by aggregators to participate the flexibility market. The network market and the energy market are participated and managed respectively by the DSO and the BRP, that the distribution-level demand-supply balance could be achieved based on the guarantee of sufficient network. DSO and Balance Responsible Party (BRP) would also be participants of the market. DSO launches flexibility procurement for voltage control and constraint management. BRP purchases flexibility portfolios to reduce unbalanced costs. The aggregators are required in some flexibility markets because of their minimum engagement threshold, that small-scall energy resources are integrated and participate the market through aggregators.

The detailed introductions of market participants:

(1) DSO: Being the distribution system operator, DSO is developed from the current distribution network operator (DNO). The energy is expected to be delivered under the cost-efficiency and sustainability, whose operation security and service quantity are guaranteed by DSO. Many DSO-related conditions require flexibilities, including congestion-management, voltage control and network reinforcement deferring.

(2) BRP: Being the trader of energy market, BRP is in charge of the demand-supply balance. BRP could be retailers, generators, or aggregators. The imbalanced cost would be charged if the balance isn't reached [93].

(3) Aggregators: Prosumer groups are integrated and managed by aggregators to participate transactions in flexibility market [94]. As limited bargaining power is required by individual market participants, and there are minimum thresholds in many flexibility markets, participants are integrated by aggregators before entering markets. Aggregators trade in the market representing individual small-scale resources and receive service remuneration from DSO and BRP.

(4) LFM Operators: The Local Flexibility Market Operators responses to market clearing and management. Both DSO and aggregators may take the responsibility of operator in the actual market application [95-97].

The buyers of flexibilities are BRP and DSO, and sellers of flexibilities are aggregators (or energy resource individuals in the future). Although competing for the flexibilities together, DSO and BRP pay attention to different feature of DSO because of their diverse requirements. BRP focuses on the available volume of flexibility rather than their location in network since BRP only cares the system balance. DSO interests in technical features and locations of the flexibilities because they pay attention to network issues. Aggregators could be BRP of themselves, and the unbalanced issues could be settled in an aggregator pool.

A four-layer architecture of local flexibility trading is proposed in paper [3]to demonstrate the potential key elements and technologies in LFM.

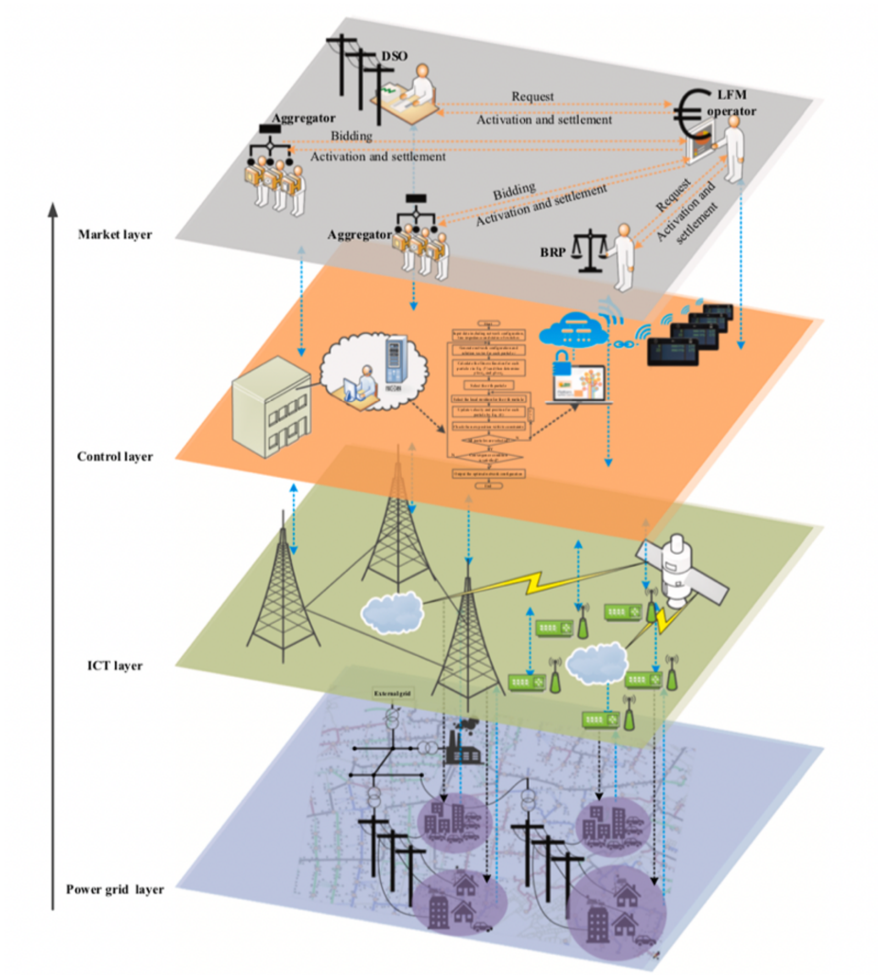



Figure 2- 11 A four-layer architecture of local flexibility trading

The explain of each layer:

(1) Power grid layer: Composed by the physical components of distribution system, the power grid layer includes supply-side flexibility components (distributed energy resources 、 storage units), demand-side flexibility components (aggregators 、 prosumers) and transmission-level flexibility components. Those components constitute the local flexibility trading system.

(2) ICT layer: Being responsible for information delivery, the ICT layer is composed by communication devices and information flow [30]. The existence of ICT layer makes it possible for the component regulation, control, and management, with the infrastructure required by the flexibility transactions.

(3) Control layer: The control layer optimizes the operation of distributed battery and storage units by publishing control strategies. The demand and grid strategies are defined in this layer to launch the demand-side resources

management. The quality and reliability of distribution system is guaranteed by controlling the power flow, voltage, and network topology.

(4) Market Layer: The participants of market layer include DSO, aggregator, BRP and operators. Being the layer supporting energy transactions, many business models are integrated in market layer to facilitate trading of diverse local flexibilities and proceed transaction management.

The market layer is the major concern of electricity market research. Three steps could summarize the market transaction progress from the transaction perspective, including contracting and bidding, activation, and settlement. The timeline and activity sequence of the three steps are shown in figure 2-12:

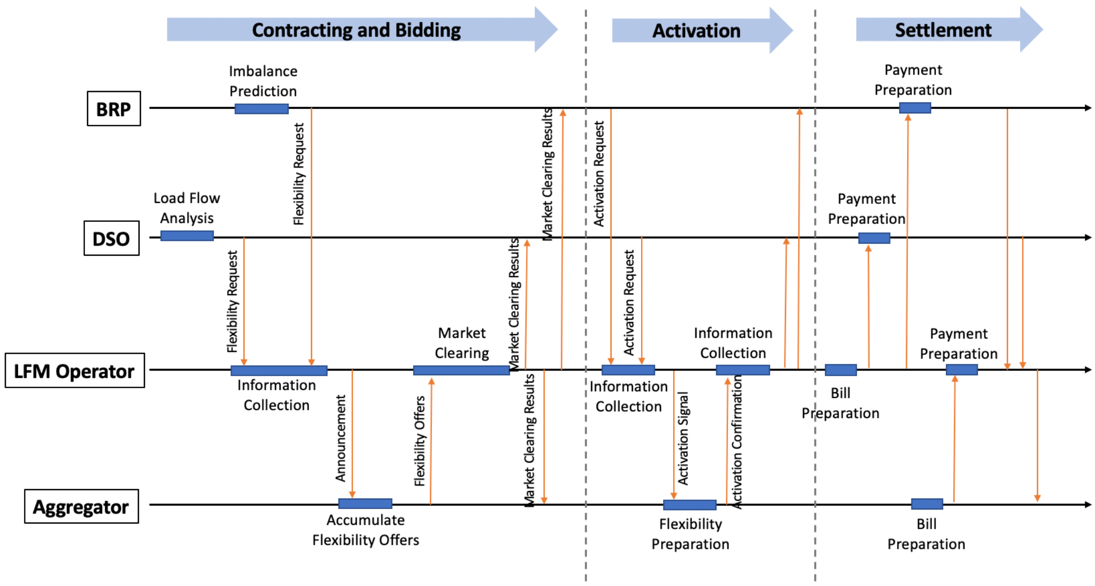



Figure 2- 12 Typical timeline of a local flexibility market

The detailed activities in the three stages are:

(1) Contracting and bidding: The power flow analysis would firstly be launched by the DSO to predict the future network issues. If demand exists, the flexibility requests would be sent from the DSO with detailed demand information including location, capacity, and problem type. Similarly, BRP would send requests to the operator if the future market demand-supply imbalance is predicted to happen. The operator would inform aggregators after integrating flexibility requests to cumulate flexibilities and provide flexibility offers. Aggregators exist through the form of aggregator pool rather than individually

under some market structures. The operator receiving offers would then proceed market clearings, and send results to DSO, BRP and aggregator [21, 69, 71, 72, 87, 98-104].

(2) Activation: DSO and BRP would send activation requests to LFM to active the flexibilities they procured. Activated flexibilities are provided to aggregators through dispatching and controlling prosumers. Aggregators would send activation request to LFM, who then offers confirmation to DSO and BRP [9, 87, 102].

(3) Settlement: The payments of flexibility transactions among DSO, BRP, LFM and aggregators are completed in the settlement process [9, 16, 19, 21, 69, 79, 98, 100-104].

### 2.2.2 Academic model of flexibility market

The flexibility market literature review in this research is launched from the perspectives of industry and academy. The industry research proceeds towards the real-world flexibility market trails. The market operation and competition are discussed. And the review from academy perspective focuses on the flexibility market simulation, including the market model construction and the algorithm application.

Academic flexibility market could be categorized into three major types: 1. Auction-based model 2. Centralized optimization model 3. Game theory-based model

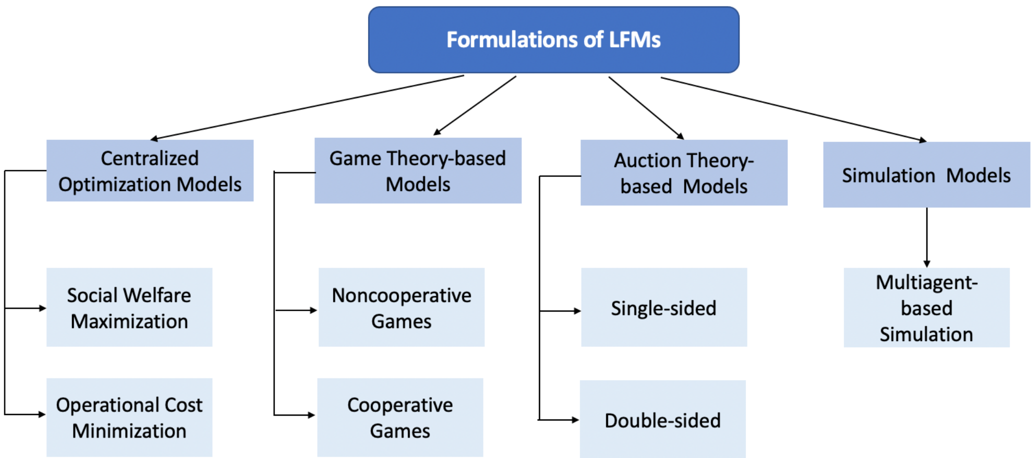



Figure 2- 13 Academic flexibility market model category

#### 2.2.2.1 Auction theory-based models

The auction theory-based model is the one first to be discussed in this research, because the real-world electricity market took or is taking auction to complete market clearing. This is the model being closest to the real situation.

Auction is a resource allocation mechanism to achieve demand-supply balance through bidding process [105]. There are multiple potential buyers and sellers coexisting in the auction market. The auction participants quote their bids and offers and settle the clearing price through specific auction rules. Generally speaking, clearing price is decided as the integration point of the cumulative supply curve in price merit order and cumulative demand curve in price descending order [106].

There are two modes of pay-as-bid and pay-as-clear in auction clearing, whose major difference is the final price settlement. In the pay-as-bid mode, sellers bidding lower than the clearing price are cleared ones who could receive payment as bidding prices [107, 108]. In the pay-as-clear mode, all the successful sellers clear at the unified clearing price [107, 108]. Auctions that proceed in the energy market are similar with those in other commodity market that a maximum economy efficiency is expected based on the balance of supply and demand. The energy market auctions then try to find the matching under the lowest cost.

Auction theory-based model includes single-sided auctions and double-sided auctions. The single-sided auctions, as the name suggests, are auctions implying single buyer with multiply sellers or multiple buyers with single sellers. Multiple buyers compete for one commodity under forward single-side auction, and more than one seller bid to satisfy one buyer in reserve the single-side auction. Multi-buyers and multi-sellers achieve matching in the double-sided auctions.

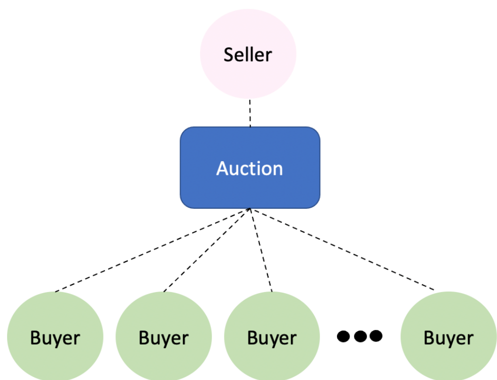
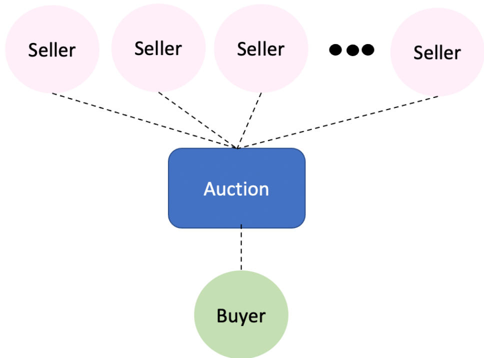
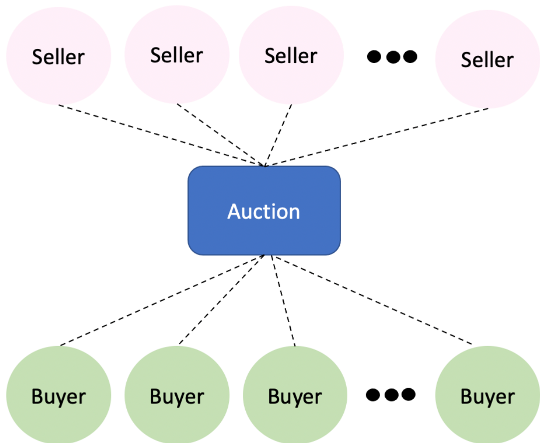



Figure 2- 14 Classification of auction theory-based models

(a). Single-sided auction: forward auction where several buyers bid for an item being sold




(b). Single-sided auction: reverse auction where several sellers offer an item that a buyer request




(c). Double-sided auction several buyers bid to buy from several sellers

Bidding structure is the key point of electricity market design. The general commodities are only focused on the economy features as the changing hands of commodities could complete automatically. However, the clearing of electricity market should pay the parallel attention to the economy and physical features of energy products, leading to the practical difficulty in electricity market application. Electricity market participants should submit their economy and technology features to the clearing engine [9, 21, 87]. Most electricity market participants possess technique-complexity, time-coupling and non-convex, which would be encapsulated in real markets [21]. The market bidding structures could be divided into simple bidding, fully complex bidding, and semi-complex bidding according to the different encapsulation complexity.

***Simple Bidding Model***

As the name suggested, simple bidding have the most direct objects composed by only volume and price. The market clearing process is to find the interaction point of the supply and the demand curves. None of the complex operating features other than the available amount and expected price could be disclosed under this bidding strategy [109]. To guarantee the concision and transparency of the market trading process, all the demands of participants are estimated by themselves [110, 111].

Only asset allocation is up to market in simple bidding structure, where the technology matching-related things are put in charge of suppliers themselves. The risk here is the differences between participants' expectations and the actual conditions, that market participants may face infeasible or inefficient dispatching, or the economy risks of cost recovery failure [111-113]. The clearing price may be increased artificially through pricing strategies so that the simple bidding participants could hedge all the potential risks, as all the market participants have preconceived the risks [114]. The price manipulation would lead to higher costs and lower market efficiency. The simple bidding structure is mostly applied in market clearing simulation rather than the real-world market application [110].

***Fully Complex Bidding Model***

Being opposite to the simple bidding structure, the fully complex bidding is expected to reveal all the complex features of the market participants. The market operators want to consider all those characteristics to satisfy the economy pursuit and physical constraints of the market [115-119]. The overall technology constraints and cost components of participants with the available volume and expected prices are offered in the fully complex bidding. The most significant advantage of this bidding structure is that all the clearing results are guaranteed to be physically feasible [120].

Many real-world electricity markets are launching fully complex biddings, including the California, PJM, New York and MISO markets in the USA and Greece, Poland, Ireland, and Northern Ireland markets in the Europe [115, 121-124]. Although increasing the accuracy and reliability of market in the fully complex bidding adaption, the pressure has transferred to the matching and calculation process of the market clearing engine. The current clearing algorithm is poor in the expansibility, because the clearing performance would degenerate rapidly under the increasing quantities of generation units and the expanding network scale [125-127]. Besides, all the technology and economy parameters are required to submit to operators by market participants, which is unaccepted for most electricity suppliers considering of the business privacy [128]. The fully complex bidding structure therefore is only feasible in the wholesale markets with few participants. The penetrating distributed energies participants of local markets would bring communication and computation issues because of the large-scale computation brought by the complexity. Hence, the fully complex bidding structure is difficult to introduce to the markets for distributed energy trading.

***Semi-complex Bidding Model***

The semi-complex bidding strategy would imitate the actual operation features of market participants without compulsive disclosure requirements to settle the privacy issues. This structure is always proceeded in the Europe, including European markets, Central Western European, Nord Pool Spot day-ahead market and Turkish market [129-131]. The orders under semi-complex bidding include complex orders and block orders, being the combinatorial bids expressing 'all-or-nothing'. The binary variables are introduced into clearing engine to illustrate the 'all-or-nothing' feature. The complex branching algorithms are applied to settle the intrinsic indivisibility.

#### 2.2.2.2 Centralized optimization models

The market under centralized optimization model would apply optimization function to match clearing objects, describing specific market through technology and economy constraints. The market model could be divided into two perspectives according to the diverse objective function types, including social welfare maximization and operational cost minimization.

***Social Welfare Maximization***

The initial concept of social welfare in economy is defined as the function expressing the sum of individual utilities, which is the satisfaction of commodities and services. This is expounded as the benefits of market participants. The social welfare could be understood as the total benefit of market participants, that is the total incomes minus total costs [46]. The market participants of local flexibility market include market operator, DSO (energy buyers) and energy suppliers. The social welfare could be illustrated as the benefit gained by the DSO minus the costs faced by aggregators [3, 132]:

$$S_t = Operator's\ benefit + DSO's\ benefit + \sum Aggregators'\ benefit \\ = [M_t - M_t] + [B_t - M_t] + [M_t - C_t] \tag{2-17}$$

Where S is the social benefit of local flexibility market, B is the procurement cost.

The elements in equation 2-17 could cancel each other out, introducing:

$$S_t = B_t - C_t \tag{2-18}$$

***Operational Cost Minimization***

An available matching method for flexibility market is to find the minimum costs of participants in reaching the maximum benefit. For example, the minimization of DSO operational cost is applied as the clearing target of objective function.

The centralized optimization modelling method could be proceeded from the perspective of any market participant. Paper [95, 133] settles the objective function target as the minimize operational cost of LFM operators. Paper [134-138] considers the minimize DSO operational costs. The aggregator operational cost minimization is achieved in paper [97].

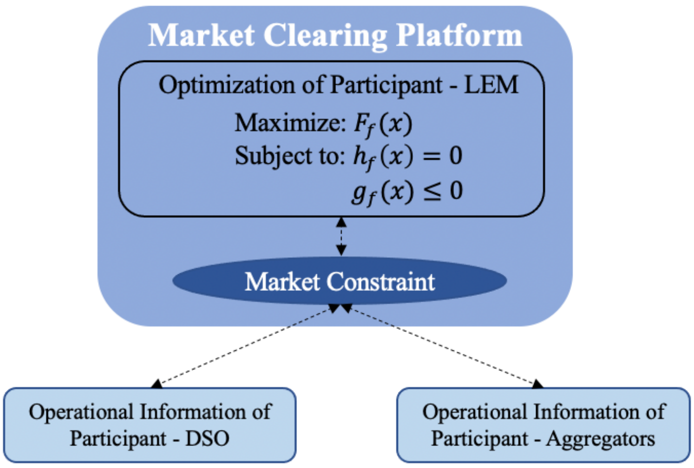



Figure 2- 15 Centralized optimisation models for market clearing

#### 2.2.2.3 Game theory-based models

Game theory is used to analyze the counterparty strategy under market competition, where the choices of participants would depend on the behaviors of other participants [139]. Other than the situation in the centralized optimization model that the clearing result would be published automatically when available volume and expected prices are submitted, the participants of game theory-based model would change their strategies considering the mutual competition. The total benefit maximization is achieved in the game theory-based formulation. The game theory model could classify into two categories including noncooperative game theory model and competitive game theory model. The participants make decisions individually in the noncooperative game theory model, and the collaboration could be reached on the competitive game theory model.

***Noncooperative Game Theory***

There are partial or complete conflicts among the participants in the noncooperative game theory model. The participants of noncooperative game theory could make decisions and take actions without communicating or cooperating with other players [139]. The noncooperative game theory is comprehensively applied in local energy trading research. The prosumers in the future local energy market are expected to take peer-to-peer trading model, where the noncooperative bidding strategies are more likely to be taken.

The market participants behaviors under noncooperative game theory model are discussed in [30, 140, 141], whose optimal solution is achieved applying Nash Equilibrium. The Nikaido-Isoda relaxation algorithm is used in [142, 143], where the game theory-based model is transferred to the easy-to-solve optimization problems. The multi-leader and multi-followers model based on Stackelberg game theory is applied for the energy transactions among microgrids and in the integrated energy system [144, 145]. The relationship between retail profits and consumer surpluses is discussed under Stackelberg game theory model in [146].

***Competitive Game Theory***

The participants under the competitive game theory model are rational ones who are willing to seek cooperation. They possess cooperative behaviors considering interaction. A demand response scheme is published in [147] based on competitive game theory to reduce the costs of industrial refrigerated warehouse. The competitive game theory-based model is applied to minimize costs by optimizing storage system. A direct electricity trading is developed in [148] to facilitate the local energy trading. Higher income is proved under cooperative game theory.

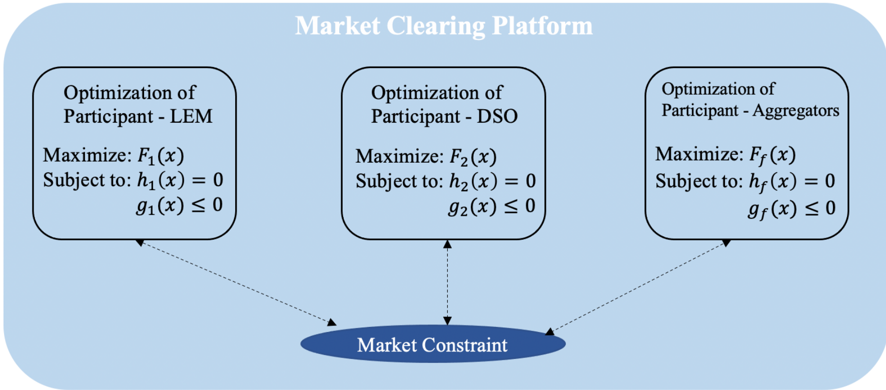



Figure 2- 16 Game theory-based models, auction theory-based models and simulation models for market clearing

#### 2.2.2.4 Advantages and disadvantages of models

The centralized optimization model is the easiest one to be realized among the models, although they have restrictions analyzing the large-scall participants due to their poor extendibility in communication and computation. The game theory-based models and the auction-based models perform better in the expandability, and the auction-based models have already been applied in the wholesale electricity markets around the world [149, 150]. However, both the game theory-based model and the auction-based model possess deficiency as well. The game theory-based model considers that rational competition or strategies would achieve by the market participants by default. Nevertheless, the strategic participants in the real-world electricity market may occupy less proportion than the model expected because of the long-term monopoly of energy market. As for competitive auction-based model, there may be multiple equilibria going against the market clearing in the game theory model. The unreasonable substantial appreciation of prices may appear in the unregulated and competitive auction-based markets [151].

The centralized optimization model simplifies most influencing factors as the determinacy or random independent variables, saving attention on the peculiar features of participants [152]. The auction-based model and game theory-based model could stimulate market operation under higher accuracy compared to the centralized optimisation one, as all the feedbacks of participants would be considered in the two models.

The optimization models do not possess absolute opposition relationship between each other. The optimization model, for example, could be applied to analyse the game theory-based model. The linear programming (LP) is sufficient in dealing with two-person zero-sum game [153]. The Nash equilibrium could achieve by the Mixed Integer Linear Programming (MILP) [154] and relaxation iteration algorithm [142, 143]. The Karush-Kuhn-Tucker (KKT) conditions under noncooperative game theory-model is published in [155], where the Nash equilibrium is reached by solving KKT conditions. The optimization model could also stimulate the behaviors of each agent in multi-agent models, whose results could be reached by optimization model [156].

The linear programming model could settle zero-sum game [153]. The Nash equilibrium could be achieved by MILP and relaxation iteration algorithm [142, 143, 154]. The simultaneous solving of KKT conditions in noncooperative game theory-based model could also reach the Nash equilibrium [155]. The agent behaviors could be stimulated by the optimization model. Therefore, the individual agent is expected to be imitated in the multi-agent models [152, 156, 157].

### 2.2.3 Market clearing algorithm

The iteration and relaxation are applied to transfer the auction-based market model and the game theory-based market model into the centralized optimization model. The clearing algorithms are chosen to solve the centralized optimization.

The specific algorithm is used to search the optimal value in reaching the objective function minimization and maximization. In general, the single objective function is optimized under many constraints. Concluded from the mathematical features, the objective function includes linear programming (LP), mixed-integer linear programming (MILP), mixed-integer nonlinear programming (MINLP), quadratic programming (QP), and mixed-integer quadratic programming (MIQP).

#### 2.2.3.1 Commercial solvers for centralized optimization

The commercial solvers are applied to solve the objective function directly, including CPLEX [158], GUROBI [159], LINDO [160], IPOPT [161], BARON [161], and SNOPT. The correspondence between solvers and the features of objective function they could solve is illustrated in the table 2-1.

Table 2- 1 Classification of direct algorithms for market clearing

| Mathematical Property | Features | Application Solvers |
|---|---|---|
| LP | Linear Objective and Constraints | CPLEX, GUROBI, BARON, IPOPT, LINDO, SNOPT |
| NLP | Some or all the equations of the objective and constraints are non-linear | IPOPT, BARON, SNOPT |
| MILP | The objective and constraints are linear; all or some variable within the set of integers | CPLEX, GUROBI, LINDO, BARON |
| MINLP | Same formulation as in MILP, with some or all the equations being non-linear | LINDO, BARON |
| QP | The objective function of a QP problem is quadratic (convex) and constraints are affine | CPLEX, GUROBI, IPOPT, LINDO, SNOPT |
| MIQP | Same formulation as in QP, with all or some variable within the set of integers | CPLEX, GUROBI, LINDO, BARON |

#### 2.2.3.2 Metaheuristic algorithms for centralized optimization

The metaheuristic algorithms are also comprehensively applied in the centralized optimisation. For example, the genetic algorithm is used to microgrid stimulation in paper [95]. The metaheuristic algorithms are theoretically available in solving all the optimization models, although the globally optimal solution could not guaranteed be found.

Table 2- 2 Summary of normally-used metaheuristic algorithms

| Metaheuristic Algorithm | Mechanism |
|---|---|
| Genetic algorithm | A GA evolves a population of candidate solutions initialized randomly in the search space to precede to the global optimum through selection, crossover and mutation operators |
| Particle swarm optimization | Each agent has a velocity and position vector, which are updated according to the best so far positions of particle and population over the course of evolution |
| Differential evolution | DE employs mutation, crossover and selection to generate new candidates according to the difference between pairs of solutions used for searching a moving direction |
| Simulated annealing | SA has been incorporated into different frameworks for dealing with optimization problems |
| Artificial bee colony | ABC is an optimization algorithm based on the intelligent foraging behavior o honeybee swarm. The colony consists of three groups of bees: employed bees, onlookers and scouts |
| Teaching learning-based optimization | TLBO mimics the teaching-learning ability of the teacher and learners in a classroom. The teacher and learner are the two vital components of the algorithm |

#### 2.2.3.3 Decomposition algorithm

The commercial solvers are widely applied in exploring characteristics of flexibility market because of its convenience in application. The market themselves rather than technology implication could be highlighted in the research using commercial solvers. However, the boundedness exists because of their high computational overhead in large-scale centralized optimization. The decomposition algorithm is published to solve the problem. The original problem is decomposed as individual-solved subproblems. The two major categories of decomposition methods include Augmented Lagrange relaxation decomposition and KKT condition decomposition.

The Augmented Lagrange relaxation decomposition is convenient to deal with large-scale dispatch with plenty constraints. Many electricity system optimizations applied this algorithm, including the multi-regional energy market integrating wind and PV [162], decentralized energy market proposed in [163, 164], real-time pricing scheme for social welfare maximization problem that can promote autonomous demand response in [165], P2P market clearing in [166], multi-regional interconnected market in [167], the coordination between transmission-level generation and distribution-level generation [168], and decentralized optimal multi-source flow of carbon trading market [169].

The optimality condition decomposition (OCD) is the most used decomposition method, where KKT conditions are settled directed. The mathematic essence of OCD is that the first-order KKT conditions are decomposed and settled by sub-problems. Newton-Raphson is used in each interaction to solve the optimized updated variables [170]. The coordination dispatch could be applied in the OCD-based decomposition. The dynamic economic dispatch of both the wind outlets and the grid markets could be settled by the OCD-based decomposition optimization [171], and the Coordinated dispatch of distributed power supply and heating supply could also achieve through OCD [172].

The dual decomposition is also a clearing method of local energy market. A pricing strategy based on dual decomposition is proposed in [173], where distributed prices are settled for the maximization of suppliers' benefit and the minimization of consumers' costs. The multi-sellers with multi-buyer model is decomposed applying dual decomposition into many single-seller with multi-buyers sub-systems [174].

#### 2.2.3.4 Bi-level algorithm

The bi-level optimization is used in large-scale optimization to settle the computational burdens. The decisions are made by the upper-level leaders, responded by the lower-level followers [175]. The leaders' decisions would be affected by the feedbacks of followers, being an interactional process. The bi-level optimization is a feasible solution as the interconnection and coordination between the transmission level and the distribution level naturally exist in the flexibility market.

The layered optimization model with the linear problems in both levels could be transferred to single-level optimization problem and settled by LP solver [135]. Operators and retailers are often the leaders in the bi-level model, where the real-time retail prices are settled to achieve the maximum profit. The followers in this model are consumers whose situations are considered for the cost minimization [173]. For the bi-level optimization with linear lower-level and nonlinear upper-level, the KKT conditions and duality theory is applied to transfer bi-level optimization into single-level one [176]. The profits of all participants could be given consideration in bi-level optimization problems.

The nesting method could also be used to settle bi-level optimization problem, that the optimization is applied in each level under iteration and nesting [177]. A bi-level retail market model is proposed in [178], the upper-level target of which is to maximize the retailer profit by settling retail prices, and the lower-level is to reduce consumer charges through load transfer. A nesting measure is proposed to deal with the bi-level optimization. GA is adapted in upper-level optimization, while the LP solver is applied in lower-level. A nesting method is proposed in [179], which includes the GA towards the upper-level and the MILP acting on the lower-level. A bi-level retail market clearing is developed in [180] where retailers and consumers launch energy transactions. The nesting is taken to solve the bi-level optimization that PSO is used in the upper level and the commercial solver is applied in the lower level.

# 2.3 Challenges of constructing distributed energy market

## 2.3.1 Requirement for technology updates

The technological barriers of local energy market include the immaturity of traded energy technologies, the immaturity of hardware technologies, and the computing complexity brought by the special P2P clearing.

#### 2.3.1.1 Immaturity of traded energy technologies

The products traded in the energy market are not the total mature ones, energies including ES systems like mental-air battery and solar fuel cryogenic, and diverse fuel cells, all possess the possibility of further maturation. The target of greenhouse emission also facilitates the development of distributed energies. Fundamentally speaking, the update of energy technologies themselves are not the concerned topics in market design, neither the attention of this research. However, it is still worthy to realize that the product design of market should pay attention to the resource technology characteristics.

#### 2.3.1.2 Immaturity of ICT technologies

The market participants' trusts towards the market itself and their counterparties should be improved to encourage the active engagement of energy suppliers and prosumers. The market transparency and the information communication are thus required. The key technique in realizing the centralized local energy market control and transactions is the ICT. Being the central component of local energy market, the ICT infrastructures could conduct the connections for market participants meanwhile guarantee the security. The controllability and observability of the physical process are realized by the ICT through ensuring communication signals. Appropriate progress is required in the integration, delivery, processing, and storage progresses of the signal. However, the network vulnerability risks themselves may be brought by ICTs, leading to issues like ineffective operational decision and the instability of voltages and frequencies.

#### 2.3.1.3 Computing complexity

The new introduced distributed energy resources possess the characteristics of small-scale and highly motivated, especially facing the demand-side responses. The computing complexity is triggered by two reasons, including the missing accuracy and its following problems brought by the error prediction, and the nonlinear modelling serving the massively introduced local energy market. The existing local market trails launches market integration to hedge the error prediction. However, the integration measure is a double-edged sword that the large-scale integration may cause the loss of control accuracy. Whether to and in what degree to adapt aggregators to integrate is an essential topic in market design. The appropriate algorithm is required after the introduction of demand-side responses to balance the local market operation speed and the objective conflicts in linear modelling. The highly tricky computing complexity would brough by the target to achieve both high economy efficiency and sufficient market matching results.

### 2.3.2 Requirement to market modelling

Considering of the smooth running and the sustainability of the market, the design of local energy market expects to possess enough attractiveness to potential market participants. For the factors that are respected by the participants, the costs play the most important role that the economic effectiveness is the primary motivation for energy exchange. The pricing settlement mechanism thus is important in market modelling. Apart from cost factors, other elements affecting the initiation of market participants include the convenience of market participation, the trust of participants towards market platform and their counterparties, and the participants' knowledge of energy markets.

#### 2.3.2.1 Convenience for market participation

Developed from the conventional consumers, the prosumers in the local energy market remain the being served mentality, preferring simple market transaction process. The operation results of Quartierstrom Market Trail show the market participants preferences in simple transaction system even when they can directly bid and affect the market prices. This result inspires the market design that market participants not only ask for the discourse power. Meanwhile, the market participants are expecting bilateral market interaction as they are not only the price taker in the market. The equal benefits of both parties in the market should be considered when repealing the energy subsidies and additional incentives.

#### 2.3.2.2 Trust towards platform and counterparties

The participants' trusts towards market are composed by trusts towards the transaction platform itself and that towards the other participants of market. Without the centralized authority in the P2P local energy market, the market participants need to realize the platform would guarantee the security and privacy of consumers meanwhile avoiding individual discrimination. The trust of participants towards counterparties evolves from their trusts towards energy suppliers in the current stage. The research from Cambridge University exposes the trust prejudice of consumers that they would predicate their selected suppliers the more enthusiastic and responsible one as long as they could receive messages from them. The actual horizontal comparison among suppliers could only be reached through the information publication and overlap, which again relies on the transparency namely the ICT technologies. The market transparency should be considered in the operation rules, including the disclosure process and the technically competent market.

#### 2.3.2.3 Knowledge towards energy markets

There is positive correlation between the market participation initiation and the policy familiarity they gain about the energy market. The involvement degree towards market would especially be triggered by the understanding of energy expenditure components. On average, the individual participant would be attracted by the immediate benefit and the perceived tangible things, indicating the importance of information disclosure in the market operation. Other unquantifiable benefits are not easy to be perceived by the consumers, like the reduction of carbon commission and the facilitation of energy transition.

### 2.3.3 Requirement to market management

The market regulation and management issues are composed by internal factors and external factors. The internal factors are mainly the roles and functions that should be taken by the market operators, while the external factors consider the policy support operating the market.

The transition from the DNO to the DSO is the maximum driving force to settle the roles and functions of market operators. Being the core of market devolution, the sufficient coordination between TSO and the DSO is crucial for grid stability. The measure and prediction under emergencies are always challenges of the market, that the appropriate functions of market operators are required in reducing unnecessary information sharing based on the problem settlement.

The systematic revolution brought by the decarbonization of the electricity system is promoted to the generation and transaction of electricity, offering development potentials to local flexibility resources and markets. Focused on the conventional centralized configuration, the on-going market regulation kind of impede the development of local flexibility markets, requiring changes of the existing regulation environment. The decline subsidies of wind and PV brings indeterminacy of the future local energy market, especially the energy community markets, making their final target to construct sufficient business model to earn profit without depending on subsides.

Meanwhile, the vulnerable and price-sensitive groups are especially protected in the market design. The guarantee of energy democratization asks for the tighter ties among energy market participants, preventing the discrimination towards participants.

## 2.4 Chapter summary

This chapter introduces the UK distributed energy market from the perspectives of both academy and industry.

From the industry aspect, three flexibility markets applying diverse typical pricing mechanism are introduced detailly. Markets are discussed from the points of product, operation rules and competition strategy respectively, and the horizontal comparison is launched among three markets to explore the consolidated rule of market design. From the academy aspect, the definition and structure of local flexibility market universally applied in the three typical markets are cognized in the chapter, with an emphasizing on modeling and clearing algorithm of the local flexibility market.

The major boundness and challenges of the distributed energy market construction includes: 1) Technical barriers including immaturity of major energy technologies, immaturity of hardware technology supporting market connection and disclosure, uncaptured of clearing algorithm supporting complex computing brought by special P2P business model. 2) discussable market design to attract adequate market participants, including the consideration of cost and price factor, market participating convenience, trust between market counterparties and the knowledge of energy market policies. 3) Dramatically-changed market form and the evocable changes in market regulations and the assorted roles of management institutions.

# Chapter 3

# Electricity Market Structure in the Distribution Sector

This chapter proposes to explore the structure of distribution-level market and its development complying with the diverse penetration levels of DERs. A multi-layered electricity market architecture is published, representing all the commercial elements in the electricity system. The entire supply chain and the corresponding stakeholders are illustrated visually.

# Statement of Authorship

| **This declaration concerns the article entitled:** | | | |
|---|---|---|---|
| Electricity Market Structure in the Distribution Sector | | | |
| Publication status: Published | | | |
| Publication details (reference) | L. Shan, Z. Zhang, C. Gu and F. Li, " Electricity Market Structure in the Distribution Sector," 2019 International Conference on Electricity Distribution, Madrid, Spain, 2019, pp. 1-5. | | |
| Candidate's contribution to the paper | The candidate proposed the idea of the paper, she designed the methodology and conducted the outlook of future electricity market structure. Other authors helped the candidate with the research direction, the format of the paper, and the improvement of academic writing. The percentage of the candidate did compared with the whole work is indicated as follows:<br>Formulation of ideas: 95%<br>Design of methodology: 100%<br>Presentation of data in journal format: 90% | | |
| Statement from candidate | This paper reports on original research I conducted during the period of my Higher Degree by Research candidature.<br>The original paper can be found on:<br>https://cired-repository.org/handle/20.500.12455/102<br>http://dx.doi.org/10.34890/204 | | |
| Signed | Lanqing Shan | Date | 21/12/2021 |

# Chapter overview

The publishment of carbon emission target policies and the development of decarbonization process enhances the infiltration of distributed energy resources in the end of electricity system. The distribution system is forced to proceed transition through smart loads brought by the integration of massive renewable energy resources and distributed energy generation. Both the complexity and the initiative of planning and operating the distribution system would be increased by the rapid-expanding distributed energy resources, creating new dimensions to the local balancing of electricity supply and demand. It's crucial to promote distribution business arrangement which could mobilize the value of DERs and assist DNO/DSO to discharge network obligation.

The entire commercial elements in the electricity system should be observed macroscopically through a sufficient electricity market structure. The current research towards electricity market structure could be divided into two categories: 1) Only energy market is emphasized on the structure, that market settling system demand0supply balance is discussed. The structure proceeding detailed exploration of energy market always proceeds in time series, including day-ahead market, adjustment period, and real-time market. For example, a market structural framework exhibiting commercial local demand-side flexibilities is proposed in FUSION project to settle the network congestion. 2) Although under the title of market structure, the actual outcome is closer to electricity industrial structure. The organization affiliation and entity syntagmatic relation is exhibited in the industrial structure. There is no mature structure could assist the exploration of market components alongside the electricity system supply chain.

To fill the gap, a market structure possessing all commercial elements in the electricity system supply chain is proposed in this chapter. The outlook of distribution-level market circumstance under the massive penetration of new-developed energies is proceeded in the research.

The main contributions of the chapter are:

1) Proposing distribution electricity system market structure which could reveal macroscopical market on the supply chain visually, offering direct understanding of the entire electricity market.

2) Representing future distribution electricity market structure which could provide fundamental cognition of transaction platforms under future energy scenario. More explicit research logic could be constructed to the target of distribution-level market.

3) Demonstrating crucial market information including market components of each layer, market functions and market stakeholders in the structure. The changes and development tendency of those key information could be traced under diverse industrial structures and future energy scenarios, offering better understanding of the responsibilities of each component in the future business.

## 3.1 Abstract

This paper proposes an electricity market structure in the distribution sector which connects all market components. Whilst existing research on the market is mostly focused on transaction arrangements and market adaptability under differing situations. The market structure of distribution systems proposed in this paper offers a systematic view of all markets in the entire supply chain, illustrating their roles and relationships. Meanwhile, a future electricity market structure of distribution systems is also discussed. This paper contributes in three areas: i) The proposed electricity market structure provides a method to study market structure from the whole picture, offering a benchmark of the current electricity market structure. ii) The functions and potential changes of market participators are explored and discussed, complying with the transition from DNO to DSO. iii) The demonstration of future market structure provides a glance of future market options, paving the way for future energy development and their commerce.

## 3.2 Introduction

The decarbonisation agenda has increased the penetration of low carbon technologies and distributed energy resources (DERs) at the end of the supply system. A large volume of distributed generation will be installed in the next ten years in the UK. The installation of distributed generation has already taken over 12% of the new capacity in the USA [181, 182]. In the meantime, the current distribution network operators (DNOs) are concerned about their roles under this energy revolution. Existing projects in the UK, such as Open Network and From Distributed Network Operator (DNO) to Distributed System Operator (DSO), reflect the enthusiasm of studying DSO business, indicating the potential value of DSO transition [183-187].

Through substantially enhanced operational efficiency at the distribution domain, a smart and flexible energy system can convert these DERs into highly valuable assets to improving the utilisation of distribution networks and critically the utilisation of distributed energy. A key step towards a smart and flexible energy system is the creation of vibrate markets at the distribution level, through which, buyers and sellers of DERs can meet at the distribution level, enabling the existing system to absorb growing DERs whilst delivering major value for DERs. It is therefore critically important to create efficient energy markets that reflect the characteristics of DERs and the needs of customers and deliver customised energy products and services to address local energy needs.

A structure of the electricity market is expected to illustrate the market from a macroscopic perspective, but unfortunately there is no mature version. The current research of electricity market structure is divided into two categories [188]: i) The structure only emphasizes the energy market. The components of the energy market are proposed alongside time sequence in the research, involving day-ahead market, adjustment period, real-time market and ancillary services. ii) Although being called as electricity market structure, some research put forward structure components according to the market liberalization degree, which is actually the power industry structure. (i.e., vertical unbundling without horizontal unbundling, partial vertical unbundling, full vertical and horizontal unbundling in generation, vertical unbundling in lesser forms than ownership unbundling, and unbundling of generation services in wholesale power markets). Very few research explores the market from the entire supply chain perspective, thus difficult to tackle the huge changes brought by the introducing of distributed energy resources and markets in the distribution sector.

To address the existing issues and promote energy transition, three pieces of work have been done in this paper: i) Proposing an electricity market structure in the distribution system and visualizing the situation of each market, offering an intuitional understanding of the entire electricity market. ii) Putting forward the future electricity market structure in the distribution system, providing a fundamental understanding of the future energy transaction platform. iii) Exploring the roles of DSO in the future electricity market and comprehending their responsibilities in the future business.

This paper is organized as follows: Section 2 introduces the multi-layer electricity market structure in the distribution system and provides a detailed discussion on market components at each layer; Section 3 proposes the future electricity market structure in the distribution system; Section 4 draws conclusions for this work.

## 3.3 Methodology

### 3.3.1 Reference Architecture

As discussed above, neither the accurate scope of the electricity market nor a clear market structure has been put forward. However, a reference architecture is valuable to electricity market construction. The Smart Grid Architecture Model (SGAM) developed by Smart Grid Coordination Group/ Reference Architecture Working Group provides reference architecture.

By using different perspectives and methodologies considering the development and conceptualization of the Smart Grid [189], the SGAM architecture proposes an overall Smart Grid-domain construction from a holistic perspective. The Smart Grid Architecture Model is illustrated in figure 3-1.

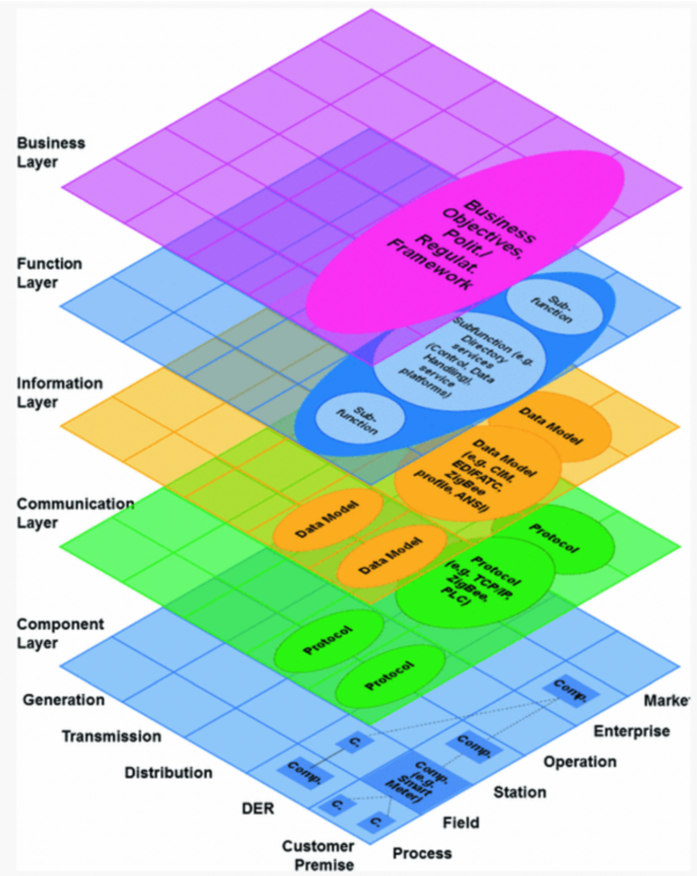



Figure 3- 1 The smart grid architecture model

Three sections (organizational, informational, and technical) are expressed in the architecture, with corresponding five layers, directly seen in the model. One single layer of the SGAM includes two dimensions, which describe not only the electrical energy conversion domains but also the electrical process management.

Taking the SGAM architecture as a reference, a similar multi-layer concept is adopted by the electricity market structure in the distribution sector proposed in this paper, which also contains necessary descriptions of a single market in each layer.

### 3.3.2 Current market structure

The electricity market structure in the distribution sector proposed in this paper presents a multi-layer architecture. The structure integrates commercial elements of the electricity system in the distribution sector with different layers and corresponding markets. The specific markets in each market layer are introduced and the function and participants are explained, providing the convenience for further exploration of each market layer. Figure 3-2 shows the proposed electricity market structure in the distribution sector under the UK electricity market background. The market presented in this structure is a generalized concept, that the entire tradable services in the electricity supply chain would be arranged and displayed under the form of market components.

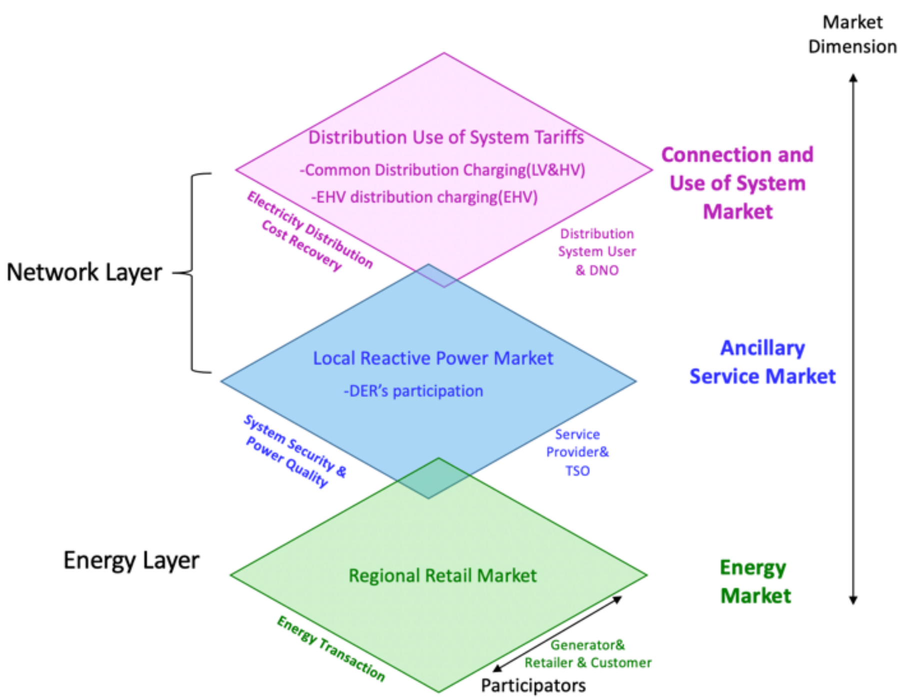



Figure 3- 2 Current electricity market structure in the distribution sector

### 3.3.3 Introduction of market dimension

Three layers are contained in the electricity market structure, corresponding to three markets from the market dimension. The energy layer only contains the energy market, responding for energy transaction. The second layer, network layer, contains two markets: i) Ancillary service market, ensuring system security and power quality ii) Connection and use of system market, recovering the cost of the transmission system.

Two perspectives of the network are illustrated in this layer, which fulfils network function (dealing with technical issues that may happen in the network delivery process) and satisfies the financial requirement.

The entire supply chain of the electricity market is expressed in the structure, whose operation and management processes are demonstrated through energy market and ancillary service market, and the financial issues are addressed through the connection and use of system market.

## 3.3.4 Introduction of different layers

Apart from different layers and corresponding markets from a macroscopic view, the major elements of markets — function and participators, are also indicated in the proposed whole-system market structure. A detailed introduction to each market layer towards those angles will be illustrated in the following parts.

## 3.3.5 Market components

### 3.3.5.1 Energy market

The energy market is the energy transaction platform, The only component of the energy market layer in the current distribution sector is the Cornwall Local Energy Market (in the UK). Operated by Centrica's Distributed Energy and Power Business, this trial in Cornwall is expected to set up a local transaction platform providing flexible demand, generation and storage, in order to fulfil the optimization of local grid capacity. The initial stage of establishing this regional local retail market is to solve the heavy grid constraints in Cornwall, which happens due to the large penetration of renewable generation with the limited network capacity. Compared to the traditional network reinforcement, the cost of the building local energy market is less and could save several years' time.

Although being constructed under specific demand, the participators of this regional retail market are similar to all other energy markets, which are generator, retailer and customer.

### 3.3.5.2 Ancillary service market

Also known as balancing services in some countries, the ancillary service market is responsible for balancing the demand and supply physically and ensuring electricity security and quality. The market, operated by Transmission System Operators (TSO), happens between TSO and corresponding service providers. The tradeable services are integrated and settled as components in the ancillary service market layer, including frequency response market, reactive power market, reserve market and security service market. The only component included in the current distributed sector is the trial of reactive power service, illustrating the penetration and participation of distributed energy resources. The reactive power service market fulfils voltage management, whose existence ensures system voltage level within an acceptable range. All the reactive power services, no matter those obligatory nor enhanced, could participate in the reactive power market.

#### 3.3.5.3 Connection and use of system market

The connection and use of the system market is the platform where network owners charge system users. Taking the function of cost recovery, the existence of connection and use of the system market ensures the long- term operation of networks and economic benefits. Some discussion towards market adapts the narrow definition of market that the network charging is not considered as market but only charges. However, the market structure proposed in this research incorporate all the tradeable services in the supply chain. Being a crucial segment which guaranteeing the long-term economy efficiency through cost recovery, the connection and use of system market is included in this market discussion.

There is a distribution use of system tariff market in the distribution sector, covering the cost of operating and maintaining electricity infrastructure (overhead lines, underground cables, substations and transformers) between the transmission system and end users. Accounting for around 15% of the overall electricity bill, the distribution use of system tariff has already been included in the electricity expense and does not need to be charged specifically [190]. However, the distribution use of system tariff market is still settled to guarantee the systematization and symmetry of connection and use of the system market layer.

Because the components of connection and use of system market appear between the network owner and system users, the Distribution Network Operator (DNO, the distribution network owner currently in the UK), is taking the responsibility of charging distribution use of system tariffs from distribution system users.

## 3.4 Future electricity market structure in the distribution sector

### 3.4.1 Future market structure

The number of market components in the future distribution sector for both the energy market and the ancillary service market. It is mainly due to the incremental independence degree of the distribution sector, as more markets for distribution level are needed when services of original markets are not covered. A future market structure in the distribution sector is provided in figure 3-3 to illustrate a clearer overview of the components.

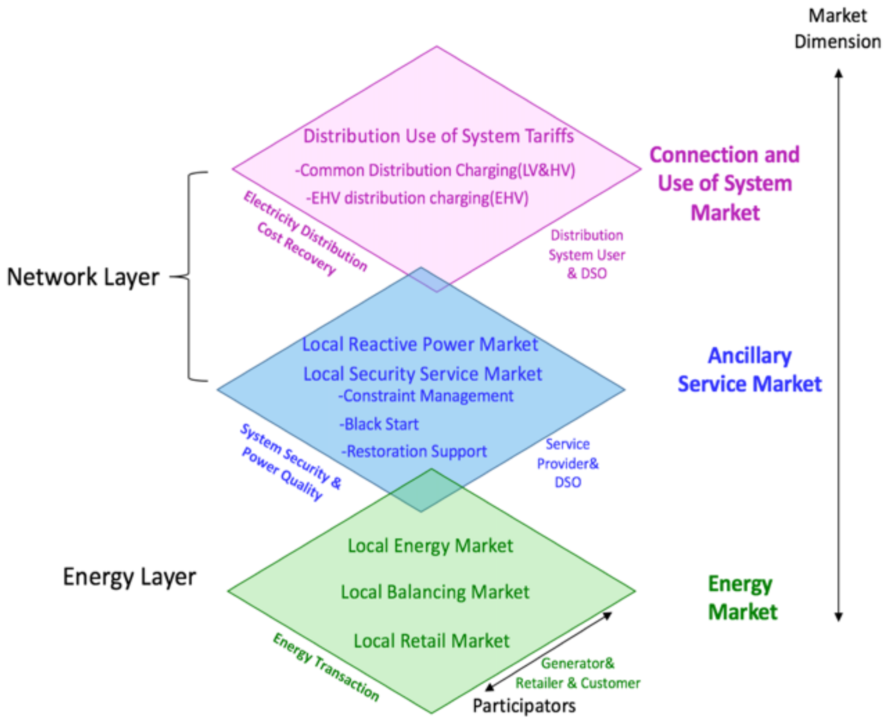



Figure 3- 3 Future electricity market structure in the distribution sector

#### 3.4.1.1 Future energy market

There are local energy markets, local balancing markets, and local retail markets in the future distribution energy market layer. Taking similar responsibilities of the national markets, the 'local' indicates the market transition from nation to distribution systems. The match of electricity supply and demand happens in the wholesale market, where generators trade with retailers or sometimes directly with customers [191]. Wholesale markets around the world adapt different trading methods. For example, transactions in the UK wholesale market take place bilaterally or on the exchange. And the National

Electricity Market (NEM) in Australia is under the pool model that trades and dispatches electricity centrally. The balancing market, i.e., the balancing mechanism in some countries, exists to ensure the real-time balance of supply and demand. Although this second-to-second balancing process in some countries may completely be synchronous with the wholesale transaction (NEM in Australia, for example), the component of balancing market is still put forward in the structure for the market symmetry. Given the opportunities to select retailers, customers in the retail market shop around their electricity suppliers to choose the one they are most satisfactory with. The retail market could be considered as a link between customers and energy, as retailers purchase electricity from the wholesale market and settle the delivery towards end consumers.

The penetration of DERs makes it a trend to construct a market specifically for the distribution sector, as the characteristics of DERs could be optimized under special market operation such as P2P trading. The current trial of the local energy market in Cornwall that introduced before also indicates the same direction. To categorize the supply-demand balance scenarios in the future distribution-level market, the local retail market and the local energy market are discussed separately on the energy market layer. Energy service companies exist in the local retail market under the discussion in this research, that a third party would connect the generators and consumers as retailers or aggregators. Local energy market is a multi-communication direction market, the prosumers launch peer-to-peer trading directly. The different trading arrangement compared to national markets leads an independent transaction system to be a better option, which means constructing the whole set of the energy market in the distribution level.

#### 3.4.1.2 Future ancillary service market

Other than the only reactive power market in the distribution sector of the current ancillary service market, the local reactive power market and the local security service market are settled in the future distribution ancillary service market.

The Open Network Project has put forward future DSO services, namely future ancillary services [192]. The real power service for constraint management, the reactive power service for voltage control, the whole-system approach to black start and restoration support are mentioned in the report. The voltage control corresponds to the local reactive power market, while the constraint management, black start and restoration support could integrate to the local security service market.

#### 3.4.1.3 Future connection and use of system market

To recover the network cost, the future connection and use of system markets in the distribution sector remain unchanged compared to the existing markets. Relating to the electricity infrastructure between the transmission system and end users, the distribution use of system tariffs exists in the connection and use of the system market layer.

For distribution use of system tariffs, there are common distribution charging and EHV distribution charging for low voltage (LV), high voltage (HV) and extreme high voltage (EHV) respectively.

### 3.4.2 Future market participants

Apart from the market components, the participators of markets in the distribution sector are also different between the current and future situations. In summary, the changes can be integrated as the transition from the DNO to DSO. The DNOs in the current electricity market structure are transferred to DSOs. To adapt the penetration of DERs, the DNO is developing from the current one-way delivery to future multiple points of variable supply and consumption of DSO. The existence of DSO in the ancillary service market layer are responsible for providing both operation and balancing services. The service providers trade with DSO, and many DSO services could also be expected according to the study of Open Network Project [193]. By charging from distribution system users, the DSO in the connection and use of system market share the same roles of DNO.

## 3.5 Conclusion

A multi-layer electricity market structure in the distribution sector is constructed in this paper, expressing entire commercial elements in the electricity system. The proposed electricity market structure covers operation and management, completing to describe the process from energy transaction, network delivery and participators’ cost recovery. Three products are offered in this paper:

- A structure to describe the current electricity market in the distribution sector is constructed, providing a macroscopic perspective of market research.

- The future market structure in the distribution sector is established, offering market situation under developing energy scenarios.
- The comparison of participators is made between current and future market structures, proposing deep understanding from perspectives of not only the structure itself but also market active parties.

This paper contributes in three areas: i) The proposed electricity market structure in the distribution sector offers a mentality to research market structure from entirety point of view, laying a foundation in understanding, constructing and operating distributed energy business. ii) The functions and possible changes in market participators are explored and discussed, complying with the transition trend from DNO to DSO. iii) The demonstration of future market structure in the distribution sector provides a glance of future market options, paving the way for future energy development and their commerce.

# Chapter 4

# Assessment of Communnity Energy Markets from Economy and Society Perspectives

This chapter proposes to assess energy market from the perspectives of economy efficiency and society feasibility under non-technical criteria. The typical trading methods applied in the real-world electricity markets are estimated, offering their feasibility under future distributed energy communities.

# Statement of Authorship

<table>
<tr><td colspan="4">This declaration concerns the article entitled:</td></tr>
<tr><td colspan="4">Assessment of Relative Efficiency of Differing Energy Markets for Community Energy</td></tr>
<tr><td colspan="4">Publication status: Published</td></tr>
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<tr><td>Candidate's contribution to the paper</td><td colspan="3">The candidate proposed the idea of the paper, she designed the methodology and assessment criteria, and conducted the comparison among existing methods. Other authors helped the candidate with the design of case studies, the format of the paper, and the improvement of academic writing. The percentage of the candidate did compared with the whole work is indicated as follows:<br><br>Formulation of ideas: 90%<br><br>Design of methodology: 100%<br><br>Simulation work: 100%<br><br>Presentation of data in journal format: 95%</td></tr>
<tr><td>Statement from candidate</td><td colspan="3">This paper reports on original research I conducted during the period of my Higher Degree by Research candidature.<br><br>The original paper can be found on:<br><br>https://www.cired-repository.org/handle/20.500.12455/1169<br>http://dx.doi.org/10.34890/248</td></tr>
<tr><td>Signed</td><td>Lanqing Shan</td><td>Date</td><td>21/12/2021</td></tr>
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# Chapter summary

The future distribution market structure and its development is proposed in chapter 3, where the end-users experience the transition from passive roles to active roles to participate the operation of distribution system with the infiltration of distributed energy resources. Some functions of market are also expanding from transmission system to distribution system. The transmission-level market may not completely fit the distribution system due to the diverse features of resources in different locations. The need to constructing appropriate distribution-level market always exists.

Existing research of electricity transaction arrangements focuses on two aspects: 1) Establishing and developing trading models 2) Stimulating the penetration of new-developed energy resources. The deficiencies are faced by current research: 1) Research emphasizes on one trading arrangement, failing to launch a horizontal comparison among different methods. 2) The market assessment criteria always launch from the technology perspective, focusing on the reliability, efficiency and security. The economy and society perspectives are less noticed.

Addressing the above problems, market assessment criteria is proposed in this chapter to fill the gap of estimating community energies from economy and society perspective. The efficiency comparison among current typical trading methods is carried out.

The major contributions of this chapter are:

1) Categorizing existing trading arrangements based on the auction theory and the contract theory, providing general analysis dimension
2) Proposing non-technical market assessment criteria containing economy efficiency and society feasibility, offering estimation benchmark for energy market and energy business models
3) Evaluating typical trading methods applied in the transmission-level markets using the proposed categorization and estimation standards, discussing their sufficiency under future energy scenarios.

## 4.1 Abstract

With the integration of distributed energy resources there is an increasing demand for small-scale trading platforms to utilise this distributed community energy effectively. The characteristics of a variety of trading methods need to be explored in order to establish a suitable trading market for community trading. However, there is minimal literature considering the distributed energy market and its trading arrangements. This paper presents a comprehensive assessment on the perspectives of theory and empirical cases of different market platforms. It: i) sets up market assessment criteria from the economy and society perspectives ii) evaluates electricity markets using listed criteria and reveals the characteristics of diverse trading arrangements according to the assessment results.

## 4.2 Introduction

The last century has witnessed a continuous increase in energy consumption which is predicted to continue. According to the International Energy Agency (IEA), global energy consumption will have a two-thirds rise in the coming 25 years, and the demand for electricity in the UK will double by 2050 [181]. In the meantime, the way of meeting demand is changing rapidly: Half of the new generation investment will be occupied by renewable energy sources, and distributed energy generation capacity will be doubled in the next ten years [182]. The development of energy supply makes it necessary to change the distribution system so that local generation and demand-side management meet the end-users' requirements and expectation.

Although the new distribution system is introduced because of its advantages of low cost, high efficiency, supply security and limited emissions, a suitable market has not been established. Therefore, there is an increasing demand for small-scale energy trading platforms to serve distributed community energy. To fulfill the requirements, it is necessary to explore the characteristics of a variety of trading arrangements through analyzing existing electricity markets worldwide.

Existing research of electricity trading arrangements mainly focused on two aspects [194-197]: 1) setting up and improving one trading model and 2) simulating current a trading model to suit the technique development (such as renewable energy involvement). This research has the following gaps: 1) Research on trading methods are likely to focus on one, specific arrangement, but fail to consider alternatives as a whole in the energy market. 2) Trading methods are not explored from the theoretical perspective, leading to ignorance of their economic principle.

To fill the research gap and deliver efficiency comparisons among existing trading methods in relation to community energy trading, this paper presents a comprehensive assessment. i) It analyzes trading methods from not only the system efficiency but also the economic efficiency perspectives. The economic principles of diverse trading arrangements are investigated, based on auction and contract theory. ii) Sets up evaluation criteria ranging from the layers of economy and society. iii) Typical electricity markets using different trading methods are estimated using the assessment criteria above. The trading method characteristics and their influences on the market are analyzed, making it possible to explore their applicability in the distribution energy system.

This paper is organized as follows: section 2 introduces different trading methods and the typical electricity markets waiting to be evaluated; section 3 presents the detailed market assessment criteria and indicators; section 4 demonstrates the performance of typical electricity markets, analysing trading methods from the perspectives of both theory and market operation results; whilst section 5 draws conclusions and gives the next steps for future work.

## 4.3 Trading method classification

There is no unified classification of trading methods and academy. A common situation is to divide the trading method into Centralized Trading and the Decentralized Trading. Centralized Trading includes the pool model, which possesses unified clearing price and the unified scheduling. Bilateral contract, trading over the counter and the electronic trading are always included in the Decentralized Trading, whose characters of peer-to-peer transactions and pay-as-negotiation model are emphasized. Another classification is to divide electricity market trading methods into the Pool Model, the Bilateral Model and the Exchange Model. The unified organization of transactions and scheduling is shown in the Pool Model, with the pay-as-clear pricing strategy. The Exchange Model possesses the uniform clearing as well, but intakes the pay-as-bid pricing strategy. The Bilateral Model includes negotiation contracts and over-the-counter trading, without central trading places.

This chapter accepts the classification definition put forward in Fundamentals of Power System Economics. Two trading methods, namely Bilateral Trading (including long-term contract, trading over the counter and electronic trading) and the Pool Model, are proposed and considered from the point of not only theory but also implication.

The parties of the contract sign bilateral contract through negotiation about the transaction amount and price in the Bilateral Trading. The delivery of the contract diverse from the intra-day to several-year ahead, with unchanged contracted quantity until gate closure.

Generators and electricity purchasers are the two sides of participants in this centralized electricity market, who quote their expected prices and quantities to the market operator as bids and offers respectively. Bids in the market are ordered by ascending price (that is also called 'in merit order') as the supply curve, and offers in the same time period are ordered by descending price as the demand curve. Taking the intersection of two curves as the market clearing points, all the bids whose quoting prices are lower than the clearing price and the offers whose quoting are higher than the clearing price have the qualification of entering real electricity transaction. As other generators are called 'out of merit', those successful ones are 'in merit' market participants。

Comprehensive market assessment criteria and their indicators from perspectives of both quantity and quality are illustrated, under which the operation of two typical wholesale electricity markets (the UK's Bilateral Trading market and the Australian Pool Model market) are estimated.

## 4.4 Assessment criteria

To estimate the application of different trading methods, assessment criteria from the perspective of economic efficiency and the society are established. Since this paper aims to evaluate trading methods from the view of market operation in theory, some technical conditions of real grids, such as network congestion, are ignored.

The indicators combine the quantity and quality analysis with the required calculation parameters and their equations are demonstrated in Table 4-1.

Table 4- 1 Numerical calculation parameters [198-203]

| Criteria/Indicator | Calculation Parameter | Formula | Description |
|---|---|---|---|
| Liquidity | Herfindahl-Hirschman Index (HHI) | $H = \sum_{i=1}^{N} s_i^2$ | $s_i$: Market share of firm i |
| | | | N: Firm number |
| | Bid-offer Spread | $SP = B - O$ | B: Bidding price |
| | | | O: Offer price |
| Stability | Price standard deviation | $s = \sqrt{\frac{\sum_{i=1}^{N}(x_i - \bar{x})^2}{N-1}}$ | $x_i$: Sample item observed number |
| | | | $\bar{x}$: Observation mean number |
| | | | N: Observation number |
| Manipulation | HHI | IB | IB |

The assessment criteria details and the indicators of each criterion are listed in Table 4-2.

Table 4- 2 Electricity market assessment criteria

| Benchmark Category | Criteria | Indicator |
|---|---|---|
| Economy Efficiency | Cost Reflectivity | Liquidity (HHI & Bid-offer spread) |
| | | Market signal |
| | | Risk |
| | Stability | Price standard deviation |
| | Market Manipulation | HHI |
| Society | Transparency | Price publicity level |
| | | Counterparty publicity level |
| | Simplicity | Ancillary mechanism number |
| | Feasibility | Technology friendly level |
| | | Customer negotiation position |

## 4.5 Case study and results

### 4.5.1 Cost reflectivity

#### 4.5.1.1 Liquidity

Theoretically, a market with a better competitiveness degree also has the advantage in liquidity, since active market participants provide more trading opportunities and a stronger transaction willingness. The liquidity of the market can be reflected by the Herfindahl-Hirschman Index (HHI), a lower value meaning a greater competitiveness. According to the Energy Trends: Competition in UK Electricity Market published by the department for Business, Energy & Industrial Strategy, the HHI in the UK wholesale energy market is 1152 in 2017 [204]. The HHI number in 2017 Australian National Electricity Market is 2473 according to the data from Australian Energy Market Commission, which is significantly higher than the value of UK in the same year. Stronger competitiveness is shown in the UK market [205].

The liquidity of the bilateral market can also be assessed by bid-offer spreads, which are shown in figure 4-1 for the UK wholesale market at different time periods [206]. The liquidity of bilateral market can also be assessed by bid-offer spreads. The bid-offer spreads in the UK published by Ofgem is shown in the figure 4-1 [206].

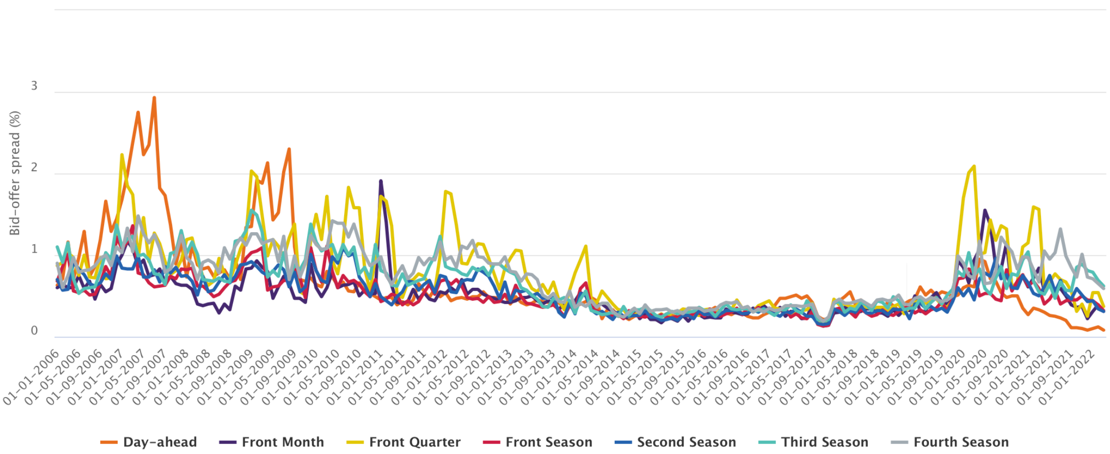



Figure 4- 1 Bid-offer spreads of UK wholesale market

Figure 4-1 indicates a downward trend of bid-offer spreads in the UK since 2006, stabilizing at a low level in 2014. The results provide evidence of good-performance liquidity in Bilateral Transaction operation, while the Pool Model has a relatively poor performance in this criteria assessment.

#### 4.5.1.2 Market signal

The definition of an efficient price signal is that a settled price could provide adequate information about market conditions (such as the relationship between supply and demand, changes in cost, etc.). Empirically speaking, the market using Bilateral Trading has a better price signal than that using the Pool Model. The price of bilateral contracts reflects more about the willingness of contracted parties, while the clearing price of marginal cost in the Pool Model can only represent the marginal information.

#### 4.5.1.3 Risk

Four species of risk, caused by diverse trading method choices, are extracted.

- Premium risk: risk of paying spread between contracted prices and spot prices
- Balancing risk: risk of taking part in the balancing market and accepting the unforeseen balancing market price.
- Counter-party credit risk: risk that counterparts may fail to perform
- Capital risk: risk of affording cash deposit against counter-party credit risk and lack of cash flow

The information of risks and their relationship between trading methods are shown in table 4-3:

Table 4- 3 Risk comparison result

| | Bilateral Trading | Pool Model |
|---|---|---|
| Premium Risk | √ | |
| Balancing Risk | √ | |
| Counter-party Credit Risk | √ | √ |
| Capital Risk | √ | |

As displayed in table 4-3, fewer risks are faced by the Pool Model, indicating an advantage in risk control and limitation.

### 4.5.2 Stability

The essence of market stability is the constancy of the price. Small fluctuations in price increase the confidence of market participants, which is beneficial for the market forecast and management.

The variability of market prices under diverse trading methods is assessed through practical market operation results. The electricity contract price of day-ahead base load in the UK wholesale market [206] and the volume weighted average spot price in the

Australia NEM [207] are considered, with the cumulative curves of the different fluctuation degrees in the two markets are depicted in figure 4-2.

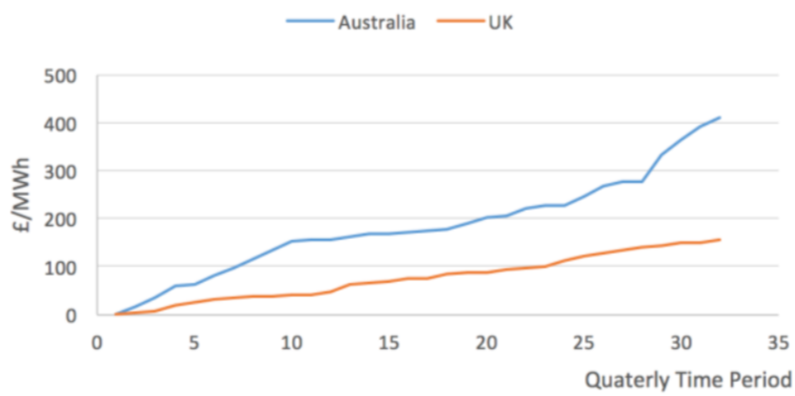



Figure 4- 2 Price cumulative curves

The price standard deviation in Australia (using the Pool Model) is 17.8 £/MWh, which is larger than the 6.34 £/MWh in the UK (using bilateral contracts), reflecting a more variable market. The low cumulative curve also reflects Bilateral Trading has a better price stability. This phenomenon can be explained as participants in bilateral contracts set prices through negotiation, which provides space for both sides to control the price scale, while prices in the Pool Model are only determined by the clearing result, dependent on marginal generation units.

### 4.5.3 Manipulation

Theoretically, more market manipulation is considered existing in the Pool Model comparing to Bilateral Trading, whose negotiation opportunities while contract making brings equal position and information disclosure to transaction parties. Collusion is easy to be reached in Pool Model. Generators in Pool Model have opportunities to observe the behaviors of other generators, which may facilitate collusion as they can detect departures from profit raising behavior and signal their displeasure.

The electricity price shown in the current Australia market illustrates the possible existence of manipulation. A preliminary report by the ACCC found that there is insufficient competition in the generation market. Rising prices and increasing entry barriers are noted. The history of the average annual capacity used by the largest generator in each region in NEM provides evidence of price control [208].

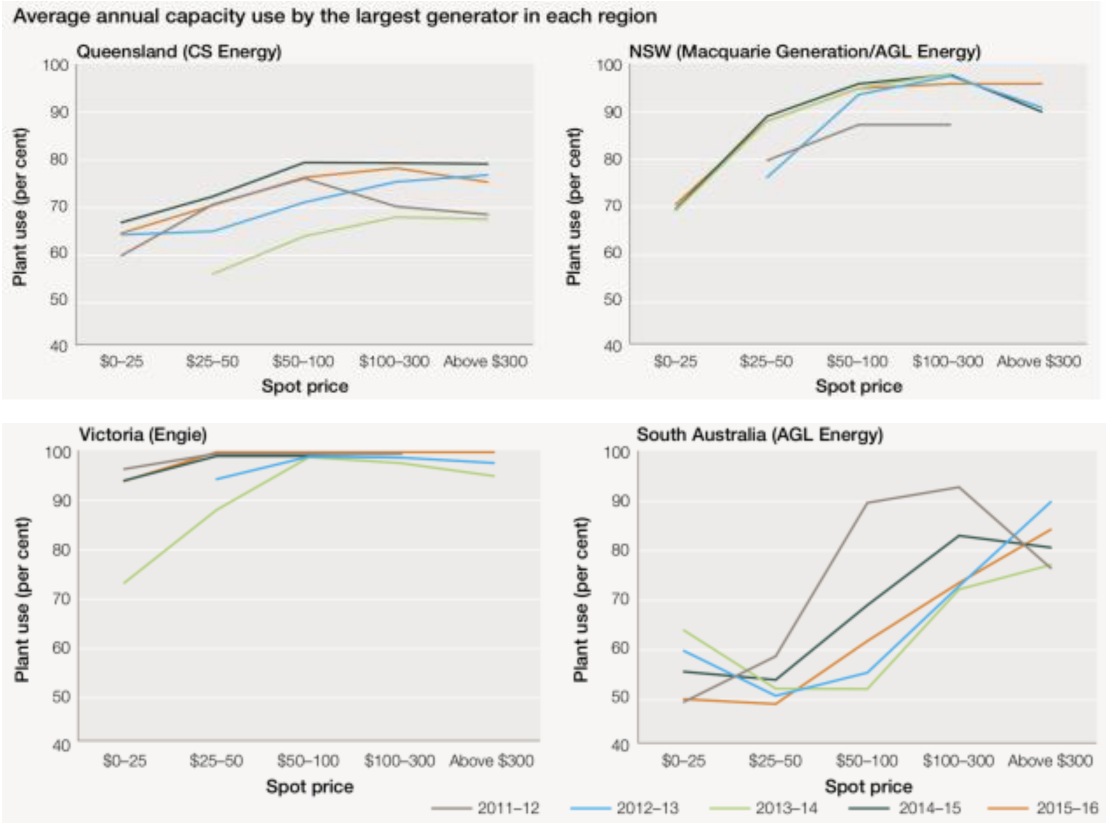



Figure 4- 3 Average annual capacity use in NEM, Australia

In a competitive market with rational generators, more power is likely to be produced when the price rising. However, the price charts above show that generators chose to reduce their output with increasing electricity price in some years. This phenomenon reflects a possibility of deliberately withholding capacity to reduce supply and influence the price.

Market manipulation can be measured by HHI, sufficient competition (low HHI) reduces manipulation as no participant has enough power to control the market result. As mentioned previously, the UK has a smaller HHI (1152) compared with Australia NEM (2473) which showed a higher market concentration.

### 4.5.4 Transparency

The transparency of Bilateral Transactions is better than the Pool Model according to the operation process of the two trading models. Three typical Bilateral Trading modes are the customized long-term contract, over the counter (OTC) and exchange trading. Closed information is used in the customized long-term contract and OTC, as only contracted parties know settled prices. The situations of the exchange transactions within the Pool Model are different, which make the clearing price of each trade public although participants are anonymous.

Both exchange trading and the Pool Model have transparent clearing prices but the transparency initiative of the two models are different. For market participants, the Pool Model is automatically transparent in price, as there is only one clearing price for the Pool Model. The price of exchange trading, on the other hand, can be seen as a mandatory disclosure--market participants can't acquire price information of other transactions through their own trading. The transparency situation of Bilateral Trading is better than that of the Pool Model for market participants but for the society the transparency of Bilateral Trading (whose price is not published) is worse than that of the Pool Model.

The opinion of the market transparency degree should be treated dialectically. On one hand, market manipulation is directly linked with poor market transparency, providing opportunities and convenience. On the other hand, the low transparency electricity market trading method is accompanied with high competitiveness, which helps to reduce the market power. The conflicted relationship between market transparency and market manipulation should be judged upon not only theory, but also experienced market operation results.

### 4.5.5 Simplicity

It is inaccurate to justify whether a trading method is simple and effective, since the trading operation under the specific arrangement is fixed. Rather than to describe a simple trading method, the level of a market's simplicity using that method is considered.

There is an appeal to value market simplicity, especially from industry, nowadays which has already been achieved in management science. Market simplicity itself gives efficiency and economy, as the simplification of process and mechanism saves both operation and human costs. A market which could remain simple while reaching construction goal must maximize utilization of resource and operation process.

Many existing mechanisms to counteract the negative effects of one trading method will change the market simplicity degree. The additional mechanisms under different trading methods reducing market simplicity are summarized in table 4-4.

Table 4- 4 Mechanism reducing market simplicity

| | Extra Mechanism | Against |
|---|---|---|
| Bilateral Trading | Contract for differences | Premium risk |
| | Balancing market | Balancing risk |
| | Individual data publishing | Low-transparency |
| Pool | Regulation and investigation | Market Manipulation |

### 4.5.6 Feasibility

The distribution energy community has particular characteristics, and a feasible trading method must satisfy those points.

From the perspective of technique, typical participants in distribution energy systems, such as storage, renewable energy and demand-side response, are small-scale and decentralize-controlled. Thus, the expecting trading method should suit the small trading volume and diversification quotation, clearing close-zero bidding normally. From the community feature point of view, the contribution of distribution energy community is to provide an efficient trading platform, mainly for incentivizing end-users. To encourage their involvement, both the economic benefits and the transaction position need to be guaranteed.

A comprehensive estimation needs to be made between two trading methods in exploring and comparing their feasibilities, thus the result of comparing feasibility will be drawn in the conclusion part.

## 4.6 Conclusion

According to the theoretical analysis and wholesale electricity market operation comparison in the UK and Australia, the result of horizontal research among different trading methods is illustrated.

- Bilateral Transaction has advantages in liquidity. market signal providing and market manipulation control.
- The Pool Model has a better performance in risk limitation, transparency, and market simplicity degree.

The number of benefits appears equal, but the final conclusion of deciding which is the better trading method involves more issues. Importance proportion and criteria preferences are practical judgments to ensure suitable characteristics for the distributed energy community. Generally speaking, Bilateral Transaction may be more applicable in dealing with close-zero bidding and ensuring all market participants' right. Nevertheless, its potential high risk, low transparency and complexity also bring problems, especially to the new and immature trading platform.

In summary, the advantages and disadvantages of different trading methods are obvious, but it is too early to jump to a final conclusion in constructing the distributed energy community. More work about the relationship between trading methods and their technical environments should be carried out in the future, and the situation of the trading method combination should also be considered as an important development direction.

# Chapter 5

# A Pay-as-bid Clearing Mechanism to Increase Transaction Quantity

This chapter proposes to increase clearing quantity of transacted energies to adapt the reliability requirements asked by the penetrating energy resources. A market design guaranteeing the priority of system reliability is published, with higher attractiveness to market participants, growth in market liquidity and the reduction in market manipulation.

# Statement of Authorship

| This declaration concerns the article entitled: | | | |
|---|---|---|---|
| A Decentralized Market Design to Increase Transaction Quantity Serving Diverse Future Energy Products | | | |
| Publication status: Published | | | |
| Publication details (reference) | L. Shan, H. Qin, Z. Zhang and F. Li, " A Decentralized Market Design to Increase Transaction Quantity Serving Diverse Future Energy Products " 2018 International Conference on Power System Technology, 2018, pp.835-842 | | |
| Candidate's contribution to the paper | The candidate proposed the idea of the paper, she designed the methodology, and predominantly executed the coding to derive the experimental results. Other authors helped the candidate with the design of case studies, the format of the paper, and the improvement of academic writing. The percentage of the candidate did compared with the whole work is indicated as follows:<br>Formulation of ideas: 85%<br>Design of methodology: 100%<br>Simulation work: 100%<br>Presentation of data in journal format: 90% | | |
| Statement from candidate | This paper reports on original research I conducted during the period of my Higher Degree by Research candidature.<br>https://ieeexplore.ieee.org/document/8601857 | | |
| Signed | Lanqing Shan | Date | 21/12/2021 |

# Chapter overview

The traditional market models applied in the mature electricity markets, no matter the pay-as-bid model or the pay-as-clear model, essentially settles the equilibrium points of the demand and supply curves as the clearing points. Although the maximum social welfare could be achieved applying those models, they are limited under the future energy scenarios. The infiltration of unpredictable and intermittent renewable energy resources brings indication to the system reliability, requiring more cleared energy volume to prevent the over-dependence of the balancing market.

To address above issues, the market model to increase clearing quantity is proposed in this chapter applied in the situation that the system reliability is considered as priority. An increased quantity pay-as-bid market model is firstly evolved from the current clearing rules in the original research, and a further optimization is explored towards the model reaching the maximum clearing quantity. The market models are discussed from both their market clearing results and their projected real-world application performances, compared with the traditional market models. The non-technical market assessment criteria proposed in Chapter 4 is applied in the market real-world operation.

The main contributions of this chapter are summarized as follows:

1) The market model which could maximize clearing quantities is proposed in this chapter, ensuring the reliability of future electricity system introduced massive renewable energies and distributed energy resources.

2) The simulations of bids and offers under the future energy scenarios are proceeded, including the hybrid energy market that the renewable energies bid together with the conventional generators, and the new-energy-only market only serving renewable energies and distributed energy market.

3) The appropriate application energy circumstance of the proposed market model is explored in the chapter through proceeding market evaluation, compared with the characters of traditional market models.

## 5.1 Abstract

This paper proposes a decentralized market arrangement that better reflects the cost of diverse energy resources and the flexibility of demand, thus able to offer a wide range of energy products. It contrasts to the centralized market that tends to represent the characteristics of the supply and demand of the entire system, but typically demand has very little price elasticity. The performances of the traditional market designs and the proposed decentralized market are compared from the perspective of market economy and system reliability under three different scenarios: i) The same market clearing prices and quantities ii) Complete market participant satisfaction arrangements are classified to those exploring centralized iii) Growth in clearing quantity and reduction in clearing price. market design (the pool model) and others working on the This paper contributes in three areas: i) An efficiency assessment by splitting the market into a number of segments in the single centralized market ii) The ability of the proposed market to promote demand flexibility iii) Market drive for more energy products to suit diverse requirements.

## 5.2 Introduction

Future 25 years is facing a great challenge in global energy consumption that the entire energy demand will have a two- thirds raise [209]. The penetration of new-developing energies such as distributed energy resources and renewable energies, brings urgent need of establishing specific transaction platforms suiting energies' economic and technical features (such as high price elasticity, dispatching flexibility and long-term prediction difficulty).

The existing market arrangements, in the classification of the decentralized market and centralized market according to the transaction divisibility, are explored to offer a future market in expectation. The centralized market arrangement in this paper refers to markets under the pool model, who has a uniform clearing price and the clearing electricity is dispatched centrally according to the operation center. The decentralized market arrangement contains bilateral contract and exchange transaction, whose clearing prices and quantities are differently settled and matched according to transaction pairs themselves. The decentralized market arrangement discussed in this paper is the exchange model. Considering the properties in trading amount and controllability of centralized market and the advantages in liquidity, competitiveness and transaction pair independence of decentralized market, it is ideally to establish a market design by combining the means of two markets.

Existing research focused on electricity market arrangements are classified to those exploring centralized market design (the pool model) and others working on the decentralized market design (the exchange model). The researches aiming to centralized market design carry out from three major perspectives: i) Investigation of pool-based market characteristics under practical situations [210, 211] ii) Optimization on economy efficiency [212] iii) Application of Pool Model with specific background [213, 214]. The research concentrating on decentralized market design focuses on two main directions: i) Bidding strategies under divers situation [215-217] ii) Modeling and simulating operation in different environment, and designing methods towards problems in operation experiences [218, 219]. It is noteworthy that bilateral negotiation market is also an important composition of the decentralized electricity market. However, it is beyond the scope of this paper because of the lack of special third-party platform in gathering bid and offer information, and there are not determined trading strategies and price settlement rules in the bilateral negotiation process.

As the summary above showed, nonexisting research ever thought outside the box and created a new market design by changing the fundamental market transaction strategies. All the current research are based on complying with transaction models and their rules.

To fill the research gap, a decentralized market arrangement is established, integrating strength of the decentralized market in flexibility, liberalization and transaction independency, as well as that of the centralized market in serving the demand of the entire system. The new market design aims to better reflect the cost of diverse energy resources and demand flexibility, thus offering a wide range of energy products. i) Specific transaction rules are cleared facing the proposed market model and its special situation that may occur ii) Performances of three market designs are analyzed from the perspectives of system reliability and market economy efficiency iii) The operation of the proposed market design under the scenario of future energy penetration is particularly analyzed, making further exploration of features and feasibility of the proposed market design.

This paper is organized as follows: section II introduces traditional market designs of both centralized market and decentralized market; Section III proposes a new decentralized market design, indicating its needed characteristics, transaction model and specific clearing rules; Section IV simulates operations under three market designs, exploring the proposed decentralized market through market result comparison. Section V draws a conclusion of the new market design on its operation result assessment and application.

## 5.3 Traditional market models

### 5.3.1 Traditional pay-as-clear market model

The pool model is a typical pay-as-clear electricity market arrangement, the transaction model of which is illustrated in figure 5-1.

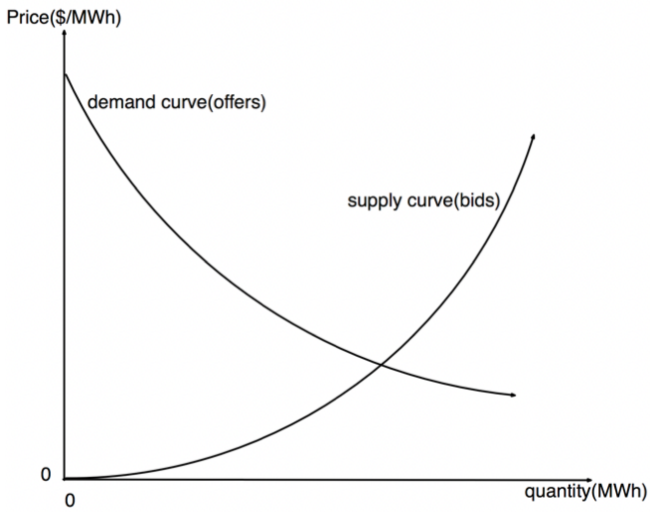



Figure 5- 1 Traditional pay-as-clear market transaction model

Generators and electricity purchasers are the two sides of participants in this pay-as-clear electricity market, who quote their expected prices and quantities to the market operator as bids and offers respectively. Bids in the market are ordered by ascending price (that is also called 'in merit order') as the supply curve, and offers in the same time period are ordered by descending price as the demand curve. Taking the intersection of two curves as the market clearing points, all the bids whose quoting prices are lower than the clearing price and the offers whose quoting are higher than the clearing price have the qualification of entering real electricity transaction. As other generators are called 'out of merit', those successful ones are 'in merit' market participants: The two key characteristics of the pay-as-clear market are uniform clearing price and central dispatching. All 'in merit' participants complete transactions at clearing price no matter how much they quote. The uniform clearing price may encourage generator offer bids in their practical cost thus stimulating healthy quoting, since they could benefit from a higher clearing price once receive the trading qualification. For central dispatching, all the 'in merit' generators are organized by system operator according to the trading day's least cost generation schedule [220].

## 5.3.2 Traditional pay-as-bid market model

Pay-as-bid market design discussed in this paper is the exchange model using in UK and EU nowadays. In a similar approach of setting clearing curves with the traditional pay-as-clear market, the exchange trading settles bids in ascending order as supply curve and offers in descending order as demand curve. Figure 5-2 indicates the transaction model of exchange trading.

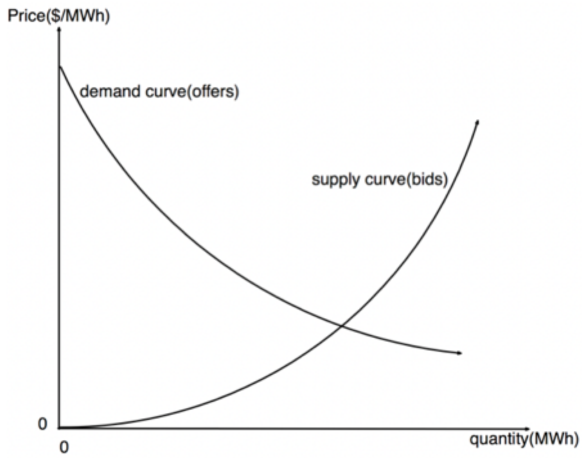



Figure 5- 2 Traditional pay-as-bid market transaction model

With the same process of determining trading qualification, the two major differences between pay-as-clear and pay-as-bid models are their imparities in price settlement and counter-party identification. Being a 'pay-as-bid' system, the successful participants under the exchange model are traded in one of their quoting prices, which are prices offered bids in reality exchange market. Without uniform clearing price, pay-as-bid trading complete not at the level of the whole system but peer-to-peer. Transaction pairs are settled as marking. The process of counter-party settlement is operated by exchange platform, who, as a third party, gather quoting information of bids and offers and confirm intersection and transaction pairs electronically. Although actual trading is completed peer-to-peer, the counter-party information in the exchange market is anonymous. Market participants, even successful ones, can only know the public prices [221].

An essential point of the pay-as-bid market is its ability of achieving market segmentation. Although all the bids and offers are gathered by a third-party platform, the transactions are processed individually but not from the perspective of the whole system. In a real balancing market using exchange model, a continuous trading is accepted. That is, new market entrants can be added into the existing order book and influence clearing immediately. With no central dispatching, the independence of the pay-as-bid market provides more freedom to participants, thus leading to a market having superiorities in liquidity, liberty and competitiveness.

## 5.4 Increased quantity pay-as-bid market model

### 5.4.1 Requirements towards the proposed market model

With the penetration of distribution resources and renewable energies, a new market platform is waiting to be set up in order to suit specific characteristics of those new-development resources.

One of the noteworthy characteristics of distribution and renewable energies is their independence, which means they enter into market in small entities. The flexibility of those individual units makes a segment-able market in requiring, stimulating the enthusiastic of market participating and optimizing new energies' application. Hence, the pay-as-bid market is a proper arrangement needing to be adapted in the new market design.

The existing pay-as-bid market is mainly served conventional generation capacities, which are mature and have no problem of lacking generation capacity. However, most renewable energies and distributed resources are more unpredictable in generation amount, leading to a low trading quantity in energy market. The potential risk in system reliability makes the enough transaction amount an important component in market establishment, especially in regions where system demand may not be totally satisfied under future energy trend. The market economy efficiency, in a sense, ranks in a lower level. Thus, the coming market is under the requirement of optimizing clearing quantity.

Although being a suitable market design as discussed above, pay-as-bid markets are literally weak in the entire-control ability. The intermittence of new-developed energies leads to the requirement of a system-level modulation, and their flexibility makes a real-time adjustment feasible. Therefore, it is essential to provide the possibility for system operators in electricity dispatching and offer options in choosing a suitable market arrangement flexibly.

### 5.4.2 Pay-as-bid market model to increase clearing quantity

Basing on three major points above, the model of new market design is shown in figure 5-3.

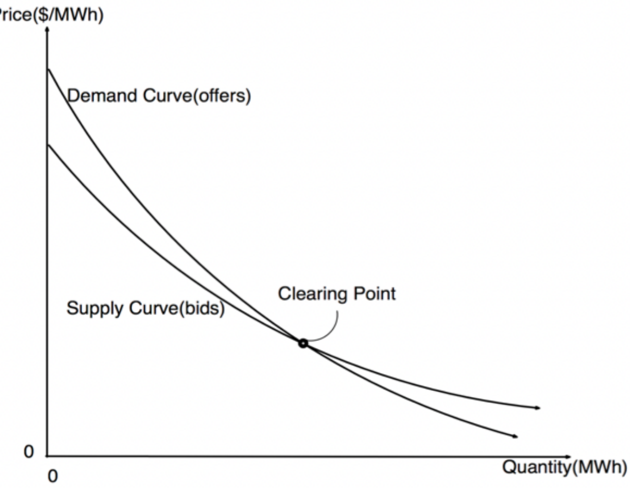



Figure 5- 3 New pay-as-bid market transaction model

Bids from generators and offers from purchasers are ordered in descending price as the supply curve and the demand curve. Being the intersection of two curves, clearing point in this model reflects the lowest price in once transaction. Being a pay- as-bid system, all bids and offers quoting higher than market clearing price have qualification in complete trading in the designed market, whose prices are settled peer-to-peer.

Different from the traditional pay-as-bid market, whose bids are ordered in merit and trades are completed pay-as-bid to reach market economy efficiency, the new market design is expecting a better performance in clearing quantity. The new market design makes changes in transaction pair matching strategy, realizing a larger range of clearing units thus leading to more clearing quantity.

### 5.4.3 Clearing rules

The proposed pay-as-bid model rationally is illustrated in the last section. As the clearing point is shown as the intersection of demand and supply curves (thus offer curve and bid curve respectively), the region in which quoting prices of both bids and offers are higher than the intersection price is transacted successfully. According to the trading process like this, all pairs whose offer quotes higher than bid are qualified in clearing, which conforms to the substance of satisfying transaction aspiration of market participants in best effort.

However, the unexpected result may occur in actual transaction process as the supply and demand curves are not smooth lines. Taking the cumulative quantity as the horizontal axis and the quoting price as the vertical axis, offers and bids complete curves in the shape of step in reality. In this way, more than one intersection of supply and demand curve can come out. The flowchart dealing with multiple intersections problem is shown in figure 5-4.

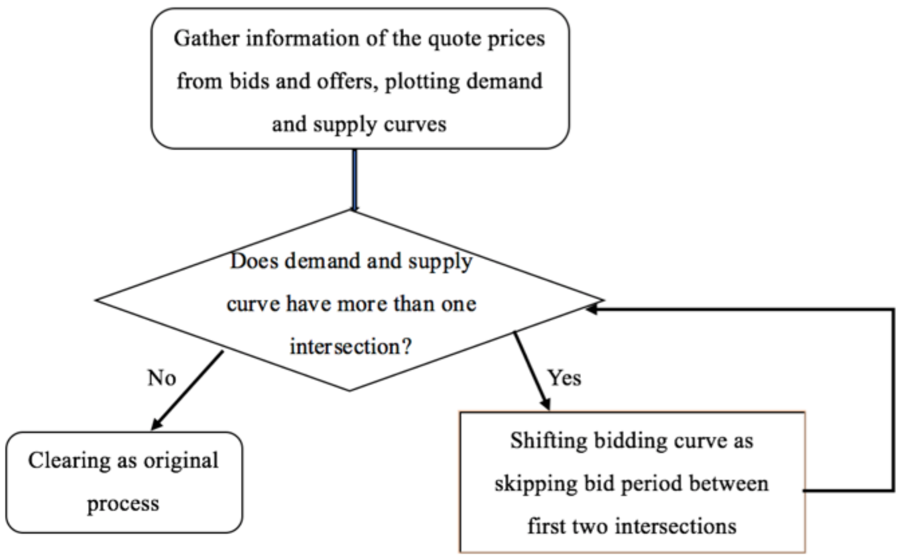



Figure 5- 4 Flowchart towards clearing curve with multiple intersections

Generally speaking, offers whose quoting price is higher than that of matching bids can conclude a transaction. Considering an extreme case that the first offer quotes higher than the first bid, leading to a success trading pair, while in the meantime the quantity provided by the first bid cannot be fully purchased by the first offer. The second offer should theoretically continue trading with the first bid, which however may not be feasible due to the uncontrollable gap between offers, that is the second offer may quote lower than the first bid. Traditional pay-as-bid model has and only has one intersection between curves, defining as the clearing point as well as the end of one transaction process. As bid prices are continually higher than offer prices after clearing point in the traditional model, it is rational to take the point as a trading boundary. However, things are much more different coming to the new pay-as-bid model as there are still some offers whose prices are higher than bid prices, leading to a need for further transaction. This is a specific issue that may occur in the clearing process of the proposed pay-as-bid model.

To deal with the problem, the precondition that clearing quantity is in the priority position in establishing the model needs to be considered, thus the transaction should continue as long as there are bids which could be satisfied by offers. On the promise of maximum matching, supply curve (bid curve) should be translated to skip the unsatisfied bid period and focus on the situation of rest bids and offers. Figure 5-5 describes both of the original and modified clearing curves.

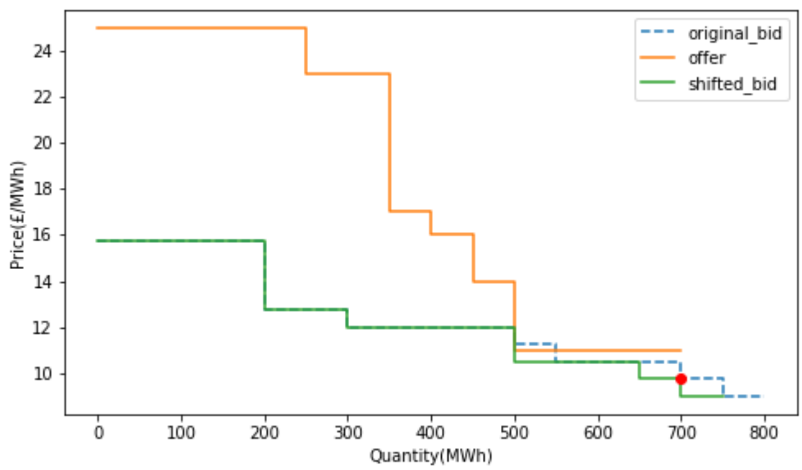



Figure 5- 5 Clearing curves holding more than one intersection

## 5.5 Case study

To explore the characteristics of the new model, a simulative market operation is organized using the bids and offers' information of Sylvania electricity pool, 11th June. Detailed input information is listed in table 5-1.

A clearing mechanism is proposed in this chapter, the comparison between which and the original clearing mechanism needs to proceed under the same quoting situations. The real bid and offer information of the electricity market is adapted in this case study with a certain relative relationship. Therefore, network modelling is unnecessary to perform to estimate the quoting information based on energy costs and network conditions.

Table 5- 1 Bids and offers' information of Sylvania electricity pool

| A | | | | B | | | | C | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Bid | | Offer | | Bid | | Offer | | Bid | | Offer | |
| Quantity | Price | Quantity | Price | Quantity | Price | Quantity | Price | Quantity | Price | Quantity | Price |
| MWh | $/MWh | MWh | $/MWh | MWh | $/MWh | MWh | $/MWh | MWh | $/MWh | MWh | $/MWh |
| 150 | 16 | 200 | 25 | 50 | 12 | 200 | 27 | 50 | 12 | 250 | 25 |
| 50 | 18 | 100 | 23 | 150 | 14 | 200 | 21 | 50 | 13 | 100 | 23 |
| 50 | 24 | 150 | 19 | 100 | 11 | 150 | 20 | 150 | 14 | 50 | 17 |
| 150 | 20 | 50 | 13 | 150 | 15 | 100 | 17 | 50 | 15 | 50 | 16 |
| 50 | 21 | 50 | 11 | 200 | 19 | 50 | 16 | 200 | 16 | 50 | 14 |
| 150 | 17 | 50 | 10 | 150 | 20 | 50 | 12 | 100 | 17 | 200 | 11 |
| 50 | 22 | | | 50 | 24 | | | 200 | 21 | | |

The market clearing results and situation of expenses/revenue under three market designs are compared, leading to further research on the assessment towards economy efficiency and system reliability of markets.

### 5.5.1 System reliability comparison

Three typical clearing scenarios are analyzed in this paper, whose numerical results under three market arrangements are illustrated in table 5-2:

Table 5- 2 Operation results under three typical clearing scenarios

| | Clearing Prices($/MWh) | | | Clearing Quantity($/MWh) | | |
|---|---|---|---|---|---|---|
| | Traditional | | New | Traditional | | New |
| | Centralized | Decentralized | Decentralized | Centralized | Decentralized | Decentralized |
| A | 18 | 18 | 17 | 350 | 350 | 450 |
| B | 19 | 19 | 16 | 550 | 550 | 700 |
| C | 16 | 16 | 16 | 450 | 450 | 450 |

The three types of clearing are classified according to the operation result relationship between the original and the proposed market design. Type A presents a scenario which has growth in quantity and reduction in price, being identical with the theoretical clearing results of the proposed arrangement. Figure 5-6 exhibits the clearing curve of type A.

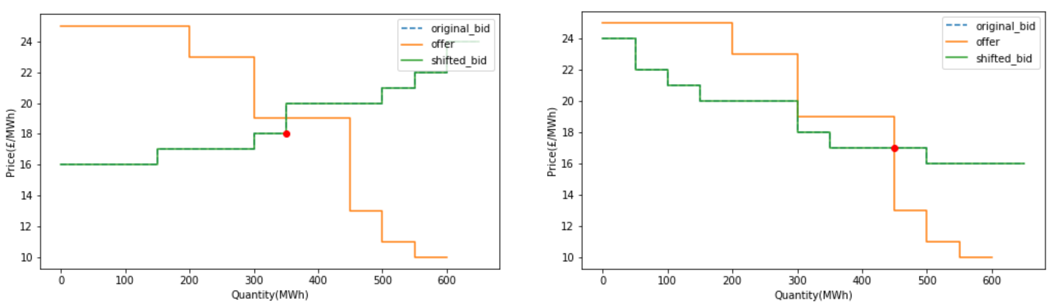



Figure 5- 6 (a) Clearing curve of traditional market designs of Type A (b) Clearing curve of proposed market design of Type A

The increasing in clearing quantity reflects an optimization in system reliability that more quantity could be transacted under the new market design. A new option is offered to market operators as thus, especially in the transaction situations where quantity weigh more than price, leading to the establishment of more flexible clearing process. This kind of selection right is essential to market operators that it has a similar function with the central dispatching process in typical pay-as-clear market. With original strength of pay-as-bid market in liquidity and competitiveness, the proposed market design also processes pay-as-clear market priority of controllability in this way.

Having the same change trend in clearing quantity and price with type A, type B is special in its completely clearing. That is, one side of bid or offer demand in the time interval can be totally satisfied. Figure 5-7 below demonstrates a situation that offers are totally cleared.

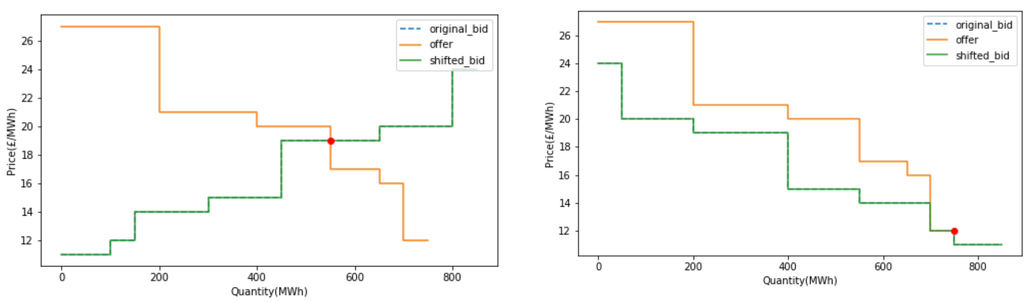



Figure 5- 7 (a) Clearing curve of traditional market designs of Type B (b) Clearing curve of proposed market design of Type B

This kind of clearing fulfill the expectations of the one side of market participants, which is impossible under traditional market arrangement. In the meantime, it owns all the priorities of Type A.

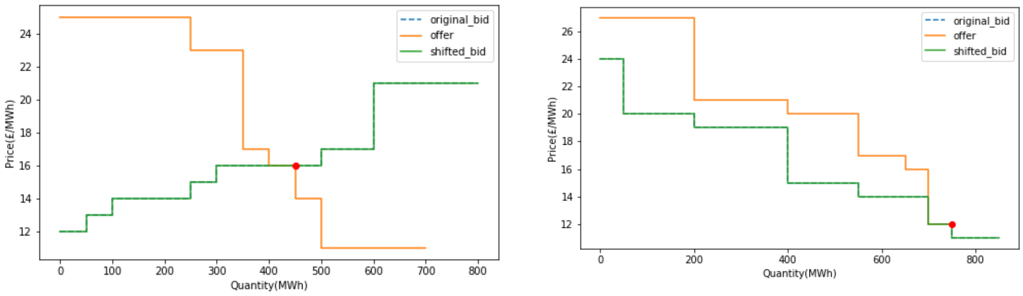



Figure 5- 8 (a) Clearing curve of traditional market designs of Type C (b) Clearing curve of proposed market design of Type C

Unlike the other two types which have increasing in clearing quantity thus a better performance in system reliability, the clearing quantity in Type C remains stable. The difference of Type C is only reflected from the market economy perspective through changes of expenses/revenues.

### 5.5.2 Economy efficiency comparison

The system economy efficiency is generally represented by the profit situation among market participants, thus expenses of offers and revenues of bids. Their ordinary formulas are:

$$Expense(Revenue) = Transaction\ Amount - Cost \tag{5-1}$$

Transaction amount here means entire money involved into the trading, and the cost is the overall cost of all the participants of one side.

Ignoring network technical problems such as congestion or network investment deferral, thus all successful units in market clearing can complete the transaction, pay-as-clear market parameter calculation before makes assumption that all generators quote in their cost. In this way, the expense/revenue function of the original pay-as-clear market is:

$$Ep_{pac} = CP \times CQ - \sum_{i=1}^{n} C_i \tag{5-2}$$

Where $Ep_{pac}$ is the total expenses of market participants in one pay-as-clear transaction, CP and CQ are clearing price and quantity. n is the number of successful participants, and $Ci$ means the unit cost of the participant i.

Under the same assumption, the formula of the traditional pay-as-bid market is:

$$Ep_{pab} = \sum_{i=1}^{n} P_i \times \sum_{i=1}^{n} Q_i - \sum_{i=1}^{n} C_i \tag{5-3}$$

$Ep_{pab}$ is the total expenses of market participants in one pay-as-bid transaction. $C_i$,$P_i$ and $Q_i$ are the unit cost, settlement price and quantity of participant i. To properly make comparison among traditional and proposed markets, guaranteeing the unification of variables, the same quoting of bids and offers are assumed in researched three markets. However, market participants who aware pay-as-bid strategy is adopted in reality will choose predicted market clearing price to ensure earnings, leading to the conflict of assuming them quoting in costs. Due to the complexity of quotation prediction, the estimation of generators' cost is avoided in this paper. Expenses of offers are used to evaluate market economy efficiency taking no account of costs. The modified expense calculation function is:

Pay-as-clear Market:

$$Ep_{pac\_modi} = CP \times CQ \tag{5-4}$$

Pay-as-bid Market:

$$Ep_{pab\_modi} = \sum_{i=1}^{n} P_i \times \sum_{i=1}^{n} Q_i \tag{5-5}$$

$Ep_{pac\_modi}$ and $Ep_{pab\_modi}$ are the modified expenses of pay-as-clear market and pay-as-bid market respectively. The calculation of expense involves the components of both price and quantity. As the quantity-related assessment is completed through system reliability comparison, this economy efficiency part tends to achieve estimation only involving price information, that is the equivalent average price.

The calculation function of average price is:

Pay-as-clear Market:

$$AveP\_pac = \frac{Ep_{pac\_modi}}{CQ} \tag{5-6}$$

Pay-as-bid Market:

$$AveP\_pab = \frac{Ep_{pab\_modi}}{CQ} = \frac{\sum_{i=1}^{n} P_i \times \sum_{i=1}^{n} Q_i}{CQ} \tag{5-7}$$

Comparison among markets is illustrated in table 5-3.

Table 5- 3 Equivalent average price of typical clearing scenarios under three market designs

| | Equivalent Average Price ($/MWh) | | |
|---|---|---|---|
| | Traditional | | New |
| | Centralized | Decentralized | Decentralized |
| A | 18 | 16.71 | 19.89 |
| B | 19 | 17.18 | 18.86 |
| C | 16 | 14.44 | 18.44 |

***Traditional Pay-as-bid Market vs Proposed Pay-as-bid Market***

As shown in table above, the equivalent prices of proposed pay-as-bid market are 19.89 $/MWh, 18.86 $/MWh and 18.44 $/MWh under three scenarios, larger than the 16.71 $/MWh, 17.18 $/MWh and 14.44 $/MWh from traditional pay-as-bid market. The equivalent average price will always show an increasing trend in the proposed pay-as-bid market design compared to the traditional pay-as-bid one, because of the synergetic ascending in trading quantities and prices. Growth in wholesale market expense may lead to a rise in retail market price. Unlike the traditional pay-as-bid market, the proposed market design cannot benefit consumers through restraining collusion thus pulling down retail prices, although adapting pay-as-bid as clearing strategy. In fact, the abilities to achieve market segmentation and individual transactions are the core significance of clearing through pay-as-bid.

***Traditional Pay-as-clear Market vs Proposed Pay-as-bid Market***

The comparison between traditional pay-as-clear market and the new pay-as-bid market is more complicated, due to the possible relationship between pay-as-bid and uniform clearing price. Shallows in figure 5-9 below drawn in two market models reflect expenses—further—the equivalent average price, under two market designs.

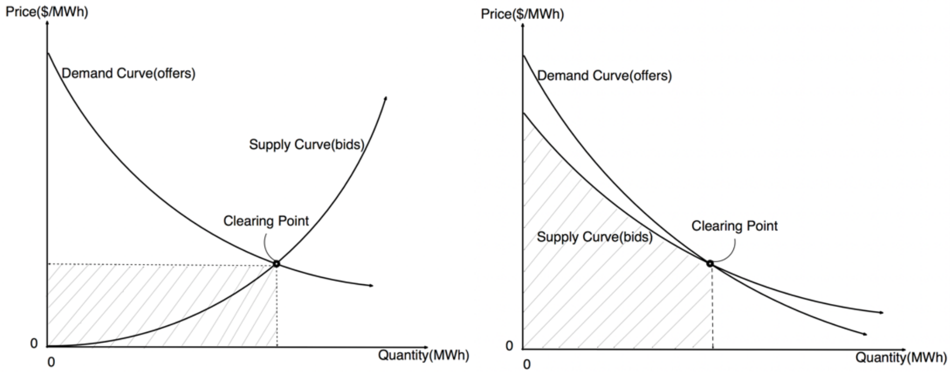



Figure 5- 9 (a) Market expense of traditional pay-as-clear market (b) Market expense of proposed pay-as-bid market

Depending on the relationship between uniform clearing price and the slope of bidding curve in the proposed market, expenses are now closely connected with the characteristics of participant technique (that is distributed energy resources and renewable energies in this paper). The result of sample case above has already indicated the undefinable relationship that the economy efficiency of type A has a better performance in new pay-as-bid model than that in the traditional pay-as-clear model, while which of type B and type C in the proposed model are inferior to that in traditional one. Since the market design is established mainly serving the future energies, a further exploration can be processed facing characteristics of new- developed generation resources.

### 5.5.3 Economy efficiency under future energy scenario

The pay-as-bid market design proposed in this paper aims at serving future energies such as renewable energies or distributed energies, which have a different quoting range comparing to conventional generation technologies. Those new-developed energies quote low in energy market because of their priority in costs, being considered as zero marginal cost (thus zero quoting) in the technology-mix market. Since the major market participants in the new market design are new- developed energies, their quoting in market are assumed as low but not zero, leading to a small slope supply curve. The supply curve of future energies compared to that of conventional generation capacities in the proposed market design is illustrated in the figure 5-10.

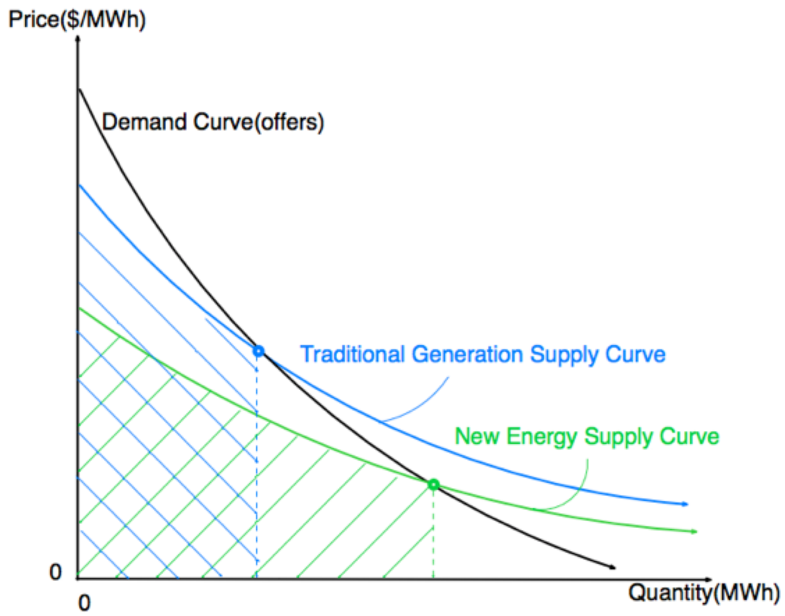



Figure 5- 10 Clearing curves of conventional generations and future energy resources

As mentioned above, the economy efficiency comparison between traditional pay-as-clear and the proposed pay-as-bid market design is uncertain, being blind in exploring market characteristics and application. Since the proposed market design is used under new-developed energy environment, a case study focusing on a small slope supply curve simulating future energy circumstance is presented.

Considering of the small quoting prices of renewable energy generators, the original bid prices are reduced in multiplying specific factors less than one. The market comparison between the traditional and the proposed market design under data assumption of future energies is illustrated in table 5-4 below:

Table 5- 4 Market operation results of three market designs under future energy scenarios

| Equivalent Average Price ($/MWh) | | | |
|---|---|---|---|
| Factor / Type | Traditional Centralized Market | Traditional Decentralized Market | New Decentralized Market |
| 1 | 18 | 16.71 | 19.89 |
| 0.9 | 18 | 15.7 | 17.9 |
| 0.8 | 16 | 13.96 | 15.91 |
| 0.7 | 14 | 12.21 | 13.72 |
| 0.6 | 12 | 10.62 | 11.4 |

The equivalent average price of traditional pay-as-clear market decreases from 18 $/MWh under factor 1 to 12 $/MWh companied under factor 0.6, which of proposed pay-as-bid market has the same trend reducing from 19.89 $/MWh under factor 1 to 11.4 $/MWh under factor 0.6.The operation result under future energy scenario of type A is quite typical that the equivalent average price of pay-as-bid market changes from bigger to smaller compared to that of the traditional pay-as-clear market, indicating a better performance in economy efficiency. The priority in economy efficiency under future energy scenarios illustrates the applicability of proposed market design, as the penetration of future energy resources has a positive incentive to market operation. The result also proves the statement mentioned before that there is not a stable economy efficiency situation, that component of the proposed market design needs to be analyzed individually under specific market participant backgrounds.

## 5.6 Commentary discussion

A proposed pay-as-clear market design has discussed in the published paper, and the optimization of that model is proceeding in the following research to achieve a model more in line with the increasing clearing quantity expectation. In the original market design, the high-priced buyers are matched with high-priced sellers, and the low-priced buyers are matched with low-priced buyers, to reach the target of as-much clearing quantity. The case analysis applying real-world electricity market data illustrate that the proposed market model could increase the market cleating quantity, which achieve the initial target to increase the system reliability facing developing future energies. However, the future energy scenario could be more cautiously explored, and a model guaranteeing the maximized clearing could constructed based on the original published model.

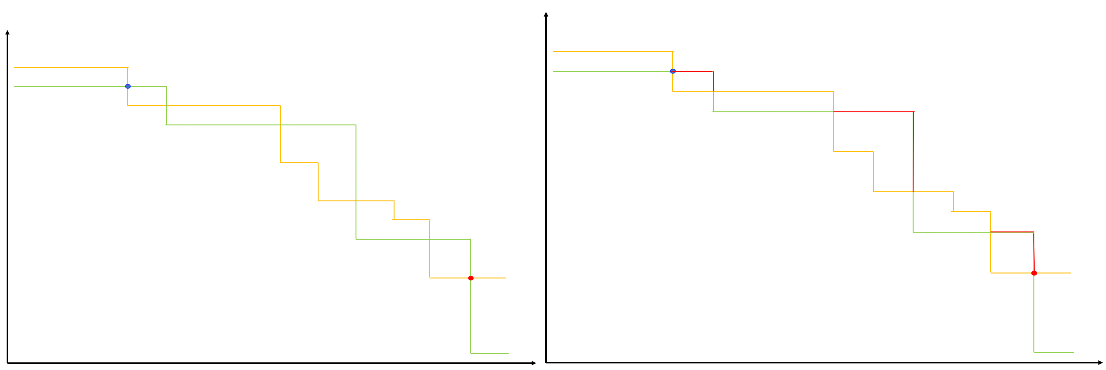
The renewable energies and distributed energy resources, who are proceeding further infiltration to the electricity system, quote much lower in the market clearing because of their features of their characteristics of low costs. The high-low mixed bids and offers brought by the mixture of new energies and conventional generators lead to changed demand-supply curves, so that the current proposed market design could not reach the best performance of increasing clearing quantity in this scenario. An optimization market model is thus presented based on the current proposed one, coming up to the more effective market clearing.

## 5.6.1 Optimized increased quantity pay-as-bid market model

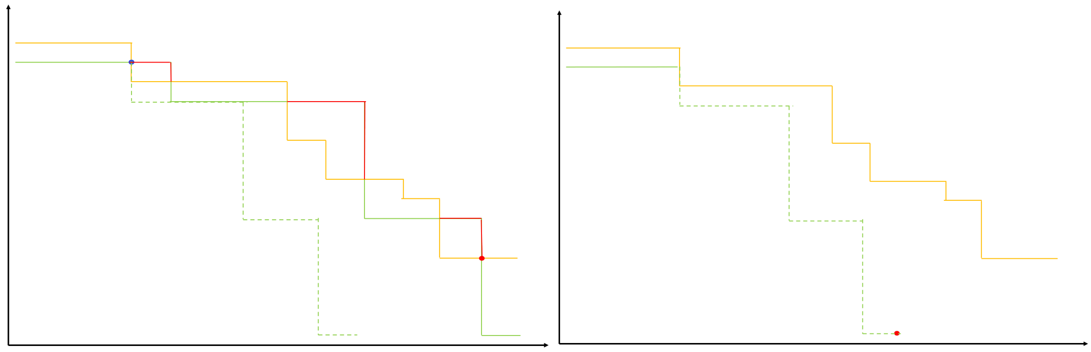
### 5.6.1.1 Limitation of original increased quantity market model

The clearing of the optimized market design is an optimization of the original published model. The bids and offers in current published market design are settled in the descending order, drawn cumulative demand and supply curves. The intersection point of the supply and the demand curve is the clearing point, indicating clearing quantity and the clearing price. Generators quoting higher than the clearing price could gain clearing certification

When there are multiple intersection points in the demand and supply curves, the bids within two intersection points are settled as 'invalid units' who cannot clear in the original clearing rule. The redrawn supply curve is composed by bids without invalid units. The clearing point are the intersection point between the demand curve and the multi-redrawn supply curve.



(a) (b)



(c) (d)

Figure 5- 11 Clearing curves and process of original-proposed pay-as-bid market

(a) Multi-intersection supply and demand curve

(b) Multi-intersection supply and demand curve with highlighted invalid units in red

(c) Clearing process of the original-proposed pay-as-bid market design

(d) Ultimate clearing of the original-proposed pay-as-bid market design

The clearing curves and process of the original-proposed pay-as-bid market are illustrated in the figure 5-11. The demand curves are drawn in yellow, and the supply curves are drawn in green. The multi-intersection supply and the demand curve are shown in (a), whose invalid units are highlighted with red lines in (b). Then the adjusted supply curve removing invalid units are illustrated in (d), whose shifting process is indicated in (c). The ultimate clearing point is the red point in figure (d).

Two points that can be optimized are found in this original proposed model:

1. The bids quoting higher prices may not clear while others quoting lower prices may receive clear certification because of the clearing rule dealing with multi-intersection demand-supply curves. This goes against the initial intention of descending clearing that higher-than-clearing bids could trade.

2. More quantities could be cleared but are prevented by the current published clearing rule. The published clearing quantity is the cumulative quantities of cleared bids, which locates within intersection point. But there may still be higher-than-bid offers who do not hold clearing certification, which could increase the clearing quantity of make success transaction.

#### 5.6.1.2 Optimized increased quantity market model

Considering of those two points, a maximize clearing quantity market model is presented as the optimized market design in this paragraph. Still allocate bids and offers under descending orders, the improved clearing rule provides the greatest opportunity between bids and offers. Participants within the first intersection point could still possess clearing certification in the improved clearing rule. The bids within lower-priced offer period should not be completely considered as invalid ones. After defining the highest-priced uncleared bid as the invalid, the following-priced bid should try to match with the first uncleared offer to expect a successful transaction. Bids and offers locate in the original uncleared period should match in this rule, until remaining prices of bids being higher than those of offers.

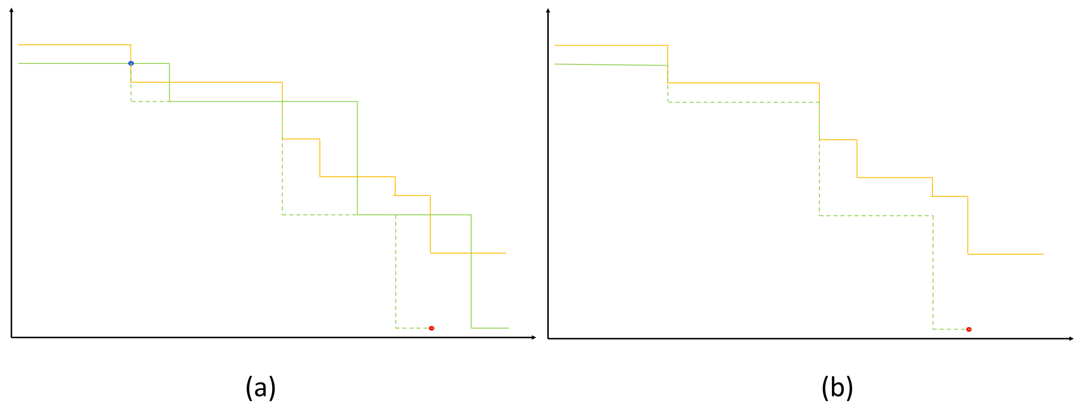



Figure 5- 12 Clearing rules of the optimized model

(a) Matching Process of the optimized model

(b) Final Clearing Curves of the optimized model

The clearing rules of the proposed model are illustrated in figure 5-12. The matching process is offered in (a), where the bids are ordered under the price descending sequence and matched with offers. The final clearing curves are shown in (b).

### 5.6.2 Commentary case study

Two perspectives including satisfying system and encouraging the engagement of new energies are required in the optimization model. The modern electricity system is equipped with basic objectives of security, reliability, and sustainability. The target of sustainability could be reinforced by the involvement of new energies, leaving the requirements of security and reliability waiting for more clearing quantity. So, from the system perspective, the clearing amount should be put in an important position when launching market design. The subsidy policies are adopted to encourage the participation of new energies in the real-world electricity market, illustrating the necessity of motivation when introducing new energies. Better market returns are expected from the perspective of energies.

#### 5.6.2.1 Renewable energy transaction settlement

The characteristics of distributed energies and renewable energies are similar, except for the flexibility feature of distributed energies, thus possess approximative bidding rules. The performance of proposed optimization model under the application of distributed energies could thus be stated under the renewable energy scenario.

The measures of renewable energies entering real-world electricity market includes:

1. Fixed feed-in tariff：The renewable energies are purchased by the grid companies under the government-decided fixed feed-in price. The over-paying money of companies could procure from subsidies or consumer apportionment. This renewable policy is applied in China, Finland, Japan, German, and Portugal [222].
2. Net metering: The residential renewable-generated energies could transfer to the utility grid reversely. This consumer surplus generation are settled at market prices. The US is the typical country undertaking net metering [222].
3. Premium Mechanism: The renewable energies would be paid at a premium rate basing on the fluctuant market prices. The premium mechanism often exists with the fixed feed-in tariff at one time, when the renewable energies could make their own option between the mechanisms. Countries including Spain, Denmark and the Netherlands adopt this mechanism [222, 223].
4. Energy Tender: Tenders for renewable energies are launched under this strategy in France, Denmark and the Netherlands. The offshore wind is the type of energy mostly traded through tenders as their contracted bidding price [222].
5. Renewable Energy Green Certification: Norway, Sweden and the U.S. is running Green Certifications. The renewable energy market is separated from the conventional energy market, where the market shares of renewable energies are stipulated [222].

6. Contract of Differences: The renewable energy generators would be paid or asked for the differences between contracted prices and market priced by the government-owned companies. This is the energy policy applied in the U.K. at present [222].

In conclusion, three major categories could summarize the renewable energy procurement including fixed price, premium payment and clearing amount guarantee. Therefore, the proposed market should also consider the satisfying price and the clearing quantity. Those methods for renewable energies entering actual market could be considered as subsidy or disguised subsidy policies, where the renewable energy market is separated to the conventional energy market in essence. The market with renewable energies should thus be discussed according to whether the renewable energies participate bidding fairly with conventional generators.

The bidding strategy for renewable energies are:

1. Pay-as-clear traditional market: The renewable energies would bid as very low price, in order to guarantee their clearing certification under the unique clearing price traditional market. The clearing price under traditional market locate in the conventional generator bidding prices, which always much higher than that of the renewable energies. The renewable energies in this kind of market would always make profits as long as they are successfully cleared, so that they would bid at close-to-zero prices to ensure clearing.

2. Pay-as-bid traditional market: The renewable energies would quote higher prices than those in the complete competitive market so that they could gain more profit in the pay-as-bid market. The energies would allocate their bidding prices between fair price and the clearing price, assuring the successful clearing with extra return.

The performances of proposed optimization market design are analyzed when introducing distributed energy resources. Two scenarios are discussed including the energy hybrid scenario and the new energy-only scenario.

#### 5.6.2.2 Simulated bids and offers of market involving renewable energies

***Hybrid energy market***

The common-used method of the hybrid energy market takes considers renewable energies as negative demand, that the demand curve would shift to a patten without the amount of participating renewable energies [224]. To discuss the feasibility of proposed market design under more participants, the actual auction data from Slovenia used in the paper's analysis are integrated in one sclearing.

Table 5- 5 The integrated data of bids and offers from the Slovenia Electricity Market

| Bid | | | Bid | | | Offer | | | Offer | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| No. | Quantity | Price | No. | Quantity | Price | No. | Quantity | Price | No. | Quantity | Price |
| | MWh | $/MWh | | MWh | $/MWh | | MWh | $/MWh | | MWh | $/MWh |
| 1 | 150 | 16 | 12 | 200 | 25 | 1 | 200 | 25 | 12 | 50 | 12 |
| 2 | 50 | 18 | 13 | 100 | 23 | 2 | 100 | 23 | 13 | 250 | 25 |
| 3 | 50 | 24 | 14 | 150 | 19 | 3 | 150 | 19 | 14 | 100 | 23 |
| 4 | 150 | 20 | 15 | 50 | 13 | 4 | 50 | 13 | 15 | 50 | 17 |
| 5 | 50 | 21 | 16 | 50 | 11 | 5 | 50 | 11 | 16 | 50 | 16 |
| 6 | 150 | 17 | 17 | 50 | 10 | 6 | 50 | 10 | 17 | 50 | 14 |
| 7 | 50 | 22 | 18 | 200 | 27 | 7 | 200 | 27 | 18 | 200 | 11 |
| 8 | 50 | 12 | 19 | 200 | 21 | 8 | 200 | 21 | | | |
| 9 | 150 | 14 | 20 | 150 | 20 | 9 | 150 | 20 | | | |
| 10 | 100 | 11 | 21 | 100 | 17 | 10 | 100 | 17 | | | |
| 11 | 150 | 15 | | | | 11 | 50 | 16 | | | |

The comparison between traditional market designs and the proposed optimization market is explored, the interrelationship is more important rather than the absolute value of prices and offers. The actual market auction data shown before could be considered as a standard one.

The National gird Future Energy Scenarios (FES) 2020 published the installed electricity capacity in 2019, and the projected installation amount in 2030 and 2050. The total installed energy in 2019 is 111.50 GW, where 50% is renewable energies. The average projected installed capacity in 2030 from four scenarios is 159.12 GW (1.5 times of the 2019 installation), where 75% is renewable energies. And the average projected total installation in 2050 is the 2.5 times of 2019 installation, with the renewable energies would take a proportion of 95%. Launching the negative load of renewable energies, the market data in 2019, 2030 and 2050 are shown in table 5-6, 5-7 and 5-8 [13]. The increased installation in future years mostly come from the incremental renewable energy resources, and the contribution of conventional energies is almost unchanged. Therefore, the bids of conventional energies are unchanged in

2030 and 2050, while the negative demand statistic should comply with both the renewable energy percentage and the increasing total demand.

Table 5- 6 Simulated bids and offers of the hybrid energy market in 2019

| Bid | | | Bid | | | 50%Offer | | | 50%Offer | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **No.** | **Quantity** | **Price** | **No.** | **Quantity** | **Price** | **No.** | **Quantity** | **Price** | **No.** | **Quantity** | **Price** |
| | MWh | $/MWh | | MWh | $/MWh | | MWh | $/MWh | | MWh | $/MWh |
| **1** | 150 | 16 | **12** | 200 | 19 | **1** | 100 | 25 | **12** | 25 | 12 |
| **2** | 50 | 18 | **13** | 150 | 20 | **2** | 50 | 23 | **13** | 125 | 25 |
| **3** | 50 | 24 | **14** | 50 | 24 | **3** | 75 | 19 | **14** | 50 | 23 |
| **4** | 150 | 20 | **15** | 50 | 12 | **4** | 25 | 13 | **15** | 25 | 17 |
| **5** | 50 | 21 | **16** | 50 | 13 | **5** | 25 | 11 | **16** | 25 | 16 |
| **6** | 150 | 17 | **17** | 150 | 14 | **6** | 25 | 10 | **17** | 25 | 14 |
| **7** | 50 | 22 | **18** | 50 | 15 | **7** | 100 | 27 | **18** | 100 | 11 |
| **8** | 50 | 12 | **19** | 200 | 16 | **8** | 100 | 21 | | | |
| **9** | 150 | 14 | **20** | 100 | 17 | **9** | 75 | 20 | | | |
| **10** | 100 | 11 | **21** | 200 | 21 | **10** | 50 | 17 | | | |
| **11** | 150 | 15 | | | | **11** | 25 | 16 | | | |

Table 5- 7 Simulated bids and offers of the hybrid energy market in 2030

| Bid | | | Bid | | | 1.5×25%Offer | | | 1.5×25%Offer | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **No.** | **Quantity** | **Price** | **No.** | **Quantity** | **Price** | **No.** | **Quantity** | **Price** | **No.** | **Quantity** | **Price** |
| | MWh | $/MWh | | MWh | $/MWh | | MWh | $/MWh | | MWh | $/MWh |
| **1** | 150 | 16 | **12** | 200 | 19 | **1** | 75 | 25 | **12** | 18.75 | 12 |
| **2** | 50 | 18 | **13** | 150 | 20 | **2** | 37.5 | 23 | **13** | 93.75 | 25 |
| **3** | 50 | 24 | **14** | 50 | 24 | **3** | 56.25 | 19 | **14** | 37.5 | 23 |
| **4** | 150 | 20 | **15** | 50 | 12 | **4** | 18.75 | 13 | **15** | 18.75 | 17 |
| **5** | 50 | 21 | **16** | 50 | 13 | **5** | 18.75 | 11 | **16** | 18.75 | 16 |
| **6** | 150 | 17 | **17** | 150 | 14 | **6** | 18.75 | 10 | **17** | 18.75 | 14 |
| **7** | 50 | 22 | **18** | 50 | 15 | **7** | 75 | 27 | **18** | 75 | 11 |
| **8** | 50 | 12 | **19** | 200 | 16 | **8** | 75 | 21 | | | |
| **9** | 150 | 14 | **20** | 100 | 17 | **9** | 56.25 | 20 | | | |
| **10** | 100 | 11 | **21** | 200 | 21 | **10** | 37.5 | 17 | | | |
| **11** | 150 | 15 | | | | **11** | 18.75 | 16 | | | |

Table 5- 8 Simulated bids and offers of the hybrid energy market in 2050

| Bid | | | Bid | | | 2.5×5%Offer | | | 2.5×5%Offer | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **No.** | **Quantity** | **Price** | **No.** | **Quantity** | **Price** | **No.** | **Quantity** | **Price** | **No.** | **Quantity** | **Price** |
| | MWh | $/MWh | | MWh | $/MWh | | MWh | $/MWh | | MWh | $/MWh |
| **1** | 150 | 16 | **12** | 200 | 19 | **1** | 25 | 25 | **12** | 6.25 | 12 |
| **2** | 50 | 18 | **13** | 150 | 20 | **2** | 12.5 | 23 | **13** | 31.25 | 25 |
| **3** | 50 | 24 | **14** | 50 | 24 | **3** | 18.75 | 19 | **14** | 12.5 | 23 |
| **4** | 150 | 20 | **15** | 50 | 12 | **4** | 6.25 | 13 | **15** | 6.25 | 17 |
| **5** | 50 | 21 | **16** | 50 | 13 | **5** | 6.25 | 11 | **16** | 6.25 | 16 |
| **6** | 150 | 17 | **17** | 150 | 14 | **6** | 6.25 | 10 | **17** | 6.25 | 14 |
| **7** | 50 | 22 | **18** | 50 | 15 | **7** | 25 | 27 | **18** | 25 | 11 |
| **8** | 50 | 12 | **19** | 200 | 16 | **8** | 25 | 21 | | | |
| **9** | 150 | 14 | **20** | 100 | 17 | **9** | 18.75 | 20 | | | |
| **10** | 100 | 11 | **21** | 200 | 21 | **10** | 12.5 | 17 | | | |
| **11** | 150 | 15 | | | | **11** | 6.25 | 16 | | | |

***New energy-only market***

It goes against to the fairness of market that renewable energies would take difficult-to-regulate bidding strategies when clearing together with conventional generators. The separated renewable energy market is thus arranged.

A notable point considering the data used to simulate the liberalized renewable-only market is that there are no referential historical statistics, since the current renewable energy markets are disguised subsidized. The quoting prices from those market have no reference value. The cost structures of diverse energies are discussed to predict the bidding prices of renewable energies. Table 5-8 shows the energy cost related information from BEIS Electricity Generation Cost [225].

The pre-development cost and the construction cost are the two components from the fixed cost, and the other costs are variable cost. Energies in the electricity market bid as marginal prices, which are economically relevant to the variable prices. The relationship between variable cost of conventional generators and renewable energies is equal to that between bidding prices of the two energy types. The average variable cost of conventional generation is 79.2 £/MWh, and those of typical renewable energies are 23 £/MWh, 26 £/MWh, 15 £/MWh and 8 £/MWh respectively. The relative prices of the energies are illustrated in the table 5-9.

Table 5- 9 Costs of diverse energy generation types and their relative prices

| | **Fossil Fuel** | | | | | **Renewable Energies** | | | |
|---|---|---|---|---|---|---|---|---|---|
| **£/MWh** | **Coal-ASC** | **Coal-IGCC** | **CCGT Post Comb** | **CCGT H Class** | **OCGT** | **Nuclear** | **Offshore Wind** | **Onshore Wind** | **Solar PV** |
| **Pre-Development Cost** | 2 | 2 | 2 | 0 | 5 | 7 | 5 | 4 | 6 |
| **Construction Cost** | 72 | 78 | 41 | 7 | 63 | 66 | 69 | 42 | 49 |
| **Fixed Cost** | 74 | 80 | 43 | 7 | 68 | 73 | 74 | 46 | 55 |
| **Fixed O&M** | 11 | 12 | 5 | 2 | 17 | 11 | 23 | 10 | 8 |
| **Variable O&M** | 6 | 5 | 3 | 3 | 3 | 5 | 3 | 5 | 0 |
| **Fuel Costs** | 24 | 26 | 48 | 40 | 60 | 5 | 0 | 0 | 0 |
| **Carbon Costs** | 6 | 8 | 3 | 29 | 43 | 0 | 0 | 0 | 0 |
| **CCS Cost** | 17 | 18 | 7 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Decommissioning &Waste** | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 0 |
| **Variable Cost** | 64 | 69 | 66 | 74 | 123 | 23 | 26 | 15 | 8 |
| **Average variable Cost** | | | 79.2 | | | 23 | 26 | 15 | 8 |
| **Relative Price** | | | 1 | | | 0.3 | 0.35 | 0.18 | 0.1 |

The relative price of fossil fuels is settled at 1 in the relative price mechanism, which could be considered as a benchmark. The relative prices of other energies are then a multiplier factor, that the simulated prices of those energies are launched as the multiply of original prices and the corresponding relative prices.

The proportions of different types of renewable energies in 2019, 2030 and 2050 are shown in the table 5-10.

Table 5- 10 Proportion of diverse renewable energies in 2019, 2030 and 2050

| Year | 2019 | | 2030 | | 2050 | |
|---|---|---|---|---|---|---|
| | **Installed Capacity(GW)** | **Proportion** | **Installed Capacity(GW)** | **Proportion** | **Installed Capacity(GW)** | **Proportion** |
| **Nuclear** | 9.25 | 20.87% | 5.35 | 6.19% | 11.22 | 6.06% |
| **Solar PV** | 12.95 | 29.22% | 25.04 | 29.01% | 58.36 | 31.5% |
| **Offshore Wind** | 9.51 | 21.46% | 32.80 | 38% | 78.92 | 43.09% |
| **Onshore Wind** | 12.61 | 28.45% | 23.13 | 26.8% | 35.84 | 19.35% |

The bids of renewable energies could be considered as a scaling-down total energy, so the relative prices and percentage of energy types in biding data are equal to those in total energy market. The bids in new-energy-only market are illustrated in table 5-11, 5-12 and 5-13.

Table 5- 11 Bids and offers of the new-energy-only market in 2019

| Bid | | | Bid | | | Offer | | | Offer | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **No.** | **Quantity** | **Price** | **No.** | **Quantity** | **Price** | **No.** | **Quantity** | **Price** | **No.** | **Quantity** | **Price** |
| | MWh | $/MWh | | MWh | $/MWh | | MWh | $/MWh | | MWh | $/MWh |
| **1** | 75 | 4.8 | **12** | 100 | 4.75 | **1** | 100 | 2.5 | **12** | 25 | 2.16 |
| **2** | 25 | 6.3 | **13** | 75 | 3.6 | **2** | 50 | 4.14 | **13** | 125 | 8.75 |
| **3** | 25 | 4.32 | **14** | 25 | 2.4 | **3** | 75 | 5.7 | **14** | 50 | 4.14 |
| **4** | 75 | 2 | **15** | 25 | 4.2 | **4** | 25 | 2.34 | **15** | 25 | 1.7 |
| **5** | 25 | 3.78 | **16** | 25 | 3.9 | **5** | 25 | 3.85 | **16** | 25 | 2.88 |
| **6** | 75 | 5.1 | **17** | 75 | 4.9 | **6** | 25 | 3 | **17** | 25 | 4.9 |
| **7** | 25 | 7.7 | **18** | 25 | 1.5 | **7** | 100 | 4.86 | **18** | 100 | 3.3 |
| **8** | 25 | 2.16 | **19** | 100 | 2.88 | **8** | 100 | 2.1 | | | |
| **9** | 75 | 1.4 | **20** | 50 | 5.1 | **9** | 75 | 4.4 | | | |
| **10** | 50 | 1.98 | **21** | 100 | 2.1 | **10** | 50 | 1.7 | | | |
| **11** | 75 | 5.25 | | | | **11** | 25 | 5.6 | | | |

Table 5- 12 Bids and offers of the new-energy-only market in 2030

| Bid | | | Bid | | | Offer | | | Offer | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **No.** | **Quantity** | **Price** | **No.** | **Quantity** | **Price** | **No.** | **Quantity** | **Price** | **No.** | **Quantity** | **Price** |
| | MWh | $/MWh | | MWh | $/MWh | | MWh | $/MWh | | MWh | $/MWh |
| **1** | 168.75 | 5.6 | **12** | 225 | 3.42 | **1** | 225 | 2.5 | **12** | 56.25 | 2.16 |
| **2** | 56.25 | 3.24 | **13** | 168.75 | 2 | **2** | 112.5 | 9.1 | **13** | 281.25 | 2.5 |
| **3** | 56.25 | 8.4 | **14** | 56.25 | 8.4 | **3** | 168.75 | 6.65 | **14** | 112.5 | 8.05 |
| **4** | 168.75 | 2 | **15** | 56.25 | 4.2 | **4** | 56.25 | 2.34 | **15** | 56.25 | 3.06 |
| **5** | 56.25 | 3.78 | **16** | 56.25 | 2.34 | **5** | 56.25 | 1.98 | **16** | 56.25 | 2.88 |
| **6** | 168.75 | 5.95 | **17** | 168.75 | 1.4 | **6** | 56.25 | 1 | **17** | 56.25 | 1.4 |
| **7** | 56.25 | 6.6 | **18** | 56.25 | 2.7 | **7** | 225 | 4.86 | **18** | 225 | 3.85 |
| **8** | 56.25 | 2.16 | **19** | 225 | 1.6 | **8** | 225 | 7.35 | | | |
| **9** | 168.75 | 2.52 | **20** | 112.5 | 5.1 | **9** | 168.75 | 6 | | | |
| **10** | 112.5 | 1.1 | **21** | 225 | 7.35 | **10** | 112.5 | 5.95 | | | |
| **11** | 168.75 | 5.25 | | | | **11** | 56.25 | 2.88 | | | |

Table 5- 13 Bids and offers of the new-energy-only market in 2050

| Bid | | | Bid | | | Offer | | | Offer | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| No. | Quantity | Price | No. | Quantity | Price | No. | Quantity | Price | No. | Quantity | Price |
| | MWh | $/MWh | | MWh | $/MWh | | MWh | $/MWh | | MWh | $/MWh |
| 1 | 356.25 | 1.6 | 12 | 475 | 3.42 | 1 | 475 | 2.5 | 12 | 118.75 | 2.16 |
| 2 | 118.75 | 5.4 | 13 | 356.25 | 2 | 2 | 237.5 | 6.9 | 13 | 593.75 | 8.75 |
| 3 | 118.75 | 4.32 | 14 | 118.75 | 4.32 | 3 | 356.25 | 6.65 | 14 | 237.5 | 2.3 |
| 4 | 356.25 | 7 | 15 | 118.75 | 4.2 | 4 | 118.75 | 2.34 | 15 | 118.75 | 3.06 |
| 5 | 118.75 | 7.35 | 16 | 118.75 | 2.34 | 5 | 118.75 | 3.85 | 16 | 118.75 | 5.6 |
| 6 | 356.25 | 5.95 | 17 | 356.25 | 1.4 | 6 | 118.75 | 3.5 | 17 | 118.75 | 2.52 |
| 7 | 118.75 | 3.96 | 18 | 118.75 | 2.7 | 7 | 475 | 4.86 | 18 | 475 | 1.1 |
| 8 | 118.75 | 4.2 | 19 | 475 | 5.6 | 8 | 475 | 7.35 | | | |
| 9 | 356.25 | 1.4 | 20 | 237.5 | 1.7 | 9 | 356.25 | 2 | | | |
| 10 | 237.5 | 3.3 | 21 | 475 | 7.35 | 10 | 237.5 | 5.95 | | | |
| 11 | 356.25 | 5.25 | | | | 11 | 118.75 | 5.6 | | | |

#### 5.6.2.3 Market clearing results analysis

The market assessment of the discussed models mainly proceeds from two perspectives: 1. Analyzing the market clearing results, including clearing quantity and clearing price. 2. Launching market estimation applying the published non-technology market assessment criteria. The proposed market model is expected to achieve the initial target of increasing clearing quantity and meanwhile reach a better performance under the comprehensive market operation assessment. The market models explored in this research are under the scenario of high infiltration of new energies, that the market models are discussed from the demand-supply balance perspective rather than considered network-related issues. Therefore, only the non-technology perspectives including economy efficiency and society impacts are discussed in the market assessment criteria.

***Hybrid energy market in 2019***

The hybrid energy markets in this research are the ones serving transaction platforms for both the conventional generators and the new energies. The introduced new energies are always settled as negative demand under this scenario [224]. The clearing results of traditional pay-as-clear model, traditional pay-as-bid model and the optimized pay-as-bid model are explored in the following discussion. The new energy takes a proportion of 50% demand in the total energy requirement in 2019, using which the simulated quotes of hybrid energy market are presented. The market clearing results of hybrid energy market scenario in 2019 are introduced in figure 5-13:

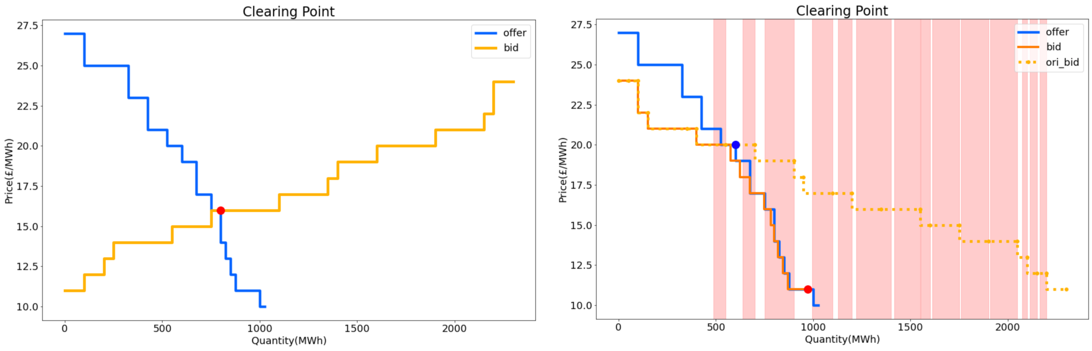



Figure 5- 13 Clearing results of the models under hybrid energy market scenario in 2019

(a) traditional market models (b) optimized market models

The clearing curves of traditional models, no matter the traditional pay-as-clear model or the traditional pay-as-bid model, are shown in figure 5-13 (a). The clearing curves and the clearing quantities of the wo models are the same. The only difference of the two traditional models is that successful bids under the pay-as-clear model are paid under the unique clearing price, while those under the pay-as-bid model receive quoting-priced bids. The 2019 hybrid market applying traditional models are cleared under the quantity of 800 MWh as a price of 16 \$/MWh.

The clearing curves of proposed optimized model are shown in figure 5-13 (b), whose demand curve and supply curve are both under the descending order. The shifted supply curve is introduced to settle the multi-intersection issue, whose detailed rules are explained in 5.6.1. The offer prices are continuously higher than the bid prices before the first blue intersection point, while others may face the problem of higher bid prices. The essence of the clearing is to reach successful match as much as possible. Therefore, the remaining offers are matched from the high-priced to the low-priced remaining bids one by one, expecting a maximize clearing. The actual clearing point is shown as the red point. The 2019 hybrid market applying optimized model is cleared under the quantity of 971 MWh as a price of 11 \$/MWh

The clearing quantity of the proposed model is 21.38% more than that of the traditional models. This result is identical to the maximize clearing idea in designing the optimized model.

According to the market expense formula and the calculation of average relative price, the average prices of three market models are 16 \$/MWh (traditional pay-as-clear model), 13.69 \$/MWh (traditional pay-as-bid model) and 18.71 \$/MWh (optimized pay-as-bid model). The average relative prices of traditional pay-as-clear model are larger than those of traditional pay-as-bid model is a certain event. The qualified units are the same in the traditional models, while the pay-as-clear model takes the maximize cleared bid price as the clearing price. The average price of traditional pay-as-bid model is thus naturally less than that of the pay-as-clear model. The optimized model, which is constructed to encourage the clearing and starts clearing from the high-priced units, would introduce more units as the successful clearing ones. Thus, the average relative price of the optimized model is hugely possible higher than that of the traditional models.

***Hybrid energy market in 2030***

The hybrid energy market in 2030 is similar with the one in 2019 from the perspectives of market quote simulated and negative demand equivalence. The bidding information is unchanged in two years since the bidding curve represents the willingness of conventional generators. As the new energies are settled by negative demand, only reduced-demand offer curve and original bid curve is required in the market clearing illustrating the transactions of conventional generators. The clearing curves of traditional models and the optimized model in 2030 hybrid energy market are:

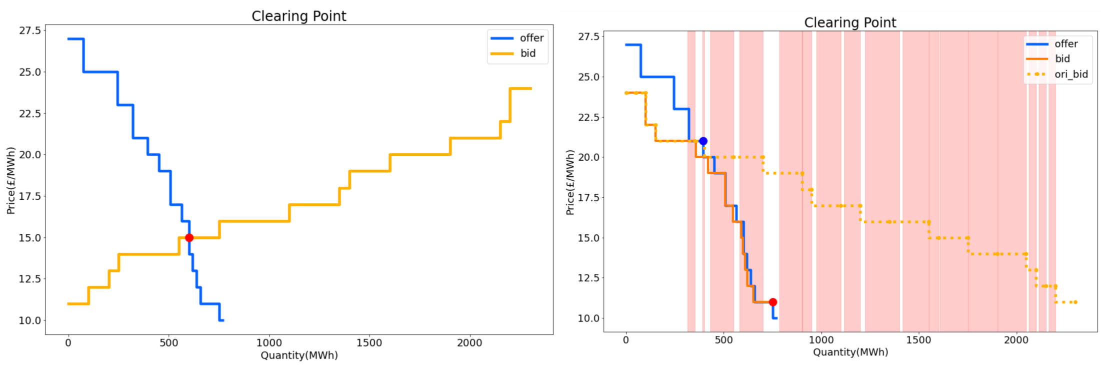



Figure 5- 14 Clearing results of the models under hybrid energy market scenario in 2030

(a) Traditional market models (b) Optimized market models

The traditional models are cleared under the quantity of 600 MWh as the clearing price of 15 \$/MWh, and the clearing quantity of the optimized model is 750 MWh with the clearing price of 11 \$/MWh. The optimized model clears more than the traditional models of 25% as expected. The average relative prices of the traditional pay-as-clear model, traditional pay-as-bid model and the optimized pay-as-bid model are 15 \$/MWh, 13.08 \$/MWh and 18.67 \$/MWh respectively. The reason of the order of three average relative prices is explained in the statement before.

***Hybrid energy market in 2050***

The 95% of the total demand in 2050 is projected to be satisfied by the renewable energies, remaining only 5% demand is met by the conventional generators. The curves of original bids and the 5% offers are introduced as the clearing curve of 2050 hybrid energy market. The clearing curves are illustrated in figure 5-15.

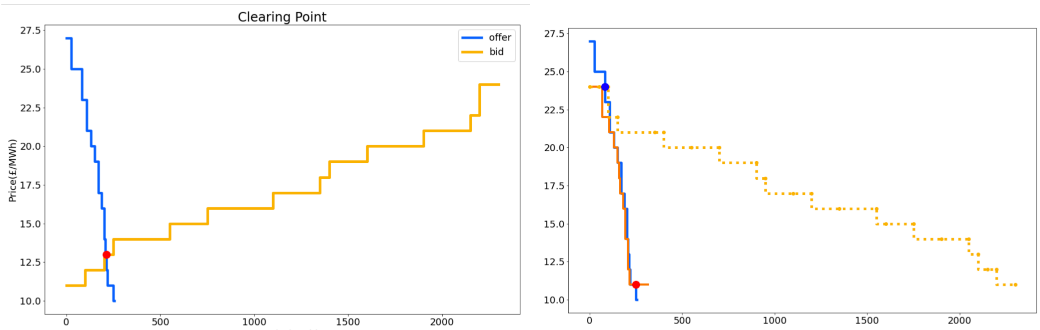



Figure 5- 15 Clearing results of the models under hybrid energy market scenario in 2050

(a) traditional market models (b) optimized market models

The clearing point of the traditional models is (212.5 MWh, 13 \$/MWh), and that of the optimized model is (250 MWh,11 \$/MWh). As expected, the optimized model performances better on the clearing amount with 15%. The average relative prices of the three models are 13 \$/MWh, 11.59 \$/MWh and 19.17 \$/MWh respectively.

***New-energy-only market in 2019***

The variable costs of diverse energies are applied to simulate the energy quoting prices in the renewable-only market, and the quoting quantities of different types of energies are relevant to the energy proportion to the total demand. The clearing curves of the traditional and optimized model under the renewable-only energy scenario are in figure 5-16:

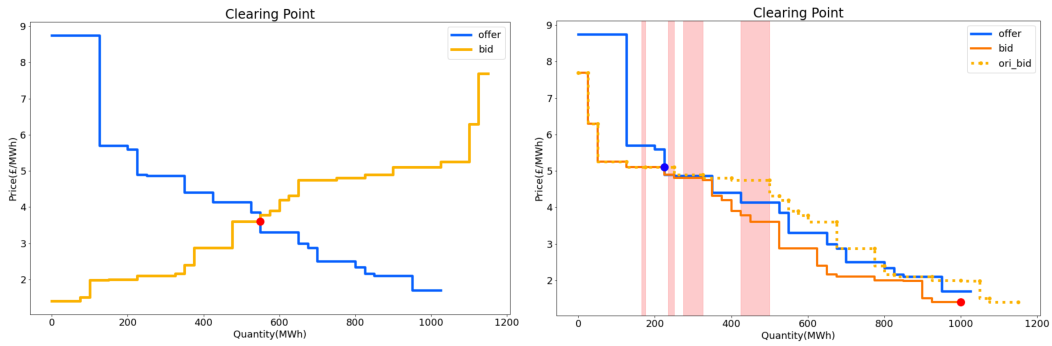



Figure 5- 16 Clearing results of the models under new-energy-only market scenario in 2019

(a) Traditional market models (b) Optimized market models

The clearing quantity and price of the traditional model are 550 MWh and 3.6 $/MWh respectively, while the optimized model possesses 1000 MWh clearing quantity and 1.4 $/MWh clearing price. The optimized model performs the 81.82% better clearing amount. The relative average prices of three models are 3.6 $/MWh (traditional pay-as-clear model), 2.32 $/MWh (traditional pay-as-bid model) and 3.5 $/MWh (optimized pay-as-bid model).

***New-energy-only market in 2030***

Being different to the negative demand settlement of hybrid energy market that only the demand curve changes in different years, the bid and offer curves both make a difference in the renewable-only energy scenario. The clearing curves of renewable-only market in 2030 are presented in figure 5-17.

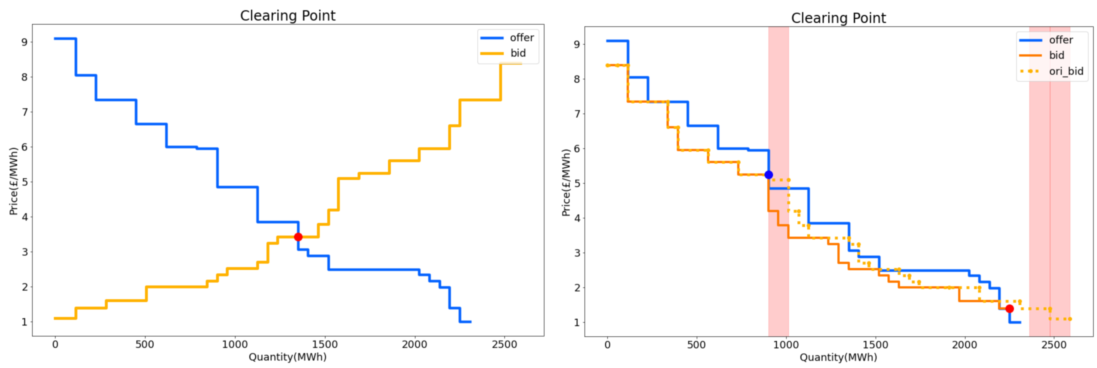



Figure 5- 17 Clearing results of the models under new-energy-only market scenario in 2030

(a) Traditional market models (b) Optimized market models

The clearing quantities under traditional model and the optimized model are 1350 MWh and 2250 MWh respectively (increases by 66.7%). The clearing prices of two models are 3.42 $/MWh and 1.4 $/MWh. The equivalent average prices of three models (in the order of traditional pay-as-clear model, traditional pay-as-bid model and proposed optimized model) are 3.42 $/MWh, 2.068 $/MWh and 4.0665 $/MWh respectively.

***New-energy-only market in 2050***

The clearing curves of renewable-only market in 2050 are similar with those in 2030 with different market quotes. For the traditional model, the clearing quantity is 2612.5 MWh under the price of 3.42 $/MWh. For the optimized market, the clearing quantity id 4393.75 MWh with the clearing price as 1.4 $/MWh. The optimized market offers better performance in clearing amount with 68.18% increase. The relative average prices of three models are 3.42 $/MWh (traditional pay-as-clear model), 2.18 $/MWh (traditional pay-as-bid model) and 4.36 $/MWh (optimized pay-as-bid model).

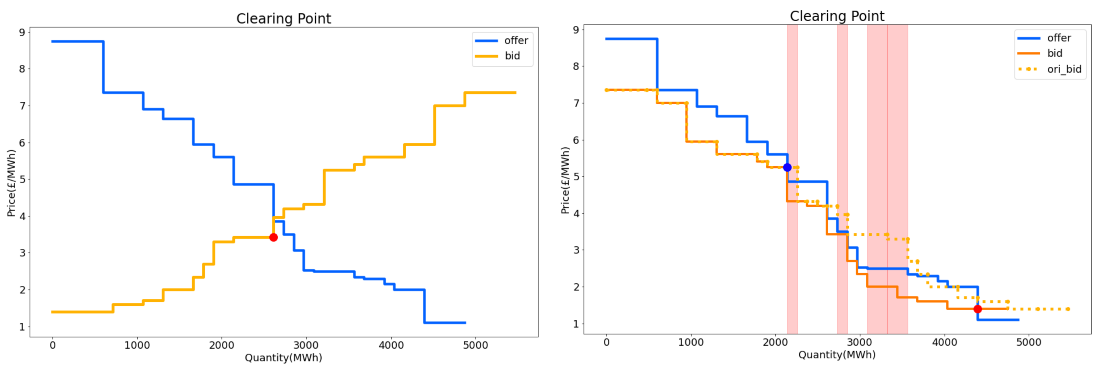



Figure 5- 18 Clearing results of the models under new-energy-only market scenario in 2050

(a) Traditional market models (b) Optimized market models

The clearing performances of three models are summarized in the table 5-14.

Table 5- 14 Quantitative clearing performance of the traditional and the optimized market models

| | | 2019 | | | 2030 | | | 2050 | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Clearing Price | Clearing Quantity | Equivalent Average Price | Clearing Price | Clearing Quantity | Equivalent Average Price | Clearing Price | Clearing Quantity | Equivalent Average Price |
| | | $/MWh | MWh | $/MWh | $/MWh | MWh | $/MWh | $/MWh | MWh | $/MWh |
| **Hybrid Energy Market** | Traditional Pay-as-clear Model | 16.0 | 800.0 | 16.0 | 15.0 | 600.0 | 15.0 | 13.0 | 212.5 | 13.0 |
| | Traditional Pay-as-bid Model | 16.0 | 800.0 | 13.7 | 15.0 | 600.0 | 13.1 | 13.0 | 212.5 | 12.0 |
| | Optimized Pay-as-bid Model | 11.0 | 971.0 | 18.7 | 11.0 | 750.0 | 18.7 | 11.0 | 250 | 19.2 |
| **New-energy-only Market** | Traditional Pay-as-clear Model | 3.6 | 550.0 | 3.6 | 3.4 | 1350.0 | 3.4 | 3.4 | 2612.5 | 3.4 |
| | Traditional Pay-as-bid Model | 3.6 | 550.0 | 2.3 | 3.4 | 1350.0 | 2.1 | 3.4 | 2612.5 | 2.2 |
| | Optimized Pay-as-bid Model | 1.4 | 1000.0 | 3.5 | 1.4 | 2250.0 | 4.1 | 1.4 | 4393.8 | 4.4 |

The law of the clearing quantity could be summarized that the clearing amount of the optimized model is the most of the three models, no matter under the hybrid energy market scenario or the new-energy-only market scenario. The result complies with the original intention of launching model optimization to achieve the maximize clearing.

The optimized market model possesses the highest relative average prices followed by the traditional pay-as-clear model. And the relative average prices belong to the traditional pay-as-bid model is the smallest one among discussed three models. The optimized model always clears at the highest average price because the as many as possible units are successful matched under the model in the price descending order. The most high-priced units are qualified cleared under the model. The other traditional models are cleared at the unique clearing price and the unit bid prices respectively. As the clearing prices are the highest one among all the successful bids, the relative average price of the traditional pay-as-clear model is higher than that of the traditional pay-as-bid model.

#### 5.6.2.4 Real-world application assessment of optimized market model

Two superiorities of the proposed optimized model could be found from the market clearing performances: 1. The original purpose of the optimized market construction is completed to increase the clearing quantity. The optimized model is then feasible under the scenario requiring guarantee of the system reliability because of its advantage in clearing amount. 2. The clearing price and the qualified bids are difficult to predict under the proposed optimized model since the participants are settled to the price descending order. The suppliers are difficult to proceed bidding strategy like reducing bidding prices to ensure clearing or driving up bidding prices to avoid clearing. The market price manipulation could be prevented under the optimized model to some extent.

The analysis towards proposed optimized market model is also launched following the discussion of market clearing performances, using the non-technology market assessment criteria from the former research. The detailed evaluation system is shown in table 5-15. The optimized market model is appraised according to the criteria.

Table 5- 15 Non-technical market assessment criteria

| Benchmark Category | Criteria | Indicator |
|---|---|---|
| Economy Efficiency | Cost Reflectivity | Liquidity (HHI & Bid-offer spread) |
| | | Market signal |
| | | Risk |
| | Stability | Price standard deviation |
| | Market Manipulation | HHI |
| Society | Transparency | Price publicity level |
| | | Counterparty publicity level |
| | Simplicity | Ancillary mechanism number |
| | Feasibility | Technology friendly level |
| | | Customer negotiation position |

***Liquidity***

Two indicators are used in market liquidity evaluation, which are Heifindahi-Hirschman Index (HHI) and bid-offer spread. The target market is more liquid possessing smaller HHI or smaller bid-offer spread.

The calculation formula of HHI is:

$$H = \sum_{i=1}^{N} s_i^2 \tag{5-8}$$

where $s_i$ is the market share of enterprise $i$, and $N$ is the total enterprise numbers.

The formula of bid-offer spread is:

$$SP = B - O \tag{5-9}$$

The $SP$ is the bid-offer spread. $B$ and $O$ in the formula are the bidding price and the offer price respectively.

The market liquidity in this original HHI formula is assessed by the participating companies and the potential impacts they would bring to the company. The quote unit in electricity market is the generator. It is not correct by definition if the clearing results of generators are used to calculate HHI according to the formula, since many of the cleared generators may belong to a same enterprise. However, this method is correct by physical meanings. The increasing generator liquidity would indicate a rising liquidity or the whole market because of the association relationship between generators and their belonging companies. Considering the penetration tendency of distributed energy resources, a large number of individual energies like EVs or demand-side responses are introduced to the market. Each quote of those energies could be considered as one enterprise because of their independence feature. Hence, the liquidity of the proposed optimized market could be assessed by the HHI indicator applying the market clearing information.

Unlike the HHI indicator, the bid-offer spread may not be accurate to estimate the market liquidity in this case since they are simulated ones. The actual value of bids and offers are unclear because of the absence of competitive renewable energy market in the real world. Since, only the HHI indicator are applied for the market liquidity evaluation at this case.

The traditional market models in the HHI calculation, both the pay-as-clear model and the pay-as-bid model, possess the same HHI index under the calculation method in this research. Therefore, the two traditional models are considered as one type and be compared with the optimized model. The HHI index figures of the two types of models under diverse energy scenarios in 2019, 2030 and 2050 is illustrated in table 5-15. The results show that the HHI index of optimized market in a specific year under one scenario is smaller than that of traditional market. The smaller HHI index figure indicates a lower market concentration and higher market liquidity. The proposed optimized market model has better performances in market liquidity compared to the traditional models.

Table 5- 16 HHI index values of the traditional market models and the optimized market model

| HHI Index | 2019 | | 2030 | | 2050 | |
|---|---|---|---|---|---|---|
| | Traditional Model | Optimized Model | Traditional Model | Optimized Model | Traditional Model | Optimized Model |
| Hybrid Energy Market | 1406 | 900 | 1805 | 1033 | 3356 | 960 |
| New-energy-only Market | 1363 | 627 | 1111 | 700 | 1280 | 708 |

***Market Signal***

An efficient market signal is expected to provide feedback of market participants' willingness through market prices. The market signal efficiency assessment is launched under diverse market models. The descriptive power of market price would be weak under models adopting the pay-as-clear rule since all the cleared bids are paid by the unique clearing price. The models adopting the pay-as-bid clearing rule are better in the market signal efficiency that the respective quoting prices could reflect more willingness of market participants.

The clearing bids in the proposed optimized market design are relative to not only their bidding prices but also the situation of other market participants because of the descending order of both bids and offers in the clearing curve. The malicious quotations---for example when the renewable energies bid as zero to guarantee clearing, or the unready suppliers bid as extreme high prices to avoid clearing --- could be avoided. The price distortion is prevented to reach fairer price signals under proposed optimized market model.

***Risk***

There are four general risks when talking about electricity market, including the premium risk, the balancing risk, the counterparty risk, and the capital risk.

The premium risk focuses on the possible differences between market contracted prices and the spot prices. The Contract of Differences mechanism is constructed in the U.K. to settle the problem. Neither the pay-as-clear model nor the pay-as-bid model would face issues like predicted price or forward price as the market are cleared at that moment, possessing equal position when talking about the premium risk. The proposed optimized model, however, is slightly superior because the fairer quotes are urged by the model, leading to a lower premium risk.

The balancing risk is the real-time demand and supply balance requesting balancing market. The counterparty risk and the capital risk focus on the possibility that the energy delivery cannot be completed on time, and the cash deposit that may be required in the unpunctual delivery respectively. Those risks are relevant to the market operation, not the clearing model. The market models discussed in this research would face equal balancing, counterparty, and capital risks.

Table 5- 17 Risks faced by the traditional market models and the optimized market model

| | Traditional Models | Proposed Optimized Model |
|---|---|---|
| Premium Risk | √ | |
| Balancing Risk | √ | √ |
| Counterparty Risk | √ | √ |
| Capital Risk | √ | √ |

***Stability***

The stability of market model is judged by the price standard deviation, which requires actual periodical market price statistics.

The market bids and offers simulated in this research are derived and from the historical data, which are efficient when analyzing market clearing results but are useless when the quotes themselves are required to be evaluated. The market stability is difficult to be estimated from the perspective of market model construction.

***Market manipulation***

The HHI index is used in not only the market liquidity but also the market manipulation assessment. The calculation before indicates that the HHI number of the proposed model is larger than that of the traditional model. Although those quote-based HHIs are sufficient in evaluating liquidity, things are different when talking about market manipulation that only the scale of company is relevant to the market manipulation. The unit-related HHIs are not satisfied.

Being difficult to analyze through the quantitative perspective, the market manipulation level of the discussed market models could be explored from the qualitative perspective. The market manipulation extent could reflect by the trend of clearing price. The Pool Model in real world electricity market applying pay-as-clear clearing was facing price manipulation issue, that the leading enterprises cooperated to promote the final unique clearing price. The actual problem was found in the historical pool markets. The pay-as-bid model was then published to avoid this. Then the models adopting pay-as-bid mechanism performs better than the pay-as-clear ones in the market manipulation perspective. However, the energies quoting in new and conventional hybrid energy market could still slightly rise their premium rate to achieve a higher clearing price on the premise of successful clearing in the traditional pay-as-bid model. The application of proposed optimized market model could help to prevent the fair market price disturbance that the market clearing price is difficult to predict, let alone the targeted adjustment of bidding prices.

***Transparency***

The market transparency is relevant to the market operation rules rather than the market model. The extent of participants information disclosure in the market mechanism lays the foundation of market transparency performance. The market models discussed in this research focuses more on the clearing rules, so the comparison among models on the transparency performances is difficult to settle. However, the suggestion would still offer for the market transparency, publishing prices and names of the market participants for example, is the easiest one. The real-time disclosure may difficult before or during the clearing in case of the illegitimate price manipulation. Detailed information could be considered to publish post clearing.

***Simplicity***

The market simplicity level depends on the requirement of auxiliary mechanism for market smooth operation. The often-used auxiliary mechanism including contract or differences settling the difference between contracted prices and spot prices, balancing market dealing with the unbalance of system, the information disclosure mechanism solving low-transparency, and regulation and investigation focusing on market manipulation issue.

The balancing risk and low transparency risk are faced by both the traditional models and the proposed optimized model. The optimized pay-as-clear model could urge the fair bidding of market participants to prevent market manipulation and premium risk, thus fewer auxiliary mechanisms are expected by the proposed model. Comprehensively speaking, the proposed model possesses the highest simplicity.

Table 5- 18 Auxiliary mechanism required by the traditional market models and the optimized market model

| Auxiliary Mechanism | Against | Required by |
|---|---|---|
| **Contract for Differences** | Premium Risk | Traditional Models Only |
| **Balancing Market** | Balancing Risk | Both |
| **Information Disclosure** | Low-Transparency | Both |
| **Regulation and Investigation** | Market Manipulation | Both |

***Feasibility***

The models under research are required to be applied under the future energy scenario targeting at renewable energies or distributed energy resources. Typical features including strong volatility, pay-as-bid control and small scale are possessed by those energies. So the expected market model should respect the diversified quotes of individual participants, which could achieve by the pay-as-clear models.

***Real-world application assessment conclusion***

Eight indicators belonging to economy efficiency and society impact perspective are applied in this research as non-technology market assessment criteria to estimate the optimized market model proposed. The comparison among the traditional pay-as-clear model, traditional-pay-as-bid model and the optimized model are launched to explore the feature and application scenario of each model. The results indicate that the proposed optimized model dominates under most perspectives including market liquidity, market signal, risk, market manipulation, simplicity, and feasibility. The remaining market stability and transparency are difficult to be compared as they require for market operation results and market operation rules, more than the market model discussed in this research.

## 5.7 Conclusion

The pay-as-bid market model which could maximize the clearing volume is proposed in this chapter, complying with the future energy scenarios. The bids and offers information in the Sylvania electricity pool is used in the market model simulation, with the predicted bids and offers introduced massive renewable energies and distributed energy resources. The proposed market models are evaluated in the chapter compared with the traditional market models, through both their market clearing results and their projected application performances in the real-world. The market assessment criteria published in Chapter 4 is used proceeding market estimation.

The results of the case analysis indicate:

- The proposed market model to maximize the clearing volume has better performances facing the introduction of massive renewable energy resources and distributed energy resources, guaranteeing the clearing capacity further the demand-supply balance in the system.

- The proposed market model possesses higher relative average prices compared with the traditional markets, mobilizing the initiative of market participants by guaranteeing their incomes.
- The proposed market model gains priorities quantitively in increasing market liquidity and declining market manipulation, and qualitatively in risk, simplicity, and feasibility. Generally speaking, the proposed model is better adapted to the future energy scenario.

This Chapter contributes to three perspectives:

1. Proposing market model adapting the infiltration of renewable energies and distributed energy resources, guaranteeing the reliability of the system
2. Enriching the market options facing demand flexibilities, and realizing the market trading strategy portfolios facing diverse energy scenarios
3. Combing the advantages of traditional market models to put forward a model both being controllable to some extent and could reflect the costs of products, gaining particularly prominent in increasing market liquidity, decreasing market manipulation and mobilizing enthusiasm of participants

# Chapter 6

# A Uber-Airbnb Mixture Flexibility P2P Market in Integrated TSO-DSO Architecture

This chapter proposes to serve automatic P2P transaction for flexibility resources. The dynamic pricing strategy is published to provide more sensitive and fairer market signals with the mobilization of participants' initiative. The proposed market design is explored under diverse coupling depth between TSO and DSO, indicating the evolution of future energy scenarios.

# Statement of Authorship

| **This declaration concerns the article entitled:** | | | |
|---|---|---|---|
| A Uber-Airbnb Mixture Flexibility P2P Market in Integrated TSO-DSO Architecture | | | |
| Publication status: Submitted | | | |
| Publication details (reference) | L. Shan, C. Gu, and F. Li, " A Uber-Airbnb Mixture Flexibility Peer-to-peer Market in Integrated TSO-DSO Architecture " in IET Smart Grid, 2022, 1-19 | | |
| Candidate's contribution to the paper | The candidate proposed the idea of the paper, she designed the methodology, and predominantly executed the coding to derive the experimental results. Other authors helped the candidate with the design of case studies, the format of the paper, and the improvement of academic writing. The percentage of the candidate did compared with the whole work is indicated as follows:<br>Formulation of ideas: 85%<br>Design of methodology: 100%<br>Simulation work: 100%<br>Presentation of data in journal format: 90% | | |
| Statement from candidate | This paper reports on original research I conducted during the period of my Higher Degree by Research candidature.<br>https://doi.org/10.1049/stg2.12076 | | |
| Signed | Lanqing Shan | Date | 21/12/2021 |

# Chapter overview

With the increasing penetration of small-scale distributed energy resources in the distribution system, the future market design for flexibilities trading is considered to be peer-to-peer(P2P) ones to comply with the independence of the resources. There are many P2P flexibility market trails in the real-world application, including the Cornwall Local Energy Market aiming at network issue settlement and the Quartierstrom Project overseeing the distribution-level demand-supply balance. However, deficiency shows in the existing P2P flexibility markets. Still being the passive receiver of prices under the auction-variant clearings, the market participants are under low enthusiasm. The market can neither automatically trade nor pay attention to the individual flexibility characteristics. The research and construction of a more sufficient flexibility market is expected.

To fill the current gap of the flexibility market, a flexibility market combining the pricing strategy and matching strategy of the mature successful P2P business models is proposed in this chapter. The flexibilities in the transaction are classified according to their shiftable parameters to diverse flexibility levels, whose prices with different reliability level distributed generations(DGs) are settled under the dynamic pricing strategy published in this chapter. To explore the future of the proposed market under future energy scenarios, the value of the market is discussed surrounding the market segmentation topic following the disintegration from the transmission system operator(TSO) to distribution system operator(DSO). The market assessment criteria introduced in Chapter 4 is also applied in this discussion, appraising the segmented P2P flexibility market and the integrated P2P flexibility market in the real-world application.

The contributions of this chapter are summarized as:

1) Proposing P2P flexibility market serving the transactions of flexibility resources, offering convenient automatic trading for individual flexibilities.

2) Publishing dynamic pricing strategy whose prices are affected by not only the characteristics of the flexible loads(FLs) and DGs, but also the other participants of the market. The price fluctuation characteristics are concluded in this pricing strategy.

3) Discussing the segmentation tendency of the flexibility market considering energy products as pure commodities. The market values and the real-world application performances between the segmented market and the integrated market are compared in the analysis.

## 6.1 Abstract

This chapter proposes the P2P flexibility market design combing the pricing strategy and matching strategy of the current successful mature P2P business models. The published market makes it realize for automatic trading, complying with the individual flexibilities' expectations for convenient market and mobilizing the market participation. The economy and business natures of the market is discussed in the research. Following the future energy scenarios with the disintegration between TSO and DSO, the market is explored from the market value and the non-technical market assessment criteria in real-world application towards the segmentation topic. This chapter contributes in three areas: 1) The proposed P2P flexibility market accommodates the future distributed energy resource infiltration. 2) The published dynamic pricing strategy simulates the fluctuation of commodity prices under liberty trading, offering equal clearing opportunities to increase transaction justice. 3) The market is discussed from not only the technology but also the business nature perspective, laying foundation to the energy market practical application.

## 6.2 Introduction

### 6.2.1 Background

Alongside decarbonization, digitalization, and decentralization, the growing penetration of distributed energy resources (DERs) is much more mobilized in the electricity system for intelligence and flexibility. A report from Berkeley Lab targeting the distribution system in a highly DER future reveals a revolutionary framework for the distribution system with the infiltration of DERs from a low to a very high adoption level [226]. In parallel with this distribution system evolution, the transition pathway of the distribution-level market is also proposed, illustrating the future P2P market environment where the distribution utilities connect with each other directly in energy transactions [184, 227]. The ideal distribution-level market form with a massive DERs penetration is the community-dominated market structure, whose bulk energy requirement is fulfilled locally. Being an 'isolated' market whose demand satisfaction and operation are independent, a considerable exploration space remains to stimulate its security, reliability, and efficiency. The concept of the isolated-operational market here is a financial rather than a physical one, as small disconnected systems constituting a complete electricity system are physically impractical. The independent schedule, dispatch, and transaction are 'isolated'.

This research considers flexibilities accessing distribution-level market as purely commercial behaviors regarding the market's autonomy feature, which means the technology-related issues like constraint management are not included. Participants under this market structure settle a P2P trading, taking advantage of flexible and independent characteristics.

To launch a further analysis of the community-dominated distribution-level market, two features need to be mastered about the market general condition. 1). The flexible features of the distributed energy resources: The precondition of the community-dominated market is to reach a significantly high DERs level, whose characteristics of small-scale and shiftable are bringing negligible changes to the future electricity system operation. 2). The liberal transaction features of the DERs individuals: The no central-dispatch and the adequate amount of DERs (taking the responsibility of the majority demand of distribution level) composes of a limit-less commercial environment. All the distributed resources could access to the market individually - no matter the large-scale ones nor the small ones, without organizers like aggregators.

The concept of peer-to-peer energy market is the subcollection of flexibility market. Flexibility market is the platform where products are flexible resources. The two types of flexibility market are network-related market and energy-related market, which are classified according to market construction goals. The original intention of network-related market is to solve network issues such as network congestions. Network capacity market and ancillary services market are included in the network-related market. Energy-related market is the one whose original intention of market construction is to solve demand-supply balance. The peer-to-peer energy market discussed in this chapter is the network-related market.

Most of studies investigating flexibility market settle the complete of market simulation as the victory of research, thus fail to proceed deeper analysis to economic or societal features of the proposed market. Lack of those exploration makes proposed flexibility markets only theoretically constructed. This paper fills in the gaps of missing economic feature exploration by proposing appropriate market segments. Energy products in the market are equipped with more commodity properties, like in the real business world.

The contributions of this paper are: 1) It proposes a dynamic pricing strategy to quantity the price between flexibilities and DGs according to their flexibility levels and market participation. 2) It presents a Uber-Airbnb mixture model for flexibility transactions, which combines the matching strategy from the Uber business model and the pricing strategy from the Airbnb business model. Automatic P2P trading of flexibility are realized under this model, where flexibilities are considered as pure commodities. 3) It explores whether and how to proceed with market segmentations in the proposed P2P market. A better understanding of this economic feature could offer a framework construction strategy for the flexibility market in the real world.

# 6.3 Methodology

As discussed in the literature review, the introduction of an appropriate P2P energy transaction platform is the mainstream solution expecting the high-flexible and individual-owned flexible resources. There are mature P2P business models which are steadily operated, where the most typical ones are Uber in travelling and Airbnb in tourism. The business models of Uber and Airbnb are analysed in this chapter, contributing to learning experiences for energy P2P platform construction. The expected P2P energy platform serves to emerge developing and flexible energy resources through quantizing individual-owned flexibilities under appropriate market operation rules.

## 6.3.1 Uber business model

### 6.3.1.1 Uber pricing strategy

The pricing strategy of Uber is under a certain degree of standardization and transparency. Uber charges from passengers as the subscribed prices, which fluctuate within the price range. The price of a specific ride is foreseen from the passengers' perspective, and they are asked to accept the price before starting the travel [228]. The price is calculated according to travelling distance and time, and the scarcity value of drivers under increasing demand and decreasing supply scenarios would be reflected by changes in fees [229]. This is called surging price [228]. The core of the surging price strategy is the surge multiplier, which is the multiplier being applied to the normal price [230, 231]. A balanced price assisting to the match between drivers' supply and passengers' demand realizes the minimum waiting time of passengers [228]. Prices under the strategy are the signals, informing passengers of the system's tense moments and inducing drivers to provide supplies in high-priced regions [228]. The gap between supply and demand could be narrowed in this process [230, 231]. As discriminatory pricing, surge price realizes profit maximization through anticipating partiers' behaviours [228].

#### 6.3.1.2 Uber matching strategy

The principle of Uber is to connect passengers and drivers through automatic matching and pricing system in the bilateral market [232]. Matching is the process that drivers are sent to take passengers. The system would firstly check the availability of in-matching passengers when a new passenger is requesting a ride. If another matchable passenger is waiting, the driver would pick up passengers in the middle of their starting points and drop them off in the mid-terminals. When a matchable passenger does not exist, the requesting passenger would be asked to wait for matching in the same batch. The system would send a driver directly to the passenger If the two mentioned matching fails [229, 232].

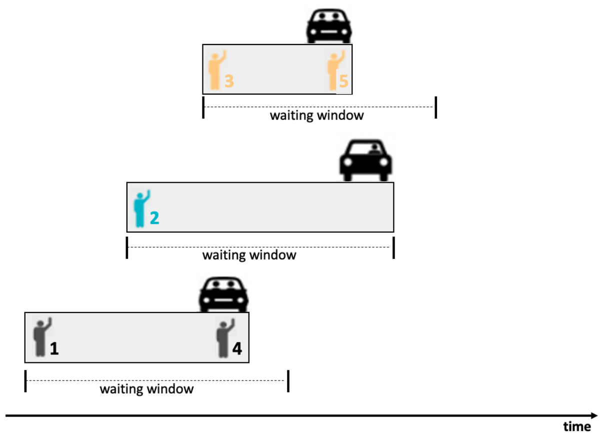



Figure 6- 1 Dynamic waiting for pool matching [229]

The matching method of Uber involves shared matching and unshared matching. One driver is specifically sent to one passenger under the unshared matching, while a passenger group possessing multiple pick-up points takes one ride under a shared matching.

Three statues are faced by the drivers including waiting, set-off, and on-trip. Drivers under the waiting status take no passengers and wait for the matching of the system.

The set-off status is the time that drivers accept and match on their way to passenger pick-up. And drivers on-trip are sending passengers to their terminals [229].

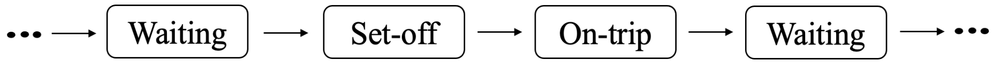



Figure 6- 2 Unshared matching circulation [229]

The riding requests from passengers are settled in batches under the shared matching, so the requests in a period would be gathered and optimized together. The unmatched supply in one batch would be prolonged to the next one.

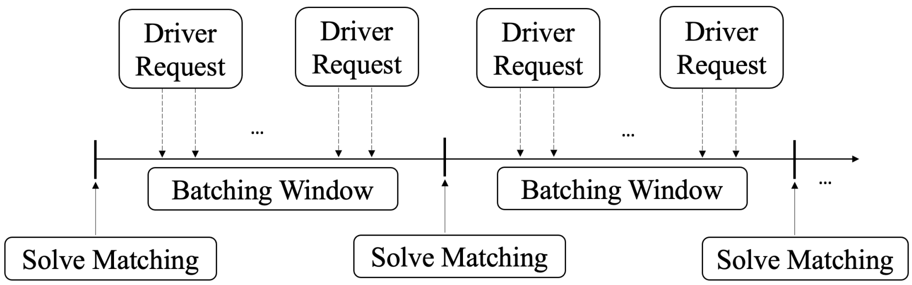



Figure 6- 3 Driver request batching [229]

Although possessing different physical interpretations, the mathematics essences of the two matchings are the same. The shared matching could be considered as a special exception to the unshared matching when there is only one request in one batch.

The potential matching between passengers and drivers is represented by the bipartite structure, in which each node corresponds to a request.

$$\max \sum_{i \in P} \sum_{j \in D} w_{ij} x_{ij} \qquad (6\text{-}1)$$

$$s.t. \sum_{j} x_{ij} \leq 1, \forall i \in P \qquad (6\text{-}2)$$

$$\sum_{i} x_{ij} \leq 1, \forall j \in D \qquad (6\text{-}3)$$

$$x_{ij} \in \{0,1\}, \forall i \in P, \forall j \in D$$

Each passenger-driver pair is connected by a weighted side, whose weight indicates the reward node received. P and D in equation 6-1 respectively represent the set of passenger nodes and driver nodes in the same batch. The binary variable $x_{ij} = 1$ when passenger i matches with driver j, otherwise $x_{ij} = 0$. The reward for matching i and j is denoted by $w_{ij}$. Then all the matches could be modelled as equations 6-1 to 6-3 [229, 232].

The total rewards gathered in matching is maximized in equation 6-1. Equations 6-2 and 6-3 make sure each passenger is served by at most one driver. The diverse weight is set to achieve different matching targets. For example, $w_{ij} = M - \delta_{ij}$ if the target is to minimize transit time. The $\delta_{ij}$ is the en-route time from driver to passenger, and the $M$ is a large-enough number [229].

## 6.3.2 Airbnb business model

### 6.3.2.1 Airbnb pricing strategy

Being different from the Uber pricing strategy which only depends on the distance and increases Surge Multiplier times during peak demands, the final decision right of Airbnb prices is held by hosts, who would adjust listing prices according to property features and demand fluctuation of tourists [233-236]. The impact factors of Airbnb prices include housing characteristics, housing reputation, host properties, and market competition. The detailed pricing factors include: 1) Accommodation types: Rent as a whole, private room, sharing room 2) Interior housing characteristics: Scale, design style, hygiene, facilities (shower, hair dryer, etc.), services (dining, parking, etc.), social function 3) Exterior housing characteristics: location, reservation policy, house ranking, landlord reputation [233-238].

Table 6- 1 Price attributes in the Airbnb pricing strategy

| *Objective* | | *Subjective* | |
|---|---|---|---|
| *Internal* | Type ( size, shape, etc.) | *Internal* | Design ( decoration, style, etc.) |
| | Furniture( sofa, bar, etc.) | | Hygiene |
| | | | Comfort ( sunny, quiet, cozy) |
| | Facility( garden, pool, Wi-Fi, etc.) | *External* | Location |
| | Rental policy( strict term, shortest staying length, etc.) | | Season |
| | | | Festival |

Airbnb adopts the hedonic pricing theory generally applied in the tourist industry, which is suitable for settling prices to multi-character products. The initial function of Airbnb price is [234]:

$$P = P(Z, \varepsilon) \qquad (6\text{-}4)$$

P is the prices of properties on the Airbnb platform. $Z$ is eigenvector and $\varepsilon$ is the residual term. Then the implicit marginal price of each character could be illustrated by derivative of P to $Z$.

$$p_z = {\partial P(z,\varepsilon)}/{\partial z} \quad (6\text{-}5)$$

Where $p_z$ is the consumers' willingness to pay marginally for feature z. The hedonic price model is generally in form of a simple function, whose fitting results are linear, linear log, double log-linear and semi log-linear functions [234, 235]. Considering the high heterogeneity in the Airbnb listing prices, the linear addictive model is the most generally be used one [235].

$$Price = c + \beta X + \varepsilon \quad (6\text{-}6)$$

$Price$ in the equation 6-6 represents prices on the Airbnb platform, $c$ is the constant vector, $\beta$ is the coefficient vector, $X$ is the matrix of all attributes, and $\varepsilon$ is the error term. The room characteristic factors that needed to be considered in the matrix are summarized in table 6-1.

Sometimes the quadratic semi-log models are also used to simulate the hedonic price function of listing [234].

$$lnP_i^{(\lambda)} = \alpha_0 + \sum \alpha_i X_i^{(\lambda)} \quad (6\text{-}7)$$

$lnP_i^{(\lambda)}$ in the equation 6-7 indicates the natural logarithm of Airbnb market price of property i. $X_i^{(\lambda)}$ is the vector of property variables, including market conditions in the lodging market such as listing features, landlord attributes, customer reviews, etc.

#### 6.3.2.2 Airbnb Matching Strategy

Being different from Uber whose matching is to reach the maximum social welfare, the matching of Airbnb is essentially completed by search [239, 240]. The search engine design of Airbnb is thus significant to reduce costs and enhance match potential [240, 241]. The matching of Airbnb is a bidirectional selection process. On the one hand, tenants filtrate the houses from the key information settled through the filters. On the other hand, most hosts possessing more freedom and subjective initiative own preferences to tenants [241]. Hosts are concerned with the tenant's length of stay and the guest type [240].

As mentioned above, the most critical hiding costs is the sufficiency of filters when using search for matching. Apart from settling appropriate filters, redundant search is also an important cause of high cost and low efficiency [240]. The refusal reason for hosts contains Congestion, Outdated Vacancy, and Preference Screening [240, 242]. Rejection is itself transaction costs for the platform. Communication is costly and involves delays and uncertainty, which may cause researchers to lose interest or even leave the platform.

## 6.4 P2P energy market model

### 6.4.1 Market structure

The electricity market is composed of the transmission-level market and the distribution-level market. The P2P market for DERs transactions to release the pressure of the network discussed in this paper are markets at the distribution level, providing an automatic trading platform for prosumers. To observe the feasibility and effects of the market design, only DGs and FLs are considered as participants in the presented market model, without conventional generators and traditional grid demand. Proposing market model consists of two stages, the inner transaction between DGs and FLs, and transferring the residual/lacking power to/from the utility grid. The basic market structure and its directions of power and money flows are represented in figure 6-4.

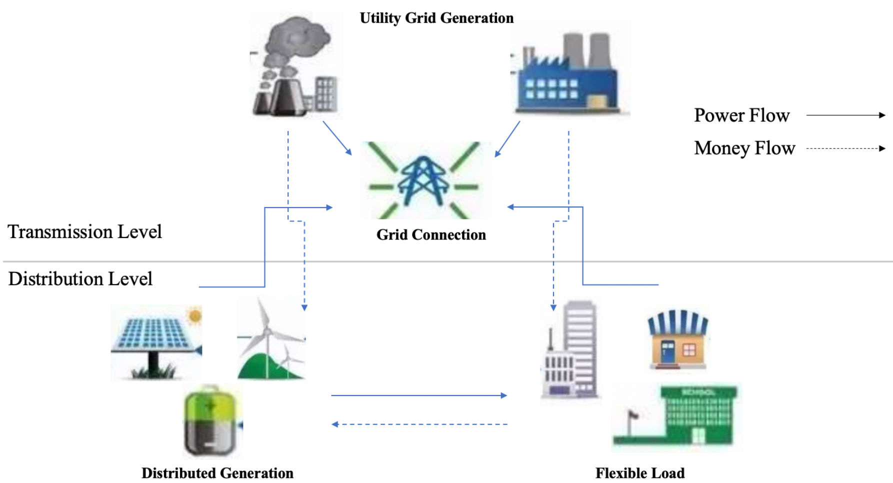



Figure 6- 4 The structure of electricity market with only the participants of DGs and FLs

The participants of the energy market discussed in this chapter take part in the platform through peer-to-peer transactions. The buyers and sellers are automatically matched, with the prices calculated by the background system. Being the buyers, flexible loads need to report their characters of load in the platform, such as available time, whether mid-way shutdown is permitted and the estimated total work. Being sellers, distributed generations are expected to report their situations including average power and generation period. The cost-information of DGs is not required to be reported on the platform but needs to be controlled by market operators. The future DSO, transformed from the current DNO, is most likely to become the operating unit of the local market. The roles of local market facilitator and coordinator are expected to be undertook.

## 6.4.2 P2P energy market participants

The DGs and FLs stated in this paper are both generalize concepts, representing the producer or consumer positions of market participants. Setting a storage in the market as an example, it is regarded as a DG at discharging moments, or a FL at charging moments.

Differing from unswitchable demand, FLs are negotiable within limits on specific factors. There are six essential parameters used to describe one FL, including available start time, available end time, working continuity, working duration, working power range and total required work. The available start time and the available end time are two timing spots for FLs, who require supplies after the available start time and before the available end time. For the types of FLs who are continuous demand, the time length of their demand is described as time duration.

FLs with different factors would be divided into three categories according to their flexibilities:

### 6.4.2.1 Time-shiftable load

Time-shiftable loads (TSLs) are the FLs only being flexible on the working time slot. They require fixed continuous power that could work between the available start time and the available end time. The demand for TSLs cannot stop once beginning. The profile of TSLs and their parameters compared to the traditional loads are:

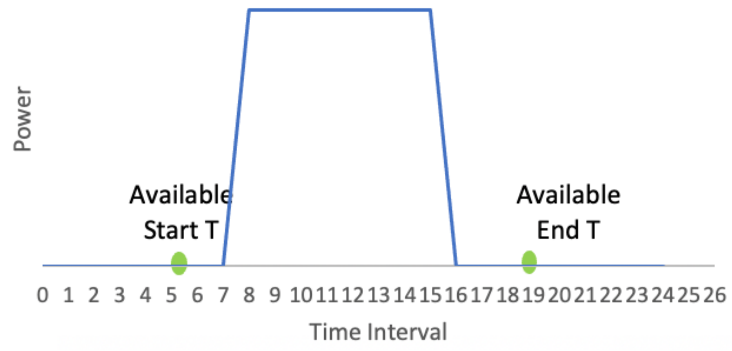



Figure 6- 5 Demand pattern of time-shiftable loads

Table 6- 2 Key parameters of time-shiftable loads

| | | Traditional Parameter | Flexible Parameter |
|---|---|---|---|
| Time | Time Scale | Fixed Start and End Time | Flexible Start Time and End Time |
| | Time Continuity | Continuous Working | Stoppable Working |
| Power | Power Scale | Fixed Working Power | Flexible Working Power |

The electricity usage behavior modelling of TSLs is illustrated in Equations 6-8 and 6-9.

$$p_t^{TSL} = k_t^{TSL} \times P^{TSL} \tag{6-8}$$

$$\sum_{t=t_{start}^{TSL}}^{t_{end}^{TSL}} |k_{t+1}^{TSL} - k_t^{TSL}| = 2 \tag{6-9}$$

Where $p_t^{TSL}$ is a continuous variable representing the power of TSL at spot t. $k_t^{TSL}$ is a binary variable illustrating the working status of TSL at spot t. The TSL is activating when $k_t^{TSL} = 1$. Equation 6-8 indicates that the final working power of TSL is codetermined by the working power and the on-off state. Equation 6-9 shows the one and only one start-up opportunity for TSL in its entire scheduling scope, while continuous working is required as it can not stop once beginning. $t_{start}^{TSL}$ and $t_{end}^{TSL}$ are the start and stop time for TSLs.

As TSLs work at the fixed power, $P^{TSL}$ in equation 6-8 is the constant for TSL's working power. [162] is the available working time scope for TSL. The relationship between the actual work time of TSL and the available slot is illustrated in equation 6-10.

$$T_{start}^{TSL} \le t_{start}^{TSL} \le t_{end}^{TSL} \le T_{end}^{TSL} \quad (6\text{-}10)$$

That the actual start-stop times should locate within the permitted hours.

**6.4.2.2 Power-shiftable load**

Power-shiftable loads (PSLs) are the FLs that are variable in both the working time slot and the working power range. The demands satisfying them are fluctuating from the minimum power to a maximum one, being negotiable as long as the total work is satisfied. PSLs also ask for continuous working supplies.

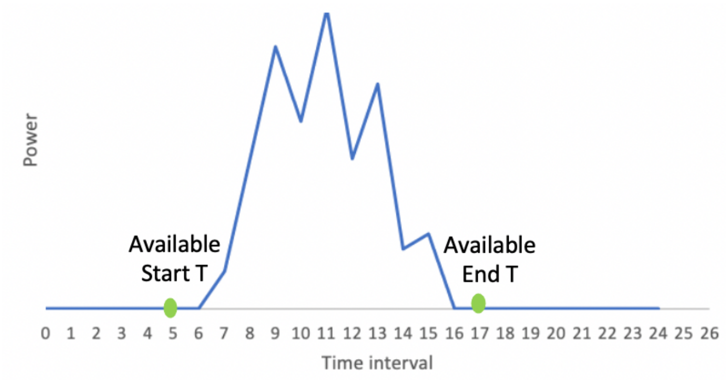



Figure 6- 6 Demand pattern of power-shiftable loads

Table 6- 3 Key parameters of power-shiftable loads

| | | Traditional Parameter | Flexible Parameter |
|---|---|---|---|
| Time | Time Scale | Fixed Start and End Time | Flexible Start Time and End Time |
| | Time Continuity | Continuous Working | Stoppable Working |
| Power | Power Scale | Fixed Working Power | Flexible Working Power |

The model of PSLs shows in Equations 6-11 to 6-13.

$$p_t^{PSL} = k_t^{PSL} \times P_{trange}^{PSL} \quad (6\text{-}11)$$

$$\sum_{t=t_{start}^{PSL}}^{t_{end}^{PSL}} |k_{t+1}^{PSL} - k_t^{PSL}| = 2 \quad (6\text{-}12)$$

$$\sum_{t=t_{start}^{PSL}}^{t_{end}^{PSL}} p_t^{PSL} dt = Q^{PSL} \quad (6\text{-}13)$$

The naming rules of PSLs' variables are similar to those of TSLs, where $p_t^{PSL}$ is the continuous variable representing the working power of PSL at the spot t, and $k_t^{PSL}$ is the binary variable illustrating on-off status. The working power scope and the working time scope are limited in Equations 6-11 and 6-12. PSLs accomplish the total work by flexibility changing working power within the allowable range, which is indicated in equation 6-13.

The actual PSL fluctuates in the range of, shown in equation 6-14. The available working time ranges within as equation 6-15.

$$P_{min}^{PSL} \leq P_{trange}^{PSL} \leq P_{max}^{PSL} \quad (6\text{-}14)$$

$$T_{start}^{PSL} \leq t_{start}^{PSL} \leq t_{end}^{PSL} \leq T_{end}^{PSL} \quad (6\text{-}15)$$

**6.4.2.3 Overall-shiftable load**

Overall-shiftable loads (OSLs) are the ones holding entire flexible parameters being opposite to the traditional loads. They ask for supply between available start time and available end time who could stop within the period. The supply needed by the FLs possesses a power range and a fixed total work.

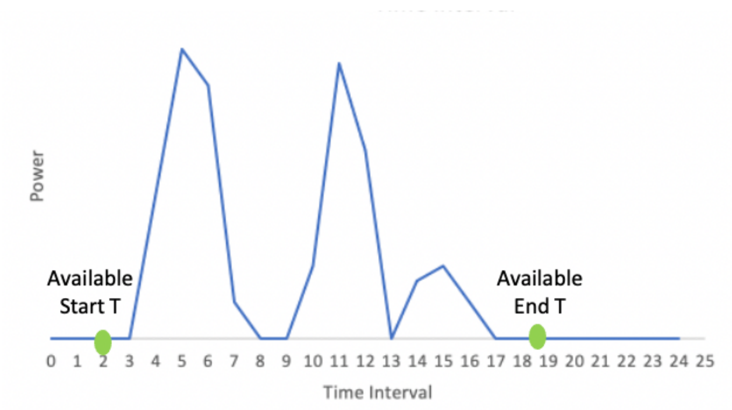



Figure 6- 7 Demand pattern of overall-shiftable loads

Table 6- 4 Key parameters of overall-shiftable loads

| | | Traditional Parameter | Flexible Parameter |
|---|---|---|---|
| **Time** | Time Scale | Fixed Start and End Time | Flexible Start Time and End Time |
| | Time Continuity | Continuous Working | Stoppable Working |
| **Power** | Power Scale | Fixed Working Power | Flexible Working Power |

The electricity usage of OSLs is modelled in equations 6-16 to 6-17.

$$p_t^{OSL} = k_t^{OSL} \times P_{trange}^{OSL} \quad (6\text{-}16)$$

$$\sum_{t=t_{start}^{OSL}}^{t_{end}^{OSL}} p_t^{OSL} dt = Q^{OSL} \quad (6\text{-}17)$$

The power of OSL at spot t is represented by continuous variable $p_t^{OSL}$. Equation 6-16 shows the relationship between status binary variable $k_t^{OSL}$ at the power at spot t. Since the OSLs could stop at any time during working, the OSL is not confined by the continuous working limit. The total work of an OSL is stipulated in equation 6-17.

Although being without the continuous working limit, the OSL still obey the power range and schedule range rules and respectively in equations 6-18 and 6-19, where are constants.

$$P_{min}^{OSL} \leq P_{trange}^{OSL} \leq P_{max}^{OSL} \qquad (6\text{-}18)$$

$$T_{start}^{OSL} \leq t_{start}^{OSL} \leq t_{end}^{OSL} \leq T_{end}^{OSL} \qquad (6\text{-}19)$$

DGs represented in the proposed market are unchangeable generators. The generation amounts from DGs are fixed, unlike the conventional generators which would plan their dispatching amount according to the forecast demand. The concept of reliability level is used to describe the error between the predetermination amount and the real generation amount. DGs generally come from renewable energy resources such as hydropower, wind power, Photovoltaic(PV), geothermal energy, etc., most of which possess high volatility and low prediction accuracy. The electricity markets have both long-term markets (like the multi-day ahead market) and short-term markets (intraday market, for example), which all require DGs forecasting before the market simulation stage. The more forward and the more special geographical locations would bring the lower prediction accuracy of DGs. The relation between the actual power generation of DGs and the projected generation in market planning is characterized by the reliability levels of DGs in this paper. DGs at higher reliability levels are offered higher prices. Existing research indicates the relationship between the costs of DGs under different reliability levels, that the cost of x%-reliability-level DGs is the x% of the costs of 100%-reliability-level DGs.

### 6.4.3 Dynamic pricing strategy

The energy P2P market proposed in this research combines the matching strategy of the Uber platform and the pricing strategy of the Airbnb platform. When talking about the projected P2P energy market, it is essential to guarantee it is Pareto optimal and the participants's adaption of matching suggestions balancing the entire system. From the perspective of pricing strategy, flexible resources possess various fluctuating features being the products on the P2P energy market. The P2P energy market then should settle prices taking the Airbnb platform as a reference, that the multi-attribute pricing strategy is expected to achieve prices showing product features more comprehensively.

The hedonic pricing theory is adopted in this research to settle the prices of flexible resources, which is the nucleus of the Airbnb pricing strategy. The initial implied price function of hedonic pricing is:

$$P = P(Z, \varepsilon) \qquad (6\text{-}20)$$

Where $Z$ is eigenvector and $\varepsilon$ is the residual term. The hedonic price model is generally in form of a simple function, whose fitting results are linear, linear log, double log-linear and semi log-linear functions. The linear additive model is the commonly used function in Airbnb pricing, contributing to illustrating the high degree of heterogeneity in the characteristics of listing. Considering the fluctuate multi-feature of flexible resources, the linear addictive function is also adopted in this paper of flexibility resource price settlement.

$$p_z = {\partial P(z, \varepsilon)}/{\partial z} \qquad (6\text{-}21)$$

$$P = c + \mu_i f(\mathbb{Q}_i{}^{\kappa}) + \varepsilon \qquad (6\text{-}22)$$

$$\sum_{i=1}^{\kappa} \mu_i = 1 \qquad (6\text{-}23)$$

$p_z$ in equation 6-21 represents the marginal paid amount for feature z, which is the importance of a specific feature occupying the pricing decision. The coefficient $\mu_i$ before character vector $\mathbb{Q}_i{}^{\kappa}$ in equation 6-22 could be considered as the importance ratio of diverse flexibility features. Constituting the flexibility resource, the sum of importance ratio completely considering the characters should be 1. $\kappa$ is the total number of features a single product.

Equation 6-22 is the nucleus pricing equation, where c is the constant and $\varepsilon$ is the error. Being the product property matrix, $\mathbb{Q}_i{}^{\kappa}$ is the main object of discussion is price settlement. The features of flexibilities in this research include the time-flexibility, time-continuity and power-flexibility, which are represented by $\mathbb{Q}_{tf}$, $\mathbb{Q}_{tc}$ and $\mathbb{Q}_{pf}$.

$$\mathbb{Q}_{tf} = \left({\delta}/{\Theta}\right) \times n \qquad (6\text{-}24)$$

$$\mathbb{Q}_{tc} = \left(-{\delta}/{\Theta}\right) \times d + 1 \qquad (6\text{-}25)$$

$$\mathbb{Q}_{pf} = \left(1/_{max\{\eta\}}\right) \times \eta_i + 1 \qquad (6\text{-}26)$$

Where $$\eta_i = Poweri_{max} - Poweri_{min} \qquad (6\text{-}27)$$

Equation 6-24 indicates the flexibility level of load considering the working time schedule. The available working section is the time interval between the demand available start time and the available end time. For example, an hourly-cleared market possesses 24 intervals in one day. The FLs which could work at any time of the day owns the maximum flexibility as 1, and the FL with the shortest available section is under the flexibility of 0. $\delta$ in equation 6-24 represents the unit interval of market clearing. $\Theta$ is the total number of intervals in a particular period, and $n$ is the number of time intervals the FL occupies.

The load flexibility level considering working time continuity is illustrated in equation 6-25. Both require continuous supply, the flexibility level of TSLs and PSLs should be lower than that of the OSLs. The working continuity of load is inversely related to the flexibility level. The extreme FLs which require the nonstop supply is under zero flexibility, and the OSLs which could change their on-off status at any time are under flexibility 1. $\delta$ in the equation is the unit market-clearing time interval. $\Theta$ is the total number of intervals and $d$ is the required continuous working duration.

Equations 6-26 and 6-27 together explain the flexibility level only considering working power. Apart from the TSLs that require fixed power, both the PSLs and the OSLs fluctuate within their power ranges. The larger the power range of the load, the high its flexibility level is. The power-related flexibility level is a relative concept that depends on market participants. $\eta_i$ indicates the difference between the maximum and the minimum power of a load, and $max\{\eta\}$ is the maximum range of working power among entire market participants. This is a dynamic value that would change with different loads participating in the market, bringing the dynamic changes in overall flexibility and price settlement.

The prices settling between DGs and FLs are negatively related to the flexibility level of load, that a load with a higher flexibility level pays less to DG in the transaction. DGs in the real market would range from the marginal costs of DGs to the market cap price. The regulated fluctuation range would guarantee the inexistence of DGs' financial loss, while confining the over-negotiation power of DGs, to reach a fair market circumstance.

As introduced in the pricing strategy of the Airbnb Model sector, the linear relationship and its variants are applied to describe the prices of commodities settled by their attributes. To maximize the nature of market, the simplest linear relationships are settled both between the load attributes and their flexibility levels, and between the load flexibility levels and their prices. Then the features of FLs could be reflected in their prices under the linear transmission. The load with the maximum flexibility level is priced as the bottom, and the one with the minimum flexibility level is priced as the cap. The price of one FL under any flexibility level could be formulated after interpolation as:

$$P = c + \Bigg( \left( P^{bottom} - P^{cap} \middle/ max\{\mathbb{Q}\} - min\{\mathbb{Q}\} \right) \times Q + \left( \frac{max\{\mathbb{Q}\}}{max\{\mathbb{Q}\}} - min\{\mathbb{Q}\} \right) \times P^{cap} - \left( min\{\mathbb{Q}\} \middle/ max\{\mathbb{Q}\} - min\{\mathbb{Q}\} \right) \times P^{bottom} \Bigg) + \varepsilon \tag{6-28}$$

Where $Q$ is the flexibility level of a specific load. $P^{bottom}$ and $P^{cap}$ are the bottom and cap price respectively in the market. The minimum and maximum flexibility levels among market participants are exacted separately by $min\{\mathbb{Q}\}$ and $max\{\mathbb{Q}\}$.

## 6.5 Market mathematical formulation

Three parties discussed in the presented market model are the DGs, the FLs and the utility grid. The first two are the players in the distribution-level market, with the utility grid settling the lack or remaining of the DGs.

Proposing market model consists of two stages, the inner transaction between DGs and FLs, and transferring of the residual/lacking power to/from the utility grid. The market design proposed in this paper applies the central-matching strategy from the Uber business model and the multi-attribute pricing strategy from the Airbnb model. The matching strategy of the distribution-level market is to find the point that participants with the existence of distribution-level market gaining the largest value compared to the situation without distribution-level market. Thus, the objective of our model is supposed to bring the maximum benefit to the DERs (which are DGs in this model) in the proposed P2P market compared to the original one.

There are two main reasons that the network-related constraints are not included in this market. 1. The market segmentation is explored from its necessity in addition to the exploration towards market performances applying dynamic pricing strategy. Being an original economic concept, the purpose of launching the segmentation research is to mobilize the business value of proposed market. The network constraints therefore are considered in constructing market model. 2. The original intention of local market construction is to release network pressure such as congestions and profile peaks. The rational assumption could be made that the implementation of sufficient P2P transactions would alleviating network problems. Therefore, network constraints are not necessarily presented in the model.

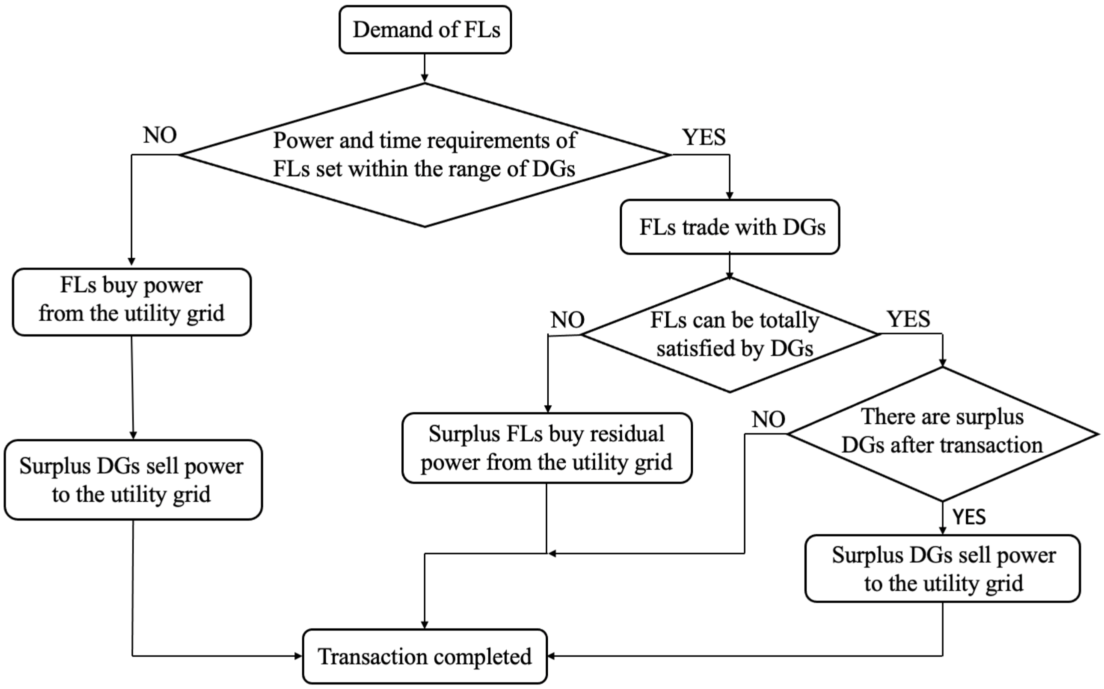



Figure 6- 8 Clearing flowchart of P2P market

### 6.5.1 Objective

The matching strategy of the distribution-level market is to find the point that participants with the existence of a distribution-level market gain the largest value compared to the situation without a distribution-level market. To reach maximum social welfare, DGs and FLs would gain or save the largest amount in the proposed market. The original intention of distribution-level P2P market construction is to mobilize the large amount of DERs in the system without bringing pressure to the network. Thus, the matching strategy is supposed to bring the maximum benefit to the DERs (which are DGs in this model) in the proposed P2P market compared to the original one. The amount of differences gained by DGs here is also considered as the market value of the P2P market. To arrange the matching from the perspective of DGs, the objective of the P2P market model is shown in equation 6-29.

$$
\begin{aligned}
(\boldsymbol{P})\max f = \sum_{t=1}^{n_{int}}(\sum_{jt=1}^{n_{TSL}} & (T_{jt}^{\widetilde{TG}} p_{t,jt}^{\widetilde{TG}} dt + T_{jt}^{\overline{TG}} p_{t,jt}^{\overline{TG}} dt + T_{jt}^{\widehat{TG}} p_{t,jt}^{\hat{T}G} dt) \\
& + \sum_{jp=1}^{n_{PSL}} (T_{jp}^{\widetilde{PG}} p_{t,jp}^{\widetilde{PG}} dt + T_{jp}^{\overline{PG}} p_{t,jp}^{\overline{PG}} dt + T_{jp}^{\widehat{PG}} p_{t,jp}^{\widehat{PG}} dt) + \sum_{jo=1}^{n_{OSL}} (T_{jo}^{\widetilde{OG}}\, p_{t,jo}^{\widetilde{OG}} dt \\
& + T_{jo}^{\overline{OG}} p_{t,jo}^{\overline{OG}} dt + T_{jo}^{\widehat{OG}} p_{t,jo}^{\widehat{OG}} dt) \\
& - \sum_{jo=1}^{n_{OSL}} \sum_{jp=1}^{n_{PSL}} \sum_{jt=1}^{n_{TSL}} (T^{\widetilde{UG}} \left(p_{t,jt}^{\widetilde{TG}} dt + p_{t,jp}^{\widetilde{PG}} dt + p_{t,jo}^{\widetilde{OG}} dt\right) \\
& + T^{\overline{UG}} \left(p_{t,jt}^{\overline{TG}} dt + p_{t,jp}^{\overline{PG}} dt + p_{t,jo}^{\bar{O}G} dt\right) + T^{\widehat{UG}} (p_{t,jt}^{\widehat{TG}} dt + p_{t,jp}^{\widehat{PG}} dt + p_{t,jo}^{\widehat{OG}} dt)))
\end{aligned}
\tag{6-29}
$$

Where $p_{t,jt}^{\widetilde{TG}}$, $p_{t,jt}^{\overline{TG}}$, and $p_{t,jt}^{\widehat{TG}}$ are power transferred between TSLs and DGs in the low, medium and high-reliability levels respectively. The naming rules of $p_{t,jp}^{\widetilde{PG}}$, $p_{t,jp}^{\overline{PG}}$,$p_{t,jp}^{\widehat{PG}}$ are similar in that they represent the PSLs with diverse-level DGs. $p_{t,jo}^{\widetilde{OG}}$, $p_{t,jo}^{\overline{OG}}$ and $p_{t,jo}^{\widetilde{OG}}$ are power flows between OSLs and DGs.

Constants in equation 6-29 contain the number of diverse subjects and prices in the market. The number of TSLs, PSLs, OSLs and time intervals in a day are represented by $n_{TSL}$, $n_{PSL}$, $n_{TSL}$ and $n_{int}$ respectively. $T_{jt}^{\widetilde{TG}}$, $\overline{T_{jt}^{TG}}$ and $T_{jt}^{\widehat{TG}}$ are the prices when TSLs are traded with DGs in low, medium and high-reliability levels. The other price constants between FLs and DGs follow the same naming rules. The prices between DGs and the utility grid are represented by $T^{\widetilde{UG}}$, $\overline{T^{UG}}$ and $T^{\widehat{UG}}$.

There is an implicit logic here that parties are only willing to trade at the distribution-level market when the prices offered at the distribution level are better than those in the original market. The relationship is illustrated in equation 6-30.

$$T^{UG} < T^{LoadG} < T^{LoadU} \tag{6-30}$$

Where $T^{LoadG}$ is the price between different loads and the DGs, and $T^{LoadU}$ is that between loads and the utility grid. $T^{UG}$ represents the transaction prices between the utility grid and DGs when the transmission level is required to guarantee the system balance.

Being a bilateral variable, constraints need to be considered from the perspectives of both limits of FLs and DGs. The requirement of system balancing should also be satisfied.

First, the clearing result should meet the requirements of each FL. A binary variable k is used to select whether the FL would work at a specific time spot. Then the following relationship exists:

$$k_t^T \times \begin{bmatrix} pk_{t,jt}^{\widetilde{TG}} \\ pk_{t,jt}^{\overline{TG}} \\ pk_{t,jt}^{\widehat{TG}} \\ pk_{t,jt}^{TU} \end{bmatrix} = \begin{bmatrix} p_{t,jt}^{\widetilde{TG}} \\ p_{t,jt}^{\overline{TG}} \\ p_{t,jt}^{\widehat{TG}} \\ p_{t,jt}^{TU} \end{bmatrix} \qquad (6\text{-}31)$$

$$k_t^P \times \begin{bmatrix} pk_{t,jt}^{\widetilde{PG}} \\ pk_{t,jt}^{\overline{PG}} \\ pk_{t,jt}^{\widehat{PG}} \\ pk_{t,jt}^{PU} \end{bmatrix} = \begin{bmatrix} p_{t,jt}^{\widetilde{PG}} \\ p_{t,jt}^{\overline{PG}} \\ p_{t,jt}^{\widehat{PG}} \\ p_{t,jt}^{PU} \end{bmatrix} \qquad (6\text{-}32)$$

$$k_t^O \times \begin{bmatrix} pk_{t,jt}^{\widetilde{OG}} \\ pk_{t,jt}^{\overline{OG}} \\ pk_{t,jt}^{\widehat{OG}} \\ pk_{t,jt}^{OU} \end{bmatrix} = \begin{bmatrix} p_{t,jt}^{\widetilde{OG}} \\ p_{t,jt}^{\overline{OG}} \\ p_{t,jt}^{\widehat{OG}} \\ p_{t,jt}^{OU} \end{bmatrix} \qquad (6\text{-}33)$$

$k_t^T, k_t^P$ $and$ $k_t^O$ are 0, 1 binary variables indicate the working status of FLs. Their corresponding FLs are shut down when they equal 0.

$pk$ represents the participating power of FLs when the status of FLs is not considered. Specifically speaking, $pk_{t,jt}^{\widetilde{TG}}, pk_{t,jt}^{\overline{TG}}$, and $pk_{t,jp}^{\widehat{PG}}$ are the power delivered between TSLs and DGs under different reliability levels not considering FL status. $Pk_{t,jt}^{TU}$ is the TSL under similar situation trading with the utility grid. The remaining variables including$pk_{t,jp}^{\widetilde{PG}}$, $pk_{t,jp}^{\overline{PG}}$ , $pk_{t,jp}^{\widehat{PG}}$ , $pk_{t,jp}^{PU}$, $pk_{t,jo}^{\widetilde{OG}}, pk_{t,jo}^{\overline{OG}}$, $pk_{t,jp}^{\widehat{PG}}$and $pk_{t,jo}^{OU}$ follow a similar naming scheme, belonging to PSLs and OSLs. $p$ is the actual matching power of FLs taking the on-off state into consideration, whose top and bottom corner marks are named in a similar way to other variables. The meanings of p-related variables are introduced in equation 6-29.

The constraints in the model are launched from two major perspectives. One aspect is the constraints coming from specific features of FLs, and the other is the system balancing requirements. The feature-related constraints include the available working time slot, the total working time, the continuous working restriction, the working power range, the total required work of FLs. The balancing-related constraints include network nodal balancing, DG capacity restrictions. The problem is subject to the following constraints.

## 6.5.2 Available working time constraint

The available working time slot constraints of FLs are illustrated in the following formula.

$$\begin{cases} k_{t,jt}^{T} = 0 \left(when\ 0 \le t \le TS_{jt}^{T} - 1\right) \\ 0 \le k_{t,jt}^{T} \le 1 \left(when\ TS_{jt}^{T} \le t \le TE_{jt}^{T}\right) \\ k_{t,jt}^{T} = 0 \left(when\ TE_{jt}^{T} + 1 \le t \le n_{int}\right) \end{cases} \quad (6\text{-}34)$$

$$\begin{cases} k_{t,jp}^{P} = 0 \left(when\ 0 \le t \le TS_{jp}^{P} - 1\right) \\ 0 \le k_{t,jp}^{P} \le 1 \left(when\ TS_{jp}^{P} \le t \le TE_{jp}^{P}\right) \\ k_{t,jp}^{P} = 0 \left(when\ TE_{jp}^{P} + 1 \le t \le n_{int}\right) \end{cases} \quad (6\text{-}35)$$

$$\begin{cases} k_{t,jo}^{O} = 0 \left(when\ 0 \le t \le TS_{jo}^{O} - 1\right) \\ 0 \le k_{t,jo}^{O} \le 1 \left(when\ TS_{jo}^{O} \le t \le TE_{jo}^{O}\right) \\ k_{t,jo}^{O} = 0 \left(when\ TE_{jo}^{O} + 1 \le t \le n_{int}\right) \end{cases} \quad (6\text{-}36)$$

The Equation 6-34 is the available working time constraints for TSLs. The Equations 6-35 and 6-36 are suitable for PSLs and OSLs respectively.

The meanings of $k$-related variables are introduced in Equations 6-31 to 6-33. Other subjects in constraints including $TS_{jt}^{T}, TE_{jt}^{T}, TS_{jp}^{P}, TE_{jp}^{P}, TS_{jo}^{O}, TE_{jo}^{O}\ and\ n_{int}$ are constants. Taking $TS_{jt}^{T}\ andTE_{jt}^{T}$ as an example, they are the available start time and the available end time for TSLs. Other constants with P and O superscripts are for PSLs and OSLs respectively.

## 6.5.3 Working length constraint

TSLs and PSLs are two FLs possessing the requirements of total work time.

$$\sum_{jt=1}^{n_{TSL}} k_{t,jt}^{T} = D_{jt}^{T} \quad (6\text{-}37)$$

$$\sum_{jp=1}^{n_{PSL}} k_{t,jp}^{P} = D_{jp}^{P} \quad (6\text{-}38)$$

The variables $k_{t,jt}^{T}$ and $k_{t,jp}^{P}$ with constants $n_{TSL}$ and $n_{PSL}$ in two equations have been illustrated in equations 6-31 to 6-33. The constants $D_{jt}^{T}$ and $D_{jp}^{P}$ here are the total working duration of TSLs and PSLs.

### 6.5.4 Continuous working constraint

The TSLs and PSLs expect continuous supplies, ones would not stop as long as they start working.

$k$ is the binary status variable in the following equations. The $k$ for a specific FL would change from 0 to 1 (or 1 to 0) when the status of that FL changes. The sum of the absolute value of the difference between adjacent time spots could represent the total number of status changes in the entire observing session. For TSLs and PSLs that should work continuously, their status would only change twice in the whole period.

$$\sum_{jt=1}^{n_{TSL}} \sum_{t=1}^{n_{int}} \left| k_{t+1,jt}^{T} - k_{t,jt}^{T} \right| = 2 \qquad (6\text{-}39)$$

$$\sum_{jp=1}^{n_{PSL}} \sum_{t=1}^{n_{int}} \left| k_{t+1,jp}^{P} - k_{t,jp}^{P} \right| = 2 \qquad (6\text{-}40)$$

The continuous working constraints for TSLs and PSLs are shown in equations 6-39 and 6-40.

### 6.5.5 Working power range constraint

TSLs are demand waiting for a fixed power, while PSLs and OSLs want supply within the minimum and the maximum power range. The variable loads after the selection of binary variables should also restrict by the limits of FL powers.

$$pk_{t,jt}^{\widetilde{TG}} + pk_{t,jt}^{\overline{TG}} + pk_{t,jt}^{\widehat{TG}} + pk_{t,jt}^{TU} = P_{jt}^{T} \qquad (6\text{-}41)$$

$$\begin{bmatrix} Pmin_{jp}^{P} \\ Pmin_{jo}^{O} \end{bmatrix} \leq \begin{bmatrix} pk_{t,jp}^{\widetilde{PG}} + pk_{t,jp}^{\overline{PG}} + pk_{t,jp}^{\widehat{PG}} + pk_{t,jp}^{PU} \\ pk_{t,jo}^{\widetilde{OG}} + pk_{t,jo}^{\overline{OG}} + pk_{t,jo}^{\widehat{OG}} + pk_{t,jo}^{OU} \end{bmatrix} \leq \begin{bmatrix} Pmax_{jp}^{P} \\ Pmax_{jo}^{O} \end{bmatrix} \qquad (6\text{-}42)$$

$$p_{t,jt}^{\widetilde{TG}} + p_{t,jt}^{\overline{TG}} + p_{t,jt}^{\widehat{TG}} + p_{t,jt}^{TU} = P_{jt}^{T} \qquad (6\text{-}43)$$

$$\begin{bmatrix} Pmin_{jp}^{P} \\ Pmin_{jo}^{O} \end{bmatrix} \leq \begin{bmatrix} p_{t,jp}^{\widetilde{PG}} + p_{t,jp}^{\overline{PG}} + p_{t,jp}^{\widehat{PG}} + p_{t,jp}^{PU} \\ p_{t,jo}^{\widetilde{OG}} + p_{t,jo}^{\overline{OG}} + p_{t,jo}^{\widehat{OG}} + p_{t,jo}^{OU} \end{bmatrix} \leq \begin{bmatrix} Pmax_{jp}^{P} \\ Pmax_{jo}^{O} \end{bmatrix} \qquad (6\text{-}44)$$

The variables in those equations have been introduced in equations 6-29 and 6-31 to 6-33. $P_{jt}^{T}$, $Pmin_{jp}^{P}$, $Pmax_{jp}^{P}$, $Pmin_{jo}^{O}$, $Pmax_{jo}^{O}$ in the equations are constants. $P_{jt}^{T}$ is the required fixed working power for TSLs. $Pmin_{jp}^{P}$ and $Pmax_{jp}^{P}$ are the minimum and maximum working power for PSLs. And the working power for OSLs ranging from $Pmin_{jo}^{O}$ to $Pmax_{jo}^{O}$. $P_{t,jt}^{TU}$ are that of TSLs traded with the utility grid. $P_{t,jp}^{PU}$ are that of PSLs traded with the utility grid. $P_{t,jo}^{OU}$ are that of OSLs traded with the utility grid.

Each kind of FLs possesses the total work constraint, which only restrains power between DGs and FLs after selection.

$$\begin{bmatrix} \sum_{t=1}^{n_{int}} p_{t,jt}^{\breve{TG}} dt + \sum_{t=1}^{n_{int}} p_{t,jt}^{\overline{TG}} dt + \sum_{t=1}^{n_{int}} p_{t,jt}^{\widehat{TG}} dt + \sum_{t=1}^{n_{int}} p_{t,jt}^{TU} dt \\ \sum_{t=1}^{n_{int}} p_{t,jp}^{\breve{PG}} dt + \sum_{t=1}^{n_{int}} p_{t,jp}^{\overline{PG}} dt + \sum_{t=1}^{n_{int}} p_{t,jp}^{\widehat{PG}} dt + \sum_{t=1}^{n_{int}} p_{t,jp}^{PU} dt \\ \sum_{t=1}^{n_{int}} p_{t,jo}^{\breve{OG}} dt + \sum_{t=1}^{n_{int}} p_{t,jo}^{\overline{OG}} dt + \sum_{t=1}^{n_{int}} p_{t,jo}^{\widehat{OG}} dt + \sum_{t=1}^{n_{int}} p_{t,jo}^{OU} dt \end{bmatrix} = \begin{bmatrix} Q_{jt}^{T} \\ Q_{jp}^{P} \\ Q_{jo}^{O} \end{bmatrix} \tag{6-45}$$

Taking the variables of the TSL as an example, the$p_{t,jt}^{\breve{TG}}$, $p_{t,jt}^{\overline{TG}}$, $p_{t,jt}^{\widehat{TG}}$ are the quantity of TSLs traded with DGs in different reliability levels. $P_{t,jt}^{TU}$ are that of TSLs traded with the utility grid. $Q_{jt}^{T}$ is the required total work constant of the TSL. Variables and constants for PSLs and OSLs are named similarly.

It is worthy to be highlighted that only the variable loads after the selection of status variables (named without k) are limited by the total work constraints, as the work is only meaningfully discussed when the on-off status of the load is settled down.

Other than the characters of FLs, the power balancing of the system and the generation limitation of DGs should also be considered.

### 6.5.6 Spot balancing constraint

From the perspective of power balancing, the power required by one FL from both the utility grid and the DGs would reach a spot balance:

$$\begin{gathered} \sum_{jt=1}^{n_{TSL}} p_{t,jt}^{\breve{TG}} + \sum_{jt=1}^{n_{TSL}} p_{t,jt}^{\overline{TG}} + \sum_{jt=1}^{n_{TSL}} p_{t,jt}^{\widehat{TG}} + \sum_{jt=1}^{n_{TSL}} p_{t,jt}^{TU} + \sum_{jp=1}^{n_{PSL}} p_{t,jp}^{\breve{PG}} + \sum_{jp=1}^{n_{PSL}} p_{t,jp}^{\overline{PG}} + \sum_{jp=1}^{n_{PSL}} p_{t,jp}^{\widehat{PG}} + \\ \sum_{jp=1}^{n_{PSL}} p_{t,jp}^{PU} + \sum_{jo=1}^{n_{OSL}} p_{t,jo}^{\breve{OG}} + \sum_{jo=1}^{n_{OSL}} p_{t,jo}^{\overline{OG}} + \sum_{jo=1}^{n_{OSL}} p_{t,jo}^{\widehat{OG}} + \sum_{jo=1}^{n_{OSL}} p_{t,jo}^{OU} = \sum_{i}^{n_{\breve{G}}} G_{t,i}^{\breve{DG}} + \sum_{i}^{n_{\bar{G}}} G_{t,i}^{\overline{DG}} + \sum_{i}^{n_{\hat{G}}} G_{t,i}^{\widehat{DG}} \end{gathered} \tag{6-46}$$

Variables here are introduced in Equation 6-29. The $G_{t,i}^{\breve{DG}}, G_{t,i}^{\overline{DG}}$ $and$ $G_{t,i}^{\widehat{DG}}$ are constants representing the generation from DGs in the reliability levels of low, medium, and high. $n_{\breve{G}}, n_{\bar{G}}$ $and$ $n_{\hat{G}}$ the number of DGs under a low, medium, and high flexibility levels respectively.

### 6.5.7 DG Capacity Constraint

The power transferred from DGs to the FLs should not exceed the capacity of DGs.

$$0 \le \begin{bmatrix} \sum_{jt=1}^{n_{TSL}} p_{t,jt}^{\widetilde{TG}} + \sum_{jp=1}^{n_{PSL}} p_{t,jp}^{\widetilde{PG}} + \sum_{jo=1}^{n_{OSL}} p_{t,jo}^{\widetilde{OG}} \\ \sum_{jt=1}^{n_{TSL}} p_{t,jt}^{\overline{TG}} + \sum_{jp=1}^{n_{PSL}} p_{t,jp}^{\overline{PG}} + \sum_{jo=1}^{n_{OSL}} p_{t,jo}^{\overline{OG}} \\ \sum_{jt=1}^{n_{TSL}} p_{t,jt}^{\widehat{TG}} + \sum_{jp=1}^{n_{PSL}} p_{t,jp}^{\hat{P}G} + \sum_{jo=1}^{n_{OSL}} p_{t,jo}^{\widehat{OG}} \end{bmatrix} \le \begin{bmatrix} \sum_{i}^{n_{\breve{G}}} G_{t,i}^{\widetilde{DG}} \\ \sum_{i}^{n_{\bar{G}}} G_{t,i}^{\overline{DG}} \\ \sum_{i}^{n_{\hat{G}}} G_{t,i}^{\widehat{DG}} \end{bmatrix} \qquad (6\text{-}47)$$

Where variables are explained in Equation 6-29 and constants are illustrated in Equation 6-46.

In all the equations from 6-29 to 6-47, $1 \le jt \le NT, 1 \le jp \le NP, 1 \le jo \le NO, 0 \le t \le NI, jt\ , jp\ , js$ and $t$ are integers.

# 6.6 Case analysis

The automatic trading distribution-level market proposed in this paper is a mixed linear programming model, solved by the CPLEX. An issue faced here is the low efficiency of large-scale matching that the distribution-level market calls for spot-to-spot clearings more than ten times every day (depends on the time interval between clearings), involving a large number of decision variables and great challenges.

To avoid the long calculation time brought by the large-scale participant matching and focus on the analysis of market nature and clearing result, the market operation simulation proposed in this paper are the scale-down cases. The dozens of DGs and FLs discussed in the paper are far less than the hundreds or thousands of market participants in the real world. The scenario explored in this market involves three parts: 1. The single type of flexible loads engagement to the flexibility market 2. The entire types of flexible loads engagement to the integrated flexibility market 3. The entire types of flexible loads engagement to the segmented flexibility market.

The details of their transactions are:

1. The single type of flexible loads engagement to the flexibility market

To discuss the price characteristics under the proposed pricing strategy and the following clearing behaviors of flexible loads, the single type of flexible loads participating the distribution-level market is firstly analyzed. The market carries out the transaction between six DGs and six flexible loads. The DGs here involves 2 low-flexibility-level ones, 2 medium-flexibility-level ones and 2 high-flexibility level ones.

The six flexible loads are in turns to the time-shiftable flexible loads, power-shiftable flexible loads and overall-shiftable flexible loads respectively. The numerical description of DGs and FLs would be introduced detailly in the case analysis paragraph.

2. The entire types of flexible loads engagement to the integrated market and segmented market

The same participants are discussed in the integrated market and the segmented market, thus reflecting whether the distribution-level market should be an overall or splitting form. 18 DGs (with 6 low-reliability level ones, 6 medium-reliability-level ones and 6 high-reliability level ones) and 18 flexible loads (with 6 time-shiftable loads, 6 power-shiftable loads and 6 state-shiftable loads) are traded with each other in a market in the cases. The numerical description would provide in the cases later. As the matching results between DGs and flexible loads are related to not only the features of participants but also the total work transacted in the market, all the comparison relationships of DGs and FLs should be taken into account. Three typical scenarios thus explored in this paper: 1. Total work provided by DGs are far less than the requirements of flexible loads 2. Total work provided by DGs are almost the same to the requirements of flexible loads 3. Total work provided by DGs are far more than the requirements of flexible loads. The market clearing results under three scenarios are analyzed detailly in the following discussion.

### 6.6.1 Flexible load in single-type-FL market

The market with the only one type of FL is firstly simulated to explore the prices and clearing quantities of loads under the proposed dynamic pricing strategy. To be more persuasive, the same key attributes are adopted on the different varieties of FLs, which are equally available start time, available end time, the total required work and continuous working hours. Considering the uncertainty of forecast DG, the DGs discussed in the paper is divided into three reliability levels (50%, 80%, 100%), being corresponding to the low-reliability level, high-. Different costs of DGs are assigned to reflect their reliability levels. There are 6 DG analyzed in this case, with an average peak generation of 700kW and a total supply of 2000kWh for each DG. The market bottom price and cap price need to be pre-set in our pricing strategy, with the importance ratios of three sub-flexibility levels. The cost of DGs in the 100%-reliability-level is set as 10 pence, thus the cost of 80%-reliability DGs and 50%-

reliability DGs are 8 and 5 pence respectively. Since the price of DGs should at least cover their cost, the market bottom prices are settled as the costs. And three times the costs are set as the cap prices. A universal result of FLs and their market is explored in this paper, then the importance ratios of sub-flexibility levels are settled as equal that $\mu_1 = \mu_2 = \mu_3 = 1/3$.

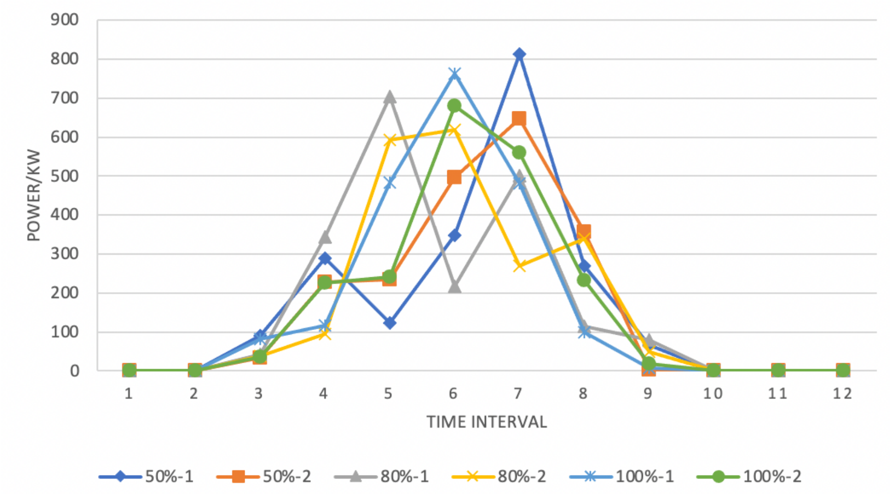



Figure 6- 9 The pattern of DGs participating one-type-FL market

To better reflect the characters of different types of flexible loads, the flexible loads discussed in the case possess the same basic parameters and are only different on the feature-reflective loads. That is, three types of participating flexible loads are holding the same available start time, available end time, continuous working duration (if required) and total work.

The detailed parameters of FLs explored in this case are illustrated in the table 6-5.

Table 6- 5 Parameters of FLs in the case study

(a)time-shiftable loads

| *Parameters* | TVL 1 | TVL 2 | TVL 3 | TVL 4 | TVL 5 | TVL 6 |
|---|---|---|---|---|---|---|
| *Available Start Time* (Interval No.) | 1 | 2 | 5 | 5 | 2 | 3 |
| *Available End Time* (Interval No.) | 9 | 7 | 9 | 9 | 9 | 7 |
| *Fixed Required Power* (kW) | 350 | 350 | 350 | 350 | 350 | 350 |
| *Duration* (Interval) | 2 | 5 | 3 | 3 | 3 | 2 |

(b)power-shiftable loads

| *Parameters* | PVL 1 | PVL 2 | PVL 3 | PVL 4 | PVL 5 | PVL 6 |
|---|---|---|---|---|---|---|
| *Available Start Time* (Interval No.) | 1 | 2 | 5 | 5 | 2 | 3 |
| *Available End Time* (interval No.) | 9 | 7 | 9 | 9 | 9 | 7 |
| *Min Required Power* (kW) | 31 | 47 | 37 | 46 | 49 | 42 |
| *Max Required Power* (kW) | 408 | 357 | 427 | 417 | 380 | 421 |
| *Duration* (Interval) | 2 | 5 | 3 | 3 | 3 | 2 |
| *Required Work* (kWh) | 700 | 1750 | 1050 | 1050 | 1050 | 700 |

(c)overall-shiftable loads

| *Parameters* | OVL 1 | OVL 2 | OVL 3 | OVL 4 | OVL 5 | OVL 6 |
|---|---|---|---|---|---|---|
| *Available Start Time* (Interval No.) | 1 | 2 | 5 | 5 | 2 | 3 |
| *Available End Time* (Interval No.) | 9 | 7 | 9 | 9 | 9 | 7 |
| *Min Required Power* (kW) | 24 | 46 | 31 | 44 | 46 | 35 |
| *Max Required Power* (kW) | 438 | 356 | 391 | 357 | 392 | 440 |
| *Required Work* (kWh) | 700 | 1750 | 1050 | 1050 | 1050 | 700 |

On the premise that DGs in different reliability levels are providing similar total work and peak power, one type of FL is mainly traded with 80%-reliability-level DGs and 100%-reliability-level DGs. The market is looking for matches between FLs and higher-price DGs to chase the maximum market existing utility. DGs with higher reliability level are under higher costs, becoming the prior transaction partner. The vertical comparison among FLs shows similar clearing quantity, because DGs are adequate and FLs under uniform factors are satisfied approximately.

Prices of three kinds of FLs under dynamic pricing strategy is emphatically discussed. The prices between FLs and DGs are roughly the same when there is only one type of FL in the market. The most significant feature of a dynamic pricing strategy is that the prices of FLs are related to their flexibility levels, influenced by the participating FLs. The flexibility levels within one type of FLs are close, leading to similar prices. The price comparison between integrated and segmented markets is explored to settle the rules of market segmentation.

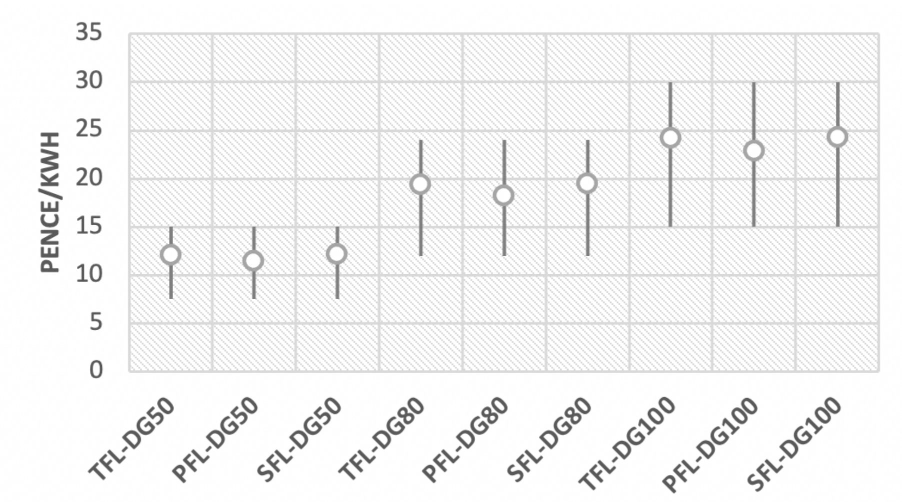



Figure 6- 10 Prices between FLs and DGs of different reliability levels in single-type-FL market

Table 6- 6 Price ranges and average prices between FLs and DGs in single-type flexibility market

| | DG With 50% Reliability | | | DG With 80% Reliability | | | DG With 100% Reliability | | |
|---|---|---|---|---|---|---|---|---|---|
| (pence/kWh) | Min | Max | Average | Min | Max | Average | Min | Max | Average |
| Time-variable Load | 7.5 | 15.0 | 12.1 | 12 | 24 | 19.3 | 15 | 30 | 24.2 |
| Power-variable Load | 7.5 | 15.0 | 11.4 | 12 | 24 | 18.3 | 15 | 30 | 22.8 |
| Overall-variable Load | 7.5 | 15.0 | 12.1 | 12 | 24 | 19.4 | 15 | 30 | 24.3 |

## 6.6.2 Comparison between segmented and integrated market

### 6.6.2.1 Market price comparison

The distribution-level markets traditionally discussed, no matter the regional or global ones, are cleared indiscriminately as a whole. A further analysis of market segmentation proceeds in this paper, making energy products be closer to the normal commodities in transactions.

Being a concept of Marketing, market segmentation originally refers to dividing the whole market into sub-markets with some common characteristics according to the needs and desires of consumers. The subdivisions of the traditional commodity market mainly include geographic subdivision, population subdivision, psychological subdivision, behavior subdivision and income subdivision, which is an inevitable product of the consumer-centered transformation towards the consumer-oriented markets. The market segmentation is realistically significant as the P2P automatic trading energy market has the characteristics of strong individuality and independent decision-making for market participants.

To simulate a distribution-level market being more like the real world, increased DGs are put in the integrated market where all kinds of FLs are cleared together. 18 DGs are analyzed in this case, with six 50%-reliability-level ones, six 80%-reliability-level ones and six 100%-reliability-level ones. Three scenarios are discussed in this comparison process, including the situation when the supply of DGs is far less than the need of FLs, the supply of DGs basically equal to the demand of FLs, and the time when that of DGs is much more than the requirement of FLs. Those scenarios indicate the future distribution system situations that the TSO-DSO would possess deep coupling when the work of DG is far less than the work of FL, because the distribution system requires the coordination from transmission system reaching the demand-supply balance. And a medium-level TSO-DSO coupling is expected when the supply of DGs is approximate to the demand of FLs. Similarly, the scenario of DG work more than FL work indicates the weak coupling between TSO and DSO. The average peak generation and total work of DGs in those scenarios are:

Table 6- 7 Key parameters of DGs participating market comparison

| | *TSO-DSO Deep Coupling* | *TSO-DSO Medium Coupling* | *TSO-DSO Low Coupling* |
|---|---|---|---|
| *Average Peak Generation*(kW) | 80 | 330 | 1300 |
| *Total Work*(kWh) | 250 | 1000 | 4000 |

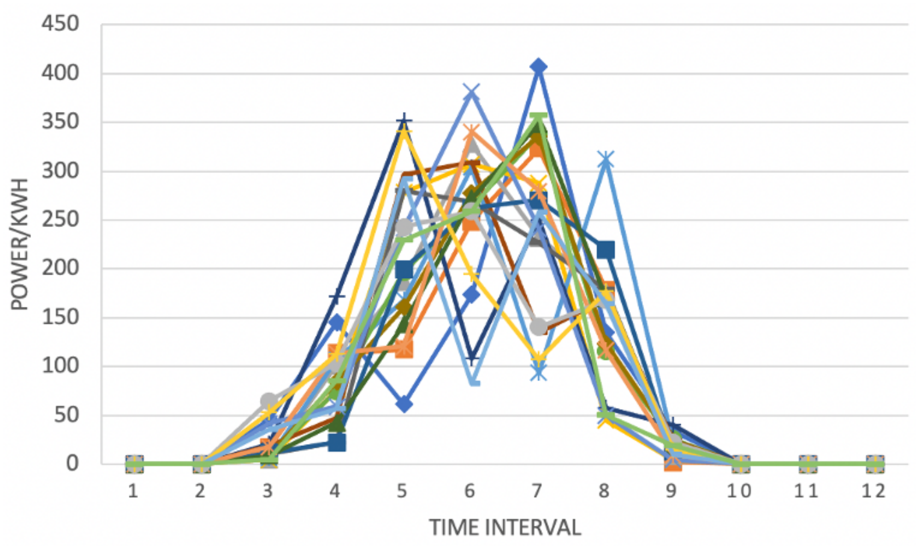



Figure 6- 11 Patterns of DGs participating market comparison

The FLs engaged in this case are the FLs mentioned in the single-type market. Rather than participating in the market respectively, all types of FLs are transacted in this case.

The participating amount of DGs would not affect the assessment of reliability level, thus being incapable to influence the market prices. Prices between FLs and DGs are only relevant to the integration or segmentation of the market.

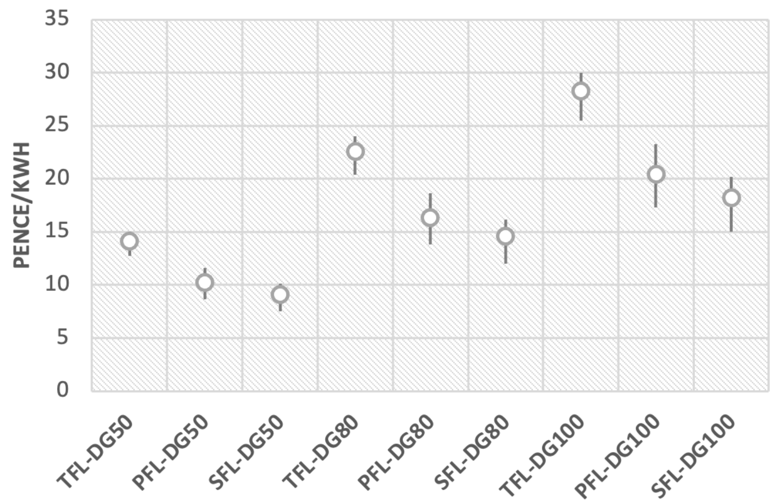



Figure 6- 12 Prices between FLs and DGs of different reliability levels in the integrated market

Table 6- 8 Price ranges and average prices between DGs and FLs in the integrated market

| (pence/kWh) | DG With 50% Reliability | | | DG With 80% Reliability | | | DG With 100% Reliability | | |
|---|---|---|---|---|---|---|---|---|---|
| | Min | Max | Average | Min | Max | Average | Min | Max | Average |
| Time-variable Load | 12.8 | 15.0 | 14.1 | 20.4 | 24.0 | 22.6 | 25.5 | 30.0 | 28.3 |
| Power-variable Load | 8.7 | 11.6 | 10.2 | 13.8 | 18.6 | 16.3 | 17.3 | 23.3 | 20.4 |
| Overall-variable Load | 7.5 | 10.1 | 9.1 | 12.0 | 16.2 | 14.6 | 15.0 | 20.2 | 18.2 |

In the integrated market, the time-shiftable loads, power-shiftable loads and overall-shiftable loads traded with the 50%-reliability-level DGs are under the price ranges of 12.8 to 15.0 pence/kWh, 8.7 to 11.6 pence/kWh, and 7.5 to 10.1 pence/kWh, with the average prices of 14.1, 10.2 and 9.1 pence/kWh. FLs traded with 80%-reliability-level DGs are under the price ranges of 20.4 to 24.0 pence/kWh, 13.8 to 18.6 pence/kWh, and 12.0 to 16.2 pence/kWh, with the average prices of 22.6, 16.3 and 14.6 pence/kWh. Prices between FLs and 100%-reliability-level DGs are under the ranges of 25.5 to 30.0 pence/kWh, 17.3 to 23.3 pence/kWh and 15.0 to 20.0 pence/kWh, with average prices of 28.3, 20.4 and 18.2 pence/kWh.

Prices of power-shiftable loads and overall-shiftable loads locate in a close range when trading with DGs in the same reliability level, while the average prices of overall-shiftable loads are lower than those of power-shiftable loads. Power-shiftable loads and overall-shiftable loads possess overlap ranges of 8.7 to 10.1, 13.8 to 16.2 and 17.3 to 20.2 pence/kWh when trading with DGs of 50%-reliability-level, 80%-reliability-level and 100%-reliability-level respectively. Prices of time-shiftable loads paying to buy DGs are significantly higher than the prices of other two types of FLs. The lowest prices in the price ranges of time-shiftable loads are higher than the largest prices of power-shiftable loads and overall-shiftable loads when traded with any reliability-level DGs. For 50%-reliability level DGs, that is 12.8 pence/kWh is larger than 11.6 pence/kWh. For 80%-reliability level DGs, that is 20.4 pence/kWh is larger than 18.6 pence/kWh. For 100%-reliability level DGs, that is 25.5 pence/kWh is higher than 23.3 pence/kWh. The price differences are generated by different flexibility levels. Comprehensively speaking, time-shiftable loads are under the lowest reliability levels because of their fixed power and continuity limit. The flexibility level of power-shiftable loads would slightly higher because they are only limited to the continuous working, but not the fixed working power. The lack of continuous working restriction assigns more flexibilities to the SFLs, leading to higher flexibility level and lower prices. The TFL prosumers would be discouraged to some extent because those differences in price, especially in the future voluntary automatic trading DER market, leading to the negative effects towards flexibility market development.

A rational market segmentation thus is required to balance the price differences between TFLs and the other two FLs. Better performances in market value and transactions are expected. To start with the visual prices, TFLs would pay for higher prices because of its low flexibility level as long as it is in the same pool with PFLs and SFLs. An individual segment of TFLs is considered, while PFLs and SFLs belong to the other segment. The prices of TFLs, PFLs and SFLs after market-splitting are:

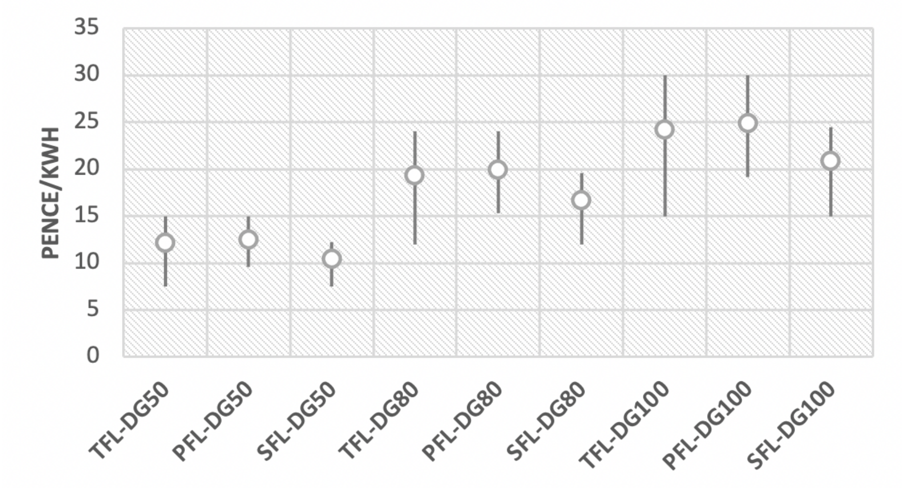



Figure 6- 13 Prices between FLs and DGs of different reliability levels in the segmented market

Table 6- 9 Price ranges and average prices between DGs and FLs in the segmented market

| (pence/kWh) | DG With 50% Reliability | | | DG With 80% Reliability | | | DG With 100% Reliability | | |
|---|---|---|---|---|---|---|---|---|---|
| | Min | Max | Average | Min | Max | Average | Min | Max | Average |
| Time-variable Load | 7.5 | 15.0 | 12.1 | 12.0 | 24.0 | 19.3 | 15.0 | 30.0 | 24.2 |
| Power-variable Load | 9.6 | 15.0 | 12.4 | 15.3 | 24.0 | 19.9 | 19.2 | 30.0 | 24.9 |
| Overall-variable Load | 7.5 | 12.2 | 10.4 | 12.0 | 19.5 | 16.7 | 15.0 | 24.4 | 20.8 |

In the segmented market, the time-shiftable loads, power-shiftable loads and overall-shiftable loads traded with the 50%-reliability-level DGs are under the price ranges of 7.5 to 15.0 pence/kWh, 9.6 to 15.0 pence/kWh and 7.5 to 12.2 pence/kWh, with the average prices of 12.1, 12.4 and 10.4 pence/kWh. FLs traded with 80%-reliability-level DGs are under the price ranges of 12.0 to 24.0, 15.3 to 24.0 and 12.0 to 19.5 pence/kWh, with the average prices of 19.3, 19.9 and 16.7 pence/kWh. Prices between FLs and 100%-reliability-level DGs are under the ranges of 15.0 to 30.0, 19.2 to 30.0 and 15.0 to 24.4, with average prices of 24.2, 24.9 and 20.8 pence/kWh.

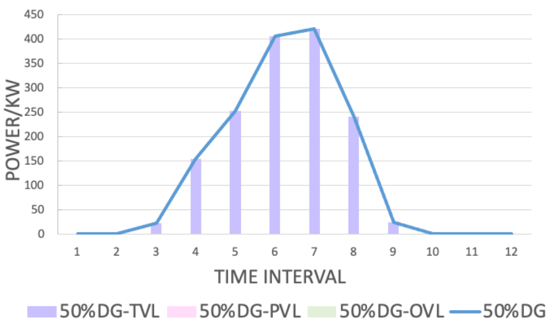
More overlap ranges of flexible loads can be observed in the figure 6-13. For flexible loads traded with 50%-reliability-level DGs, the range of 9.6 to 12.2 pence/kWh is the overlap. And for 80%-reliability-level DGs and 100%-reliability-level DGs, this overlap would be 15.3 to 19.5 pence/kWh and 19.2 to 24.4 pence/kWh. The increasing overlap ranges of prices between DGs and FLs mobilizes the participation of flexible loads and stimulate the complete of market equity, as the matching of flexible loads and DGs lies more on the features of flexible loads but not their species.

#### 6.6.2.2 Market clearing comparison

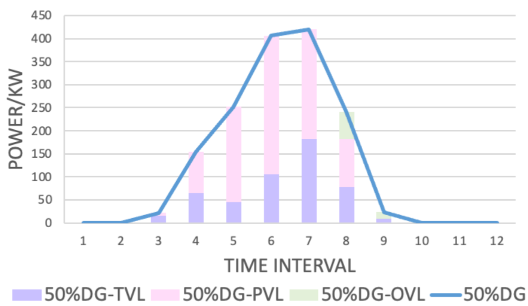
To compare the integrated market and the segmented market comprehensively and fairly, three scenarios are analyzed in this paper. The discussion contains all the extreme situations that would happen in the flexibility market.

The diverse infiltration degree of distributed energy resources participating the distribution sector causes different distribution-level independence stages, which is the disparate TSO-DSO coupling levels. When the penetration rate of distributed energy resources is very limited, that is the total work of DG is far less than that of FL, the distribution sector requires deep affiliation with the transmission sector due to its nonindependence. This scenario indicates the TSO-DSO high-level coupling. The total work of DG being basically the same to that of FL leads to the equal responsibility between transmission level and the distribution level with the development of energy resources, indicating the TSO-DSO medium-level coupling. The distribution sector would achieve autonomy when DG are far more than the FL, representing the TSO-DSO low-level coupling.

***TSO-DSO High-level Coupling***




(a)

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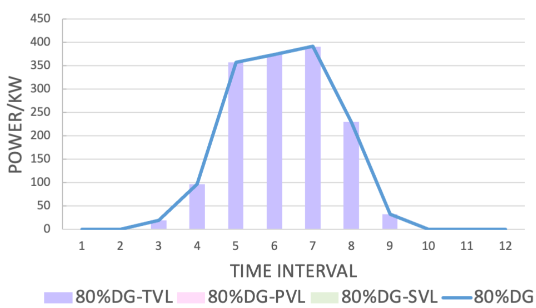


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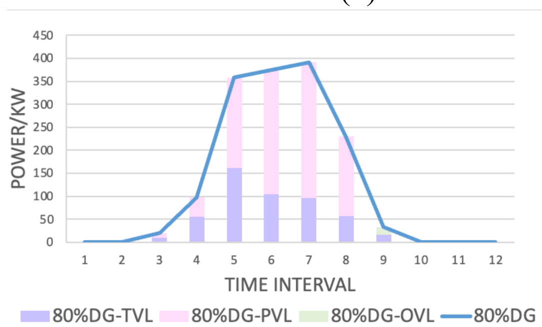


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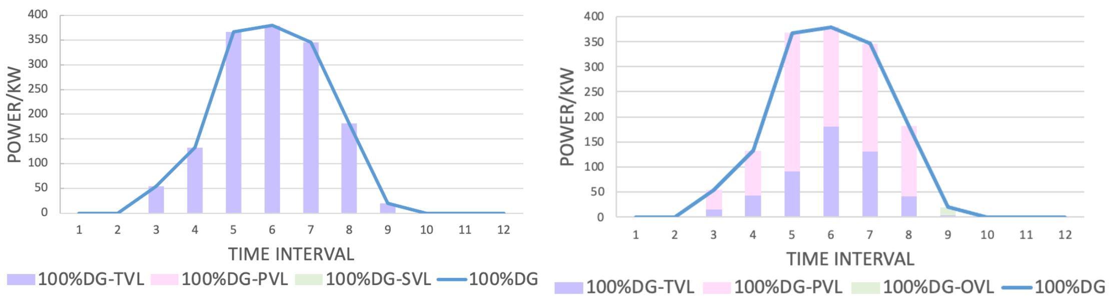



(e) (f)

Figure 6- 14 Integrated market clearing results between FLs and (a).50%-reliability DGs (c).80%-reliability DGs (e).100%-reliability DGs and segmented market clearing results between FLs and (b).50%-reliability DGs (d).80%-reliability DGs (f).100%-reliability DGs under TSO-DSO high-level coupling

The first scenario explored is the time when the supply from DG being less than the demand from FLs. In this case, DGs are holding the option of transactions. The purpose of DGs is to complete transactions with FLs in the proposed flexibility market as much as possible, so to save the most amount of money compared with trading directly with the utility grid. To achieve the maximum saving target, DGs tend to match with higher priced FLs.

In the integrated market where TSLs, PSLs, and OSLs are under mixed clearing, loads with lower flexibilities under the dynamic pricing strategy are higher priced. TSLs, with restrictions of fixed working power and continuous working time, are under lower flexibility levels than the other two types of FLs, thus always matching with DGs first.

When the total work of DGs is less than that of FLs in the integrated market, the 100% of DGs could trade with flexible loads without the backup of the utility grid. This indicates that the adequate flexible loads would achieve the DG digestion, helping to avoid the issues of DG connection. The entire DGs are traded with TSLs at this time, without the participation of PSLs and OSLs. The priority trend of TSLs trading with DGs is shown in the clearing result.

While in the segmented market that TSL is a segment itself, and PSLs and OSLs are under the same market segment, PSLs also have the matching opportunity because they are the lower-flexibility-level loads in their own segment.

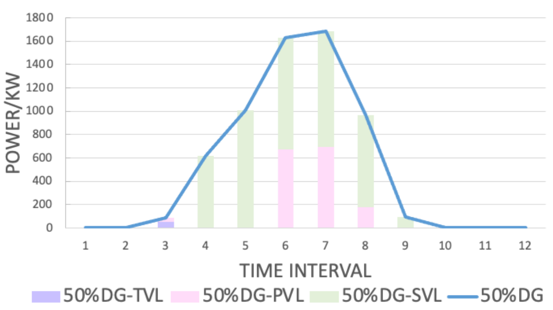
The 100% amount of DGs could trade with the distribution-level flexibility market, indicating the effectiveness of the market. In the clearing result of 50%-reliability-level DGs, TSLs are traded with 1000.6 kWh DGs, PSLs are traded with 1891.4 kWh DGs, and OSLs are traded with 145.4 kWh of DGs. The proportion of the three types of FLs is 34.04%, 64.8%, and 1.11%.

For the total 3007.6 kWh of 80%-reliability-level DGs, transactions of TSLs take 33.26% of the 1000.2 kWh amount. The clearing result of PSLs and OSLs are 1974.2 kWh and 33.4 kWh respectively, with a proportion of 65.64% and 1.11%. TSLs, PSLs, and OSLs are traded with 1008 kWh, 1920 kWh, and 32.8 kWh 100%-reliability-level DGs, in the percentages of 34.04%, 64.8%, and 1.11%.

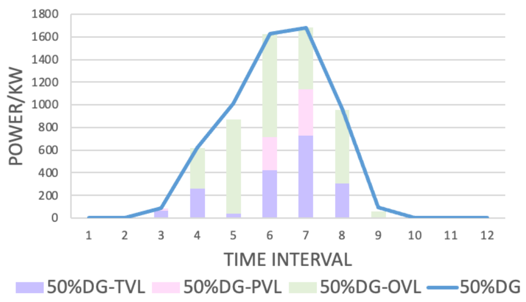
Discussing the comprehensive market situation, 33.41% of DGs are traded with TSLs, 64.24% are traded with PSLs, with the remaining 2.35% with OSLs.

The horizontal comparison between integrated market and segmented market shows that more types of FLs are involved in the segmented one, increasing the equity of transactions and incentivizing the enthusiasm of market participants.

***TSO-DSO Medium-level Coupling***




(a)

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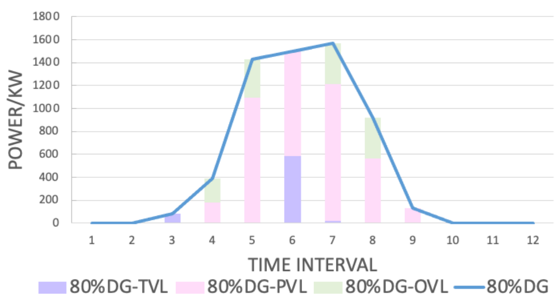


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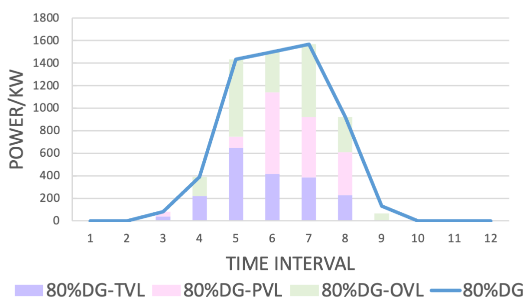


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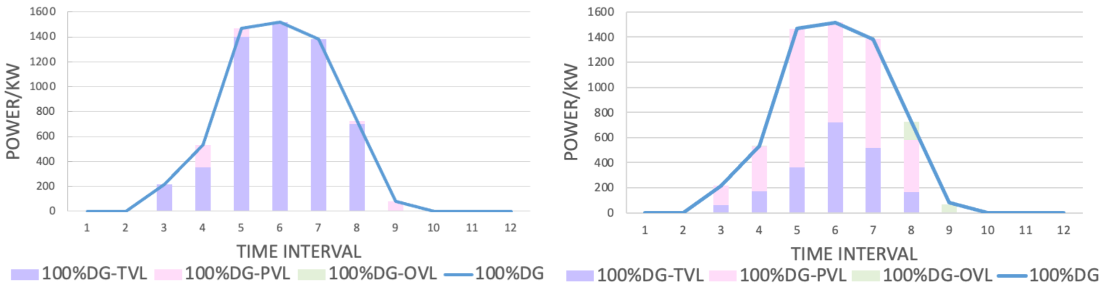



(e) (f)

Figure 6- 15 Integrated market clearing results between FLs and (a).50%-reliability DGs (c).80%-reliability DGs (e).100%-reliability DGs and segmented market clearing results between FLs and (b).50%-reliability DGs (d).80%-reliability DGs (f).100%-reliability DGs under TSO-DSO medium-level coupling

This scenario represents the time when the supply of DGs approximately equal to the demand flexible loads, that the backup of utility grid is not required.

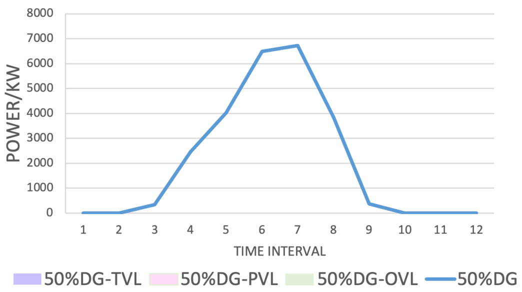
In the integrated market, the FLs traded with 50%-reliability-level DGs are 104.6 kWh for TSLs, 3172.2 kWh for PSLs, and 8873.2 kWh for OSLs, taking proportions of 0.86%, 26.11%, and 73.03%. The FLs traded with 80%-reliability-level DGs are 1359.6 kWh, 8144.6 kWh, and 2526.4 kWh, taking proportions of 11.3%, 67.7%, and 21%. The FLs traded with 100%-reliability-level DGs are 11135.8 kWh for TSLs, 708.2 kWh for PSLs, and 0 kWh for OSLs, taking proportions of 94.02%, 5.98%, and 0%. Taking the market as a whole, the transaction amount of TSLs, PSLs, and OSLs are under the proportions of 34.98%, 33.38%, and 31.64% respectively.

All three kinds of FLs have opportunities to be matched when the amount of supply from DGs is similar to the demand from FLs. The mutual-choice process is represented in the integrated market vividly. DGs with lower reliability levels, that is lower prices traded with FLs, are acquired by the higher flexibility level loads occupying a dominant position in the transactions. While DGs with higher reliability levels are matched with low-flexibility-level loads because of their high costs and prices.

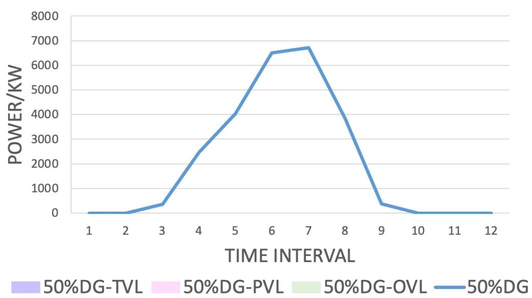
In the segmented market, the 3639.8 kWh 50%-reliability-level DGs are traded with TSLs, with a proportion of 29.96%. The 1448.6 kWh of 50%-reliability-level DGs are traded with PSLs, and the 6699.2 kWh are traded with OSLs, in a proportion of 11.92% and 55.14% respectively. For 80%-reliability-level DGs, the 3872.4 kWh are under the transactions with TSLs. And the trading amount between PSLs and OSLs are 3560.2 kWh and 4469.6 kWh respectively. The percentages between 80%-reliability-level DGs and FLs are 32.19%, 29.59%, and 37.15%. For 100%-reliability-level DGs, the 4004.4 kWh of 11816.2 kWh are under the transactions with TSLs. And the trading amount between PSLs and OSLs are 7392.4 kWh and 419.4 kWh respectively. The percentages between 100%-reliability-level DGs and FLs are 33.81%, 62.41%, and 3.54%. Looking at the overall, 31.97% of entire DGs are traded with TSLs, 34.42% are traded with PSLs, and 32.17% are traded with OSLs.

The types of loads traded with 50%-reliability-level DGs, 80%-reliability-level DGs and 100%-reliability-level DGs in the segmented market are more than that in the integrated market respectively. The mix of flexible loads is more balanced in the segmented one, indicating a more equal opportunity for flexible loads transacted with DGs in different reliability levels.

***TSO-DSO Low-level Coupling***




(a)

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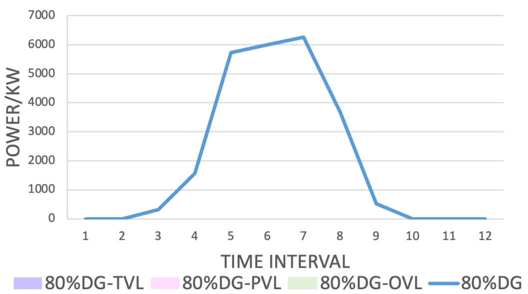


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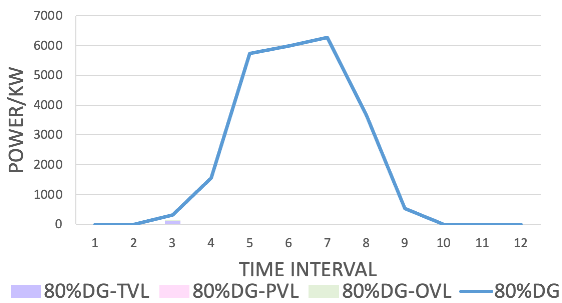


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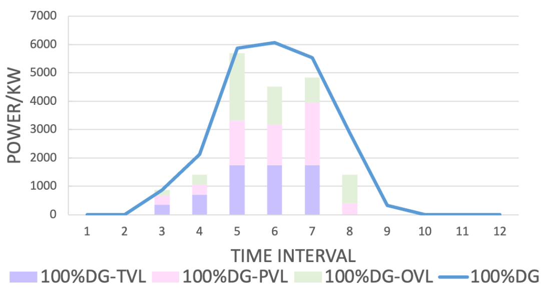


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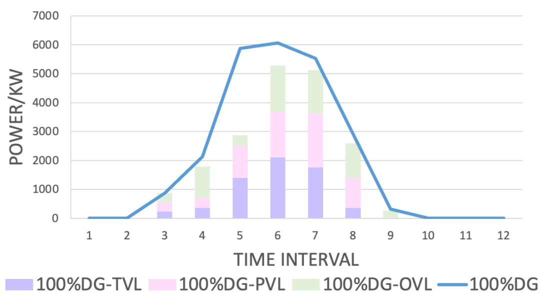


(f)

Figure 6- 16 Integrated market clearing results between FLs and (a).50%-reliability DGs (c).80%-reliability DGs (e).100%-reliability DGs and segmented market clearing results between FLs and (b).50%-reliability DGs (d).80%-reliability DGs (f).100%-reliability DGs under TSO-DSO low-level coupling

Scenario 3 stimulate a situation when DGs in the market are more than the demand of flexible loads, which is also the resource condition in the future electricity system.

DGs cannot be entirely consumed by the flexible loads on the distribution-level market in this scenario.

The 50%-reliability-level DGs and 80%-reliability-level DGs would not trade with FLs in the integrated market of this scenario, while the transacted 100%-reliability-level DGs are 12600 kWh for TSLs,12600 kWh for PSLs, and 12342 kWh for OSLs, with a percentage of 26.6%, 26.6%, 26.1% respectively. The 50%-reliability-level DGs do not participate in the transactions in the segmented market. There are 256.9 kWh 80%-reliability-level DGs and 18771.5 kWh 100%-reliability-level DGs traded with FLs, under the proportion of 0.53% and 79.24% respectively. Setting off the transaction comparison of three types of FLs. The traded percentages of TSLs, PSLs, and OSLs are 26.60%, 26.60%, and 26.60% in the integrated market. And in the segmented market, those percentages are 8.74%, 8.74%, and 8.74%.

FLs are majorly traded with high-reliability-level DGs when there are sufficient DGs in the market. This would maximize the value of the distribution-level market, while conforming to the requirement of system security and reliability.

#### 6.6.2.3 Market value comparison

The difference between the amount gained by DGs with and without the distribution-level market is used in this paper to measure the market value. A larger absolute value is welcomed. The clearing amounts and prices between DGs and FLs are different in the integrated and the segmented market under three proposed scenarios (DG>FL, DG=FL and DG<FL), with a corresponding change of distribution-level market value.

Table 6- 10 Market value comparison under three scenarios

| | *TSO-DSO Deep Coupling* | *TSO-DSO Medium Coupling* | *TSO-DSO Low Coupling* |
|---|---|---|---|
| *Integrated Market* | 132960 | 383068 | 478981 |
| *Segmented Market* | 127974 | 413623 | 534173 |

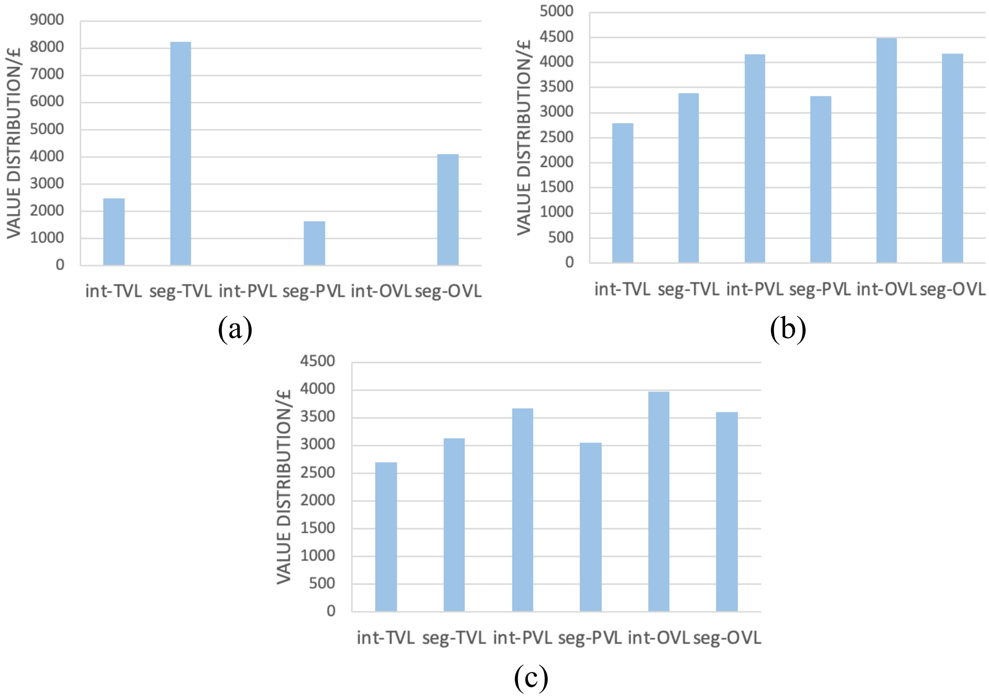


Figure 6- 17 Comparison of FLs' market value contribution under integrated market and segmented market

(a) TSO-DSO high-level coupling (b) TSO-DSO medium-level coupling (c) TSO-DSO low-level coupling

With the penetration of DERs and the increasing amount of DGs in the electricity system, the value of the proposed distribution-level market is increasing. Under the scenario of DG>FL without the backup from the utility grid, which is also the future trend of the flexibility market, the value of segmented market is larger than that of the integrated market under the proposed dynamic pricing strategy. The necessity of market splitting and market segmentation in the future automatic trading flexibility market is confirmed.

### 6.6.3 Market assessment under chapter 4 criteria

The P2P local flexibility market model applying dynamic pricing strategy is discussed from the perspectives of not only the market clearing results, but also the market assessment criteria. The non-technical assessment criteria proposed in the former research is adopted in analysis of P2P market. The case study in the research locates emphasis on whether to launch segmentation towards local P2P market, so the comparisons between integrated market and segmented market are proceeded under diverse energy scenarios. The market assessment is also launched to compare the integrated and the segmented markets.

The detailed non-technical assessment criteria are summarized in table 6-11, which carries out market evaluation from the perspectives of economic efficiency and social feasibility.

Table 6- 11 Market assessment criteria

| Benchmark Category | Criteria | Indicator |
|---|---|---|
| Economy Efficiency | Cost Reflectivity | Liquidity (HHI & Bid-offer spread) |
| | | Market signal |
| | | Risk |
| | Stability | Price standard deviation |
| | Market Manipulation | HHI |
| Society | Transparency | Price publicity level |
| | | Counterparty publicity level |
| | Simplicity | Ancillary mechanism number |
| | Feasibility | Technology friendly level |
| | | Customer negotiation position |

### 6.6.3.1 Economy efficiency

***Market Liquidity***

The HHI index is adopted as the indicator to appraise market liquidity. A smaller HHI is expected that smaller HHI means larger market liquidity. The calculation formula of HHI index is:

$$H = \sum_{i=1}^{N} s_i^2 \tag{6-48}$$

where $s_i$ is the market share of enterprise $i$, and $N$ is the total enterprise numbers.

The ownership relation of the cleared units in the market is required in the calculation of HHI that the units belonging to the same enterprise are settled together. The construction of local flexibility market is based on the tendency of DERs' penetration, indicating more and more flexible loads like demand-side responses and EVs would enter the market. Considering of the individuality of those energy resources, each flexibility in the market could be considered as one enterprise. The error of this arrangement is acceptable.

The figure of HHI indexes of the proposed integrated and segmented market is shown in table 6-12. The analysis of market is proceeded from two aspects, including overall HHI and the DG-related HHI. All the traded flexible loads in the flexibility market are calculated together to reach the overall HHI, no matter DGs in what reliability level they are traded with. The overall HHI could reflect the liquidity when considering the local market as a whole. For DG-related HHI, the HHI of one local market is calculated according to the diverse reliability-level DGs. DGs in this research are categorized to low, medium, and high reliability level ones, that the DG-related HHIs include HHI in 50%-reliability-level DG transaction, HHI in 80%-reliability-level DG transaction, and HHI in 100%-reliability-level DG transaction. The HHI between cleared flexibilities and the specific reliability-level DG is calculated separately. The ideal HHI result, no matter in the integrated market or the segmented market, is that the DG-related HHIs in one market are almost equivalent. The similar DG-related HHIs in one market indicates the better fairness of the market and the stronger participating willingness for flexibilities because of the equal clearing opportunities.

Table 6- 12 HHI value of integrated market segmented market under diverse energy scenarios

| | | TSO-DSO High Coupling | | TSO-DSO Medium Coupling | | TSO-DSO Low Coupling | |
|---|---|---|---|---|---|---|---|
| | | **Integrated** | **Segmented** | **Integrated** | **Segmented** | **Integrated** | **Segmented** |
| **Overall HHI** | | 2382 | 2304 | 609 | 601 | 617 | 617 |
| **DG related-HHI** | **50% Reliability DG** | 2064 | 2155 | 1504 | 1239 | NA | NA |
| | **80% Reliability DG** | 3667 | 2562 | 1450 | 1292 | 10000 | 7891 |
| | **100% Reliability DG** | 7096 | 4128 | 1753 | 1794 | 613 | 613 |
| | **Total** | 12827 | 8845 | 4707 | 4325 | 10613 | 8504 |

The figures in the table indicate that the overall HHI values belonging to segmented markets are smaller than those of the integrated market in each energy scenario. The segmented market performs better in liquidity than the integrated market when analyzing the market as a whole. However, there are only small differences between the HHI indexes of the segmented market and the integrated market, making the liquidity of the two types of market could be considered as equal. Apart from the overall angle which settles the cleared capacity between FLs and DGs in any reliability levels as an integration, the matching amount between FLs and diverse reliability-level DGs could be discussed separately to explore the clearing balancing among different energy products. The DG-related HHI index is calculated in the case.

When DSO and TSO are under high-level coupling, the 80%-reliability-DG-related HHI and the 100%-reliability DG-HHI of segmented market are smaller than those of the integrated market. The remaining 50%-reliability-DG HHI are approximate. Those kind of DG-related HHI indicates reflects more balanced clearing in the segmented market that participants in any reliability and flexibility levels would possess similar clearing opportunities, which could mobilize the enthusiasm of participants. The comparison between the DG-related HHIs of integrated markets and segmented markets when DSO and TSO are under medium-level and low-level coupling states the same superiority of segmented markets.

***Market Signal***

A sufficient market signal is the price contains adequate information to better reflect the market situation. The dynamic pricing strategy is proposed in this model, where the price settlement of flexible loads relates to not only their costs, but also the reliability levels of suppliers, and the flexibility levels of other market participants. More features of demand and suppliers could be reflected under the dynamic pricing strategy, thus leading to better market signals.

The prices of integrated market and segmented market under different energy scenarios are illustrated in table 6-13.

Table 6- 13 Prices of integrated market and segmented market between different types of flexible loads and DGs under different reliability levels

| (Pence/kWh) | | 50% Reliability DG | | 80% Reliability DG | | 100% Reliability DG | |
|---|---|---|---|---|---|---|---|
| | | Integrated | Segmented | Integrated | Segmented | Integrated | Segmented |
| Time-variable Load | Range | 12.8-15.0 | 7.5-15.0 | 20.4-24.0 | 12.0-24.0 | 25.5-30.0 | 15.0-30.0 |
| | Average | 14.1 | 12.1 | 22.6 | 19.3 | 28.3 | 24.2 |
| Power-variable Load | Range | 8.7-11.6 | 9.6-15.0 | 13.8-18.6 | 15.3-24.0 | 17.3-23.3 | 19.2-30.0 |
| | Average | 10.2 | 12.4 | 16.3 | 19.9 | 20.4 | 24.9 |
| Overall-variable Load | Range | 7.5-10.1 | 7.5-12.2 | 12.0-16.2 | 12.0-19.5 | 15.0-20.0 | 15.0-24.4 |
| | Average | 9.1 | 10.4 | 14.6 | 16.7 | 18.2 | 20.8 |

The flexibilities possessing the same parameters are under different prices in the integrated market and the segmented market, because of the different flexibility level settlements for specific flexibility facing diverse market participants. Those price differences between integrated and segmented market illustrate the sufficient signal provided by the dynamic pricing strategy. In conclusion, the integrated markets and the segmented markets possesses equal performances in offering market signal, and the proposed pricing strategy is superior in providing market signals.

***Risk***

The common risks introduced in the former research include the premium risk, the balancing risk, the counter-party risk, and the capital risk. The situations including differences between contracted prices and spot prices, the requirement of balancing market, the possibility that the counterparty does not pay by convention, and the required cash deposit to pretend the promise break from counter-parties are associated respectively with the risks. The premium risk occurs frequently in the forward contracts, but not the P2P automatic trading discussed in this research. The counterparty risk and the capital risk relate to the market operation rules, not within the scope of market model exploration. Thus, the integrated market and the segmented market have similar possibilities to face those risks.

***Stability***

The market stability is explored via the price fluctuation of market. Two measures could be used in assessing market stability, including collecting historical price statistics and making prediction of the future market prices. Since there is no P2P flexibility market dealing with demand-supply balance in the system, no historical prices could be achieved. The prices settled by dynamic pricing strategy are relative to the characteristics of energy resources themselves. Although the energy prediction provides projected energy demand in a specific year in the future, more detailed information of the individual energy resources could be acquired. The prices of proposed market model in a period are thus difficult to settle. The stability of no matter the integrated market nor the segmented market is hard to state according to the existing models and statistic.

***Market Manipulation***

Being the same with the market liquidity indicator, the market manipulation is also evaluated by the HHI indexes. The HHI figures are provided in table 6-13 in the case analysis of this research. The HHI indexes of segmented market are smaller than those of integrated market under the same energy scenario, indicating less market manipulation. However, there are slight differences between HHIs of integrated market and segmented market under one scenario. The HHIs are under the same order of magnitude. Then the integrated market and the segmented market could be considered impartial performances in the market manipulation.

**6.6.3.2 Society feasibility**

***Transparency***

A transparent market requires the publicity of market prices and participant basic information, the disclosure of which is decided by market operation rules. However, the model proposed in this research emphases on the market clearing and matching, without the detailed rules in operating market. The transparency of the integrated market and the segmented market discussed thus cannot be evaluated under the current proposed model. The measures to increase market transparency, however, could be adopted. The information disclosure channel such as publicity platform could be considered to guarantee the market transparency.

***Simplicity***

Extra mechanism may be required against the market risks. A market with higher simplicity needs less auxiliary mechanism. The common mechanisms including contract for differences against premium risk, the balancing market against balancing risk, the data publishing platform against low-transparency, and the regulation and investigation against market manipulation. Both the integrated market and the segmented market discussed in this model would face the balancing risk and the low transparency risk, with no need to think about the premium risk. The market manipulation, as discussed in the former section, could be considered as the same between integrated market and segmented market. Generally speaking, the simplicity of integrated market is under an equal level to that of the segmented market.

Table 6- 14 Market simplicity comparison between integrated market and segmented market

| Extra Auxiliary Mechanism | Required by Integrated Market | Required by Segmented Market |
|---|---|---|
| Contract For Differences | × | × |
| Balancing Market | √ | √ |
| Data Publishing Platform | √ | √ |
| Regulation & Investigation | √ | √ |

***Feasibility***

The feasibility of one market focuses on the market practicability in the future energy situations. From the technology friendly perspective, the P2P trading mechanism proposed in this model takes references from the real-world P2P business models, including Uber and Airbnb. So, the implementation of the P2P trading model could be guaranteed from the technology perspective. The market model in this research is proposed to complete the future energy resource consumption, so the model must be applicable in the future energy scenarios.

### 6.6.3.3 Market assessment conclusion

In conclusion, the integrated market and segmented market are compared under non-technical assessment criteria with the simulation of real-world application. The results indicate that the segmented market possesses slight advantages in market liquidity and market manipulation. The two market performs approximately in perspectives of market signal, risk, transparency, simplicity, and feasibility. The dynamic pricing strategy proposed in the chapter provides more sufficient market signals compared to the traditional market design. The market transparency, no matter the segmented market or the integrated market, requires the construction of disclosure process. The assessment indicator of stability is indetermined due to the lack of periodic historical market statistics.

## 6.7 Conclusion

A P2P market serving the transaction of the flexibility resources is proposed in this chapter, aiming at the increasing infiltration of the distributed energy resources. The characteristics including small-scale and independence of the flexible resources are considered in the flexibility market construction, combining the pricing strategy and the matching strategy of existing successful mature business models. A dynamic pricing strategy is proposed, where prices are fluctuated according to the features and portfolio of market participants. The discussion surrounding whether to proceed segmentation is explored in the research, with the market evaluation applying criteria published in chapter 4.

The results of the case study indicate:

- The extreme prices are remitted by introducing market segmentation in the proposed P2P flexibility market, that the flexible loads are matched more impartial without the constant low or constant high flexibility levels.
- The market segmentation is worthy to proceed when considering energy products as pure commodity. The segmented market processes better performances in market value.
- The segmented market possesses slight advantage in market liquidity and market manipulation compared to the integrated market in the real-world application simulation. In general, the two markets are under very little differences estimated with the real-world application market assessment criteria.

This chapter contributes in three perspectives:

1) The proposed P2P flexibility market helps the distribution system accommodating the infiltration of the future distributed energy resources. The automatic trading could be implemented in the proposed market, mobilizing the initiative of market participation and complying the individual participants' requirement for convenient market
2) The dynamic pricing strategy published in this chapter facilitates the fair opportunity to the clearing of diverse flexibility resources, promoting the equity of market.

3) Belonging to the exploration towards commercial nature, the market segmentation discussion focuses on not only the traditional technology but also the economy and business laws of the energy market.

# Chapter 7

# Roles and Functions of Distribution System Operators in Local Electricity Market Development

The chapter proposes to support the transition from the Distribution Network Operators to the Distribution System Operators. The roles and functions of DSOs are discussed when considering the evolution as dynamic. The distribution-level electricity market transition pathway is published, with DSOs under different market engagement levels. The coordination and cooperation between DSO and other regulation institutes are also analyzed.

# Statement of Authorships

| **This declaration concerns the article entitled:** | | | |
|---|---|---|---|
| Roles and Functions of Distributed System Operators in Local Electricity Market Development | | | |
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| Publication details (reference) | L. Shan, W. Kong, C. Gu and F. Li, " Roles and Functions of Distributed System Operators in Local Electricity Market Development", Journal of Global Energy Interconnection, 2020, 3(1): 70-18 (in Chinese) | | |
| Candidate's contribution to the paper | The candidate proposed the idea of the paper, she designed the methodology, and predominantly executed the coding to derive the experimental results. Other authors helped the candidate with the design of case studies, the format of the paper, and the improvement of academic writing. The percentage of the candidate did compared with the whole work is indicated as follows:<br>Formulation of ideas: 90%<br>Design of methodology: 100%<br>Presentation of data in journal format: 90% | | |
| Statement from candidate | This paper reports on original research I conducted during the period of my Higher Degree by Research candidature.<br>https://www.gei-journal.com/cn/upload/files/2020/2/20200108.pdf | | |
| Signed | Lanqing Shan | Date | 21/12/2021 |

# Chapter overview

The decarbonization process around the world has facilitated by the penetrating low-carbon technologies and distributed energy resources. The value of DERs is mobilized by smart and flexible energy system, reducing the costly network investment. The local consumption of renewable energies could also be facilitated, with the reduction of system uncertainty brought by intermittent energy resources. The appropriate distribution-level market needed under the circumstance. The chapters before discussed distributed energy market-related topics from market structure in Chapter 3, assessment criteria in Chapter 4, to market designs under diverse penetration level of energy resources in Chapter 5 and Chapter 6. The macroscopic research perspectives and the market internal elements including operating and trading rules are comprehensively analyzed, with the need to explore market external aspects which is the stakeholder-related issues.

The research towards roles and functions of DSO goes through three perspectives: 1) Realizing the issues brought by the expanding DERs and presenting feasible processing methods. 2) Proposing the concept of DSO required in managing future distribution system and exacted three aspects being charged by DSO. 3) Categorizing 8 future functions and detailed behaviors of DSO. Limitations are still existed in the current study however, including the superficial cognition of the collaboration and coordination between the DSO and other institutes, the underrepresenting of the effects of distribution system with the gradual access of DERs, and the inability to consider the DSO development as a dynamic progress.

To fill the gap, management functions of DSO required in the distribution-level market dynamic development is discussed in this chapter.

The key contributions of this chapter are:

1) Proposing distribution-level market transition pathway which represents three market structures corresponding to the three typical stages under the expanding penetration of DERs.

2) Summarizing four roles of DSO based on the current research of DSO's functions and indicating diverse detailed functions and behaviors assumed by DSO under different engagement levels, reflecting the dynamic development process.

3） Analyzing the responsibility distinction and cooperation execution within DSO and other institutes in each stage in the autonomous development process of the distribution-level market.

## 7.1 Abstract

The increasing application of distributed energy resources (DERs) alongside digitalization and decentralization drives the development of electricity distribution system. Decentralization is essentially developing responsibilities from transmission to distribution systems on account of the optimal use of DERs. However, the current distribution system cannot integrate DERs without major network modifications or investment, posing a major threat to their growth at a local level. Introducing energy markets and network services at the distribution level will not only support cost-effective integration of DERs, but will also critically deliver value to DERs to accelerate their growth. These emerging markets require a more active management of distribution systems, which leads to the necessity of exploring the roles and functions of the distribution system operator (DSO). During this process, the current approach focuses on comprehensive DSO functions and activities in a future situation in which there is high penetration of DERs. Therefore, it fails to consider the development of DSOs a dynamic progress and to provide sufficient attention on the coordination of DSOs with other system-oriented activities. In this article, we propose the future structures of markets in the distribution system by synchronizing the transition of distribution system evolution; categorizes four roles of the DSO based on functions and illustrates variations in its activities; analyses the evolution of the responsibilities to be taken by DSOs under diverse future market structures, and their coordination with other system-oriented activities. Taking the UK distribution with other system-oriented activities. Taking the UK distribution market as a reference, the exploration of market operations and regulations covered in this paper provide relevant experiences for other countries.

## 7.2 Introduction

The involvement of distributed energy resources (DERs) in the electricity system is increasing with the promotion of low-carbon energy process all over the world. A smart and flexible energy system is benefit for exploring DERs value through boosting the operation efficiency in the distribution system, the expensive network investment could thus be reduced or deferred. The uncertainty and complexity brought by DERs could also be declined through the process, being profiting from the local consumption of renewable resources.

The growing DERs would affect the distribution electricity system to some extent. The ***Distribution System in a High Distributed Energy Resources Future*** report published by Berkeley National Laboratory proposes a three-stage distribution system evolution under the penetration of DERs [3]:

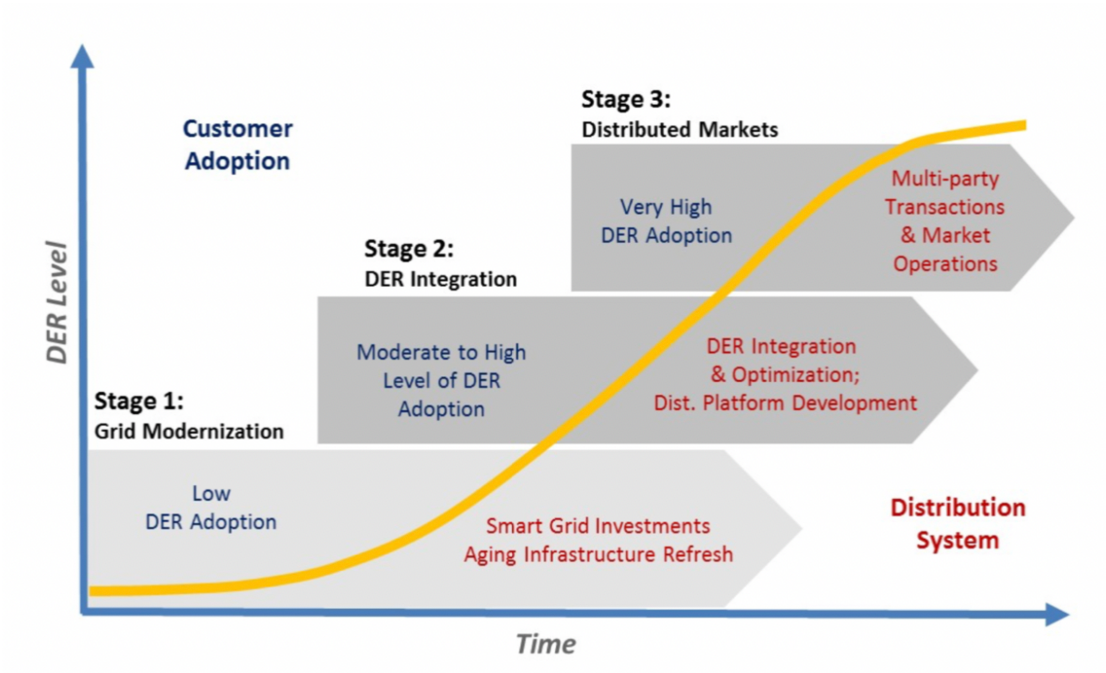


Figure 7- 1 Distribution system evolution

Stage 1 – Grid Modernization: This is the initial stage of DERs participating electricity distribution system that the consumers possess low acceptance of the resources. The existing distribution system could utilize the newly increased DERs without big changes towards the system infrastructures or operation.

Stage 2 – DER Integration: The volume of DERs in the system is continue growing and achieving threshold in this stage. The system functional maturation is required to guarantee the operation reliability with the considerable quantity of DERs. DERs at this stage could bring benefits to the system.

Stage 3 – Distributed Markets: The value of DERs could be leveraged more in this stage to elevate the efficiency of distribution system. The reliability operation could be supported by the procurement of flexible DERs, thus complete the replacement to the traditional network investment.

The penetration of DERs in the system would also advance the evolution of distribution system. The transactions in the distribution-level market are increasing because of the dispatching and management right devolution from the transmission system, mobilizing the autonomy of distribution system. Market trails for DERs are launched globally to offer alternative solutions to the traditional power supply. The proposed measures are confined to settle network issues by DERs' stimulation. Nevertheless, the network capacity market is incapable to consume more DERs without the large-scale network reinforcement or investment. This causes barriers to the development and value realization of the DERs. The distribution-level market is thus represented, benchmarking the national wholesale electricity market, to increase the utilization rate of DERs and realize their additional value. Meanwhile, the local ancillary services market is mobilized by the local network capacity market to achieve developments towards functions. The adequate accommodation of low-cost DERs is guaranteed.

There are three typical stages in the transition pathway of market on the distribution system, corresponding to the three-stage distribution system evolution. The proportion of local energy consumption is different in the diverse stages of the evolution, which is rising with the autonomy degree increasing. The roles and functions of the system operator are expected to be explored to satisfy market requirements with the emerging distribution-level market.

The traditional distribution network operator (DNO) owns network facilities like cables and towers, confining to the distribution network investment, maintenance, and operation. The most distinguishing feature of DNO is the single direction, that power is delivered from transmission level to distribution level. Distribution System Operator (DSO) is developed from DNO, overseeing the distribution system with gradually increased DERs. DSO undertakes multi-direction communication at the distribution level, matching multi-point power generations with the consumers.

The first step of the research was aware of the potential issues of future electricity system with the expanding DERs and proposed feasible treatments. The problems that would be faced by the future system could be summarized as: bidirectional current control, local energy integration and balance, DERs control, boundary changes of transmission and distribution systems, and characteristic changes of electricity resources and consumers [243-256]. Meanwhile with putting forward solutions to those specific questions, the needs of reform are faced by system operators urgently [243-246, 249, 250, 252, 257-267].

The second step of research presented the concept of DSO, who was proposed to satisfy the operation and management of future distribution system. The responsibilities of DSO were categorized into three parts (planning, operation, and market), and the detailed management activities should be proceeded under each responsibility were analyzed respectively. Considering of the potential coordination and collaboration demands between future transmission system and distribution system, three models were proposed as Transmission Responsibility, Transmission and Distribution Cooperative Responsibility, and Distribution Liberalised-management Responsibility. Under the model of Transmission Responsibility, the transmission system operator is taking responsibility to the operation and economic dispatch of global electricity system. DERs under the model would participate the national wholesale electricity market in individual units. DSO only takes the minimum responsibility under this model, which is guarantee the reliability of the distribution system rather than taking responsibility to the transmission-level markets. Under the model of Transmission and Distribution Cooperative Responsibility, the transmission system operator is only in charge of the DERs dispatch, without analyzing the physical distribution and circuits on the distribution-level. DSO under this model is responsible for the internal interconnection in the distribution system, and the coordination between national wholesale market and distribution-level markets. The DERs physical coordination and instruction response to transmission-level dispatch are also in charged by DSO. The transmission system operator only launches remote dispatch to DERs. There are minimum engagement restrictions towards DERs under the Distribution Liberalised-management Responsibility model. DERs are required to integrate to a specific scale before participating national wholesale electricity market. The transmission system operator under the model acquired the integrated DERs' information on the transmission level. DSO is taking responsibility to the coordination and integration among DERs units [226, 247, 268, 269].

The third step of research were mainly completed by the Open Network Project from Energy Network Association (ENA). Eight functions of future DSO were highly refined in the project, including system coordination, network operation, investment planning, service and market facilitation. The detailed management activities corresponding to each function were cleared [183-187, 192, 270, 271].

The research towards DSO is still going on, and there is imperfection in the outcomes of the three-step research. The first step looked at the potential technical problems and challenges brought by the large-scale DERs in the electricity system, while failed to propose the novel management requirements from the perspective of system operators. That the management-related issues are not comprehensively considered. The second step of the research conclude the responsibilities of DSO, but without further exploration to the DSO detailed functions. This step possesses the advantage of presenting three distribution system management models. Although being subjected to the limited recognition to the future distribution-level market, the proposed three models only discussed DSO and their effects on a superficial layer. The dynamic feature of DSO engagement degree is initially revealed. The third step of research prospected sophisticated functions of future DSO, but the research based on the promise that transition from DNO to DSO would one-time complete, failing to consider the development of DSO as a dynamic process.

There are three contributions of this paper:

1) Proposing the three-stage transition pathway of market on the distribution system corresponding to the three-stage distribution system evolution with the penetration of DERs
2) Presenting four roles of DSO based on the DSO functions published by the Open Network Project, and illustrating the detailed management activities under three market structures
3) Analyzing the dynamic responsibilities taken by DSO in the developing distribution market autonomy process, with the responsibility division and collaboration between DSO and other management entities

The background of the research towards distribution-level electricity markets and their operational management is the liberalized market in the electricity system, aiming at avoiding the expensive large-scale distribution network investment brought by the DER connection to the system. DERs are the first choices of medium and small systems because of their characteristics including facing users directly and on-site supplying on demand， possessing the increasing importance in the energy development in China. Till 2020, the distributed energy installation has reached fifty million kW in Chinese cities above designated size, where distributed PV took a proportion of 22%. This preliminary of the industrialization of distributed energy resource equipment conforms to the target of ***China Electric 13$^{th}$ Five-year Plan*** and achieves the medium and long-term development planning of renewable energy resources. Paper [272-276] conduct market on the distribution system to adapt the gradually increasing DERs drawing lessons from the market experiences in the U.K., which is also a rational option under the current energy tendency for China. It is worthy to be noticed that the electricity market in the U.K. has developed into a mature competitive liberalized market after experiencing three electricity reforms, possessing the national-unified wholesale electricity market, and the electricity trading, balancing and settlement system. The market is led by six vertically integrated companies who dominates the generation, distribution, and power selling. The DERs solutions proposed in paper [277, 278] adapted similar default liberalized market environment. However, the liberalized management is in parallel with the traditional planned and instructive treatments in China nowadays, because the country is still in the progress of the second electricity reform. The market vitality has hugely unleashed with the electric power system reformation, that the incentives have acted on microgrids, storages and electric selling markets. The relative market supporting mechanism is waited to be improved with increasing needs towards legislation, regulation, information disclosure and credit-system construction. The future markets on the distribution system in the U.K. and their operation are discussed in paper [279, 280], providing DERs adoption advice to the liberalizing Chinese electricity market. The research towards operation entity and models in the liberalized U.K. market could offer experiences and references to the incomplete Chinese electricity market regulation system.

## 7.3 Market structures on the distribution system

The distribution system is experiencing three-stage evolution with the high speedy development of DERs.

The transition pathway of market on the distribution system is demonstrated in figure 7-2. With the devolution of transmission system and the decarbonization and digitalization of the system, the transmission system is transferring the responsibility of market operation to the distribution system. Each colored layer in the exhibit represents one type of the market in the electricity system. The charging market in charge of the network investment recovery is illustrated in the green layer. The ancillary services market protecting system short-term security is represented in the blue layer. And the pink layer and the yellow layer displays the energy market and the capacity market respectively, contributing in increasing energy cost efficiency and protecting long-tern system security.

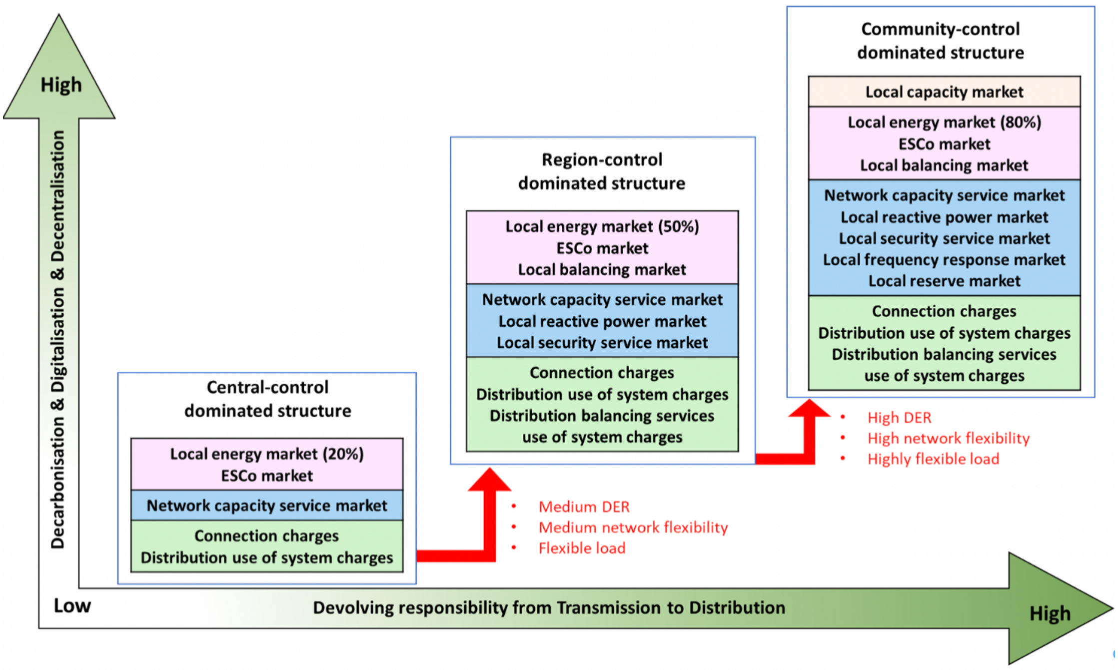


Figure 7- 2 Transition pathway of market on the distribution system

The three typical structures of markets on the distribution system correspond to the three stages of the distribution system evolution, with the expending scale of DERs and the potential development of energy technologies. The distribution-level market is under the central-control dominated structure at the first stage, where the electricity demand of the system is majorly satisfied by the transmission system, leaving limited local energy requirement waiting for the local DERs. To achieve the balancing, the local energy market is expected to launch the transaction. The local ancillary service market under this structure only provides the traditional network capacity services, with no need to proceed extra function expansion.

The distribution-level market is under the region-control dominated market structure under the second stage, where equal supply responsibilities are taken by the transmission system and the distribution system. The market autonomy degree is further increasing compared to the central-control structure in the first stage. The growing DERs contribute more on the distribution system balancing because of the more active market, thus sharing the responsibility for balancing markets between transmission and distribution levels. The reliability services and security services could be provided by the ancillary service market with sufficient DERs.

The distribution-level in third stage of the distribution system evolution is under the community-control dominated structure. The majority of the power demand is satisfied by the local supply in this stage, with the independent market in the distribution system benchmarking the transmission-level national electricity market. Although the current technology cannot completely support this highly independent market structure, this community-control dominated market could be valuable to be applied with the breakthroughs in energy storage technologies and the wide and flexible application to the large-scale batteries. The construction of distribution market ensures individuals in the local market operating in a secure, reliable, and economy efficient way.

The electricity resource in China is under reverse distribution, that resources distribute concentratedly in the Western and Northern areas while demand locate in economic centers including Northern, Eastern and Southern China. Many economic problems, such as high cost of supply, transmission losses and expensive electric investment, are brought by the unbalanced distribution. The long-distance transmission is the current solution to settle this geography mismatching. Another method is proposed in paper [281] by applying DERs and conducting distribution-level market to settle the geographic unbalancing of energy resources in China. Since DERs are directly user-oriented and onsite supplying, introducing distribution-level market in the high-demand regions could reduce pressure of power supply, long-distance delivery, and transmission costs.

The three distribution markets proposed in this paper, rather than a necessary development process along the DERs increasing, is a bold prediction according to the energy policies all around the world. The three distribution-level market structures proposed in this paper would coexist in China following the power marketization evolution. The high demand low resource regions, like Northern, Eastern and Southern China, are tending to utilize more DERs so to launch region-control dominated or community-control dominated markets. The other regions possessing abundant energy resources would remain central-control dominated markets, where the power demand is satisfied by the transmission-level national wholesale market.

The electricity marketization in China aims at achieving self-regulation of prices utilizing the commodity property of electricity. All kinds of the electricity markets, no matter the constructing unified national electricity market in China or the distribution-level market proposed in this paper, are the platforms completing value realization. Those markets conform to the marketization process in Chinese policies.

## 7.4 Roles of future DSO

The eight DSO functions prospect in the Open Network Project base on the hypothesis that the transition from DNO to DSO would complete in one time. Considering of the procedural structure evolution of distribution system, the functions of DSO are developing by degrees. To facilitate a smooth transition meanwhile equipping productive DSO functions, the roles of DSO are categorized into four parts, including distribution system planning, distribution system operation, market operation and coordination. The distribution system planning role takes the responsibility of network investment planning, connection management and charging. The role of distribution system operation is in charge of system defense and maintenance. The market operation needs to complete market facilitation and market internal service improvement. The overall coordinator is responsible for system internal coordination. The four roles classified in this paper extend the function definition and responsibility scope based on the original eight functions of DSO.

Four roles of DSO and their interrelation are indicated in figure 7-3.

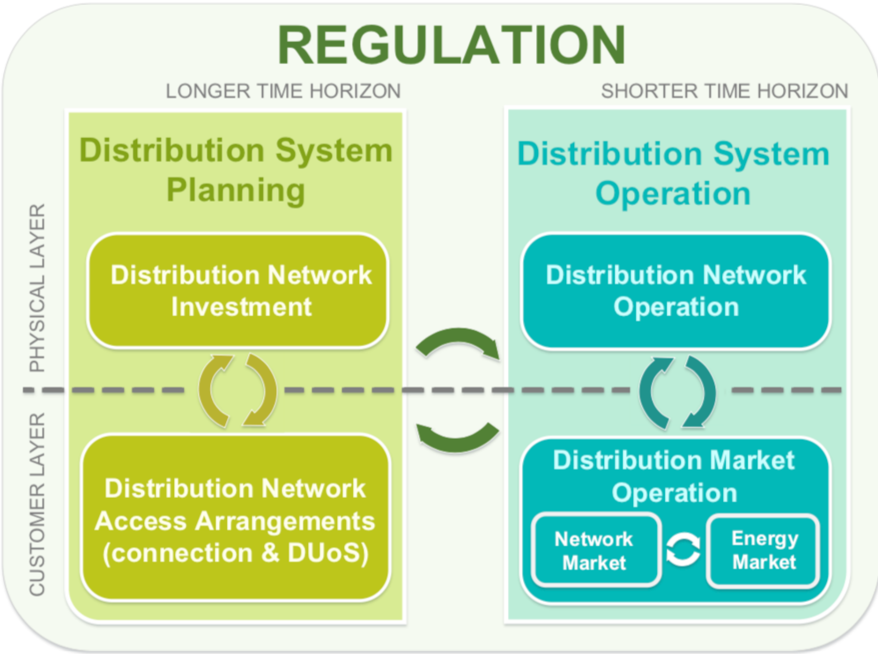


Figure 7- 3 Distribution system management structure

The two management directions for distribution system are the distribution system planning and the distribution system operation. Distribution system planning guarantees the long-term security of electricity system, focusing on the network investment and gird-connection management. Distribution system planning places emphasis on the short-term to real-time demand-supply balance, including the operation of network and the distribution-level market.

The distribution network investment and network planning related issues are the physical-layer network requirements, while management and market related ones locate on the user-layer. Due to the potential conflicts between the economically optimal strategy and the physical-feasible solutions, the interactions are required between the long-term decisions and the short-term decisions in the system to proceed the coordination within each layer of the system management. The arrows in figure 7-3 reflect the coordination within different parts. The coordination between system planning and operation is the highest level one, followed by the coordination between system planning and the physical and economic inner-system decisions. The most detailing one is the coordination within market components. The requirement of market coordination reflects the rising market autonomy.

The requirement of system coordination ability is increasing because of the growing complexity of distribution network. The concept of coordination is thus more extensive.

1) The coordination within distribution markets (for example, ancillary services market and energy market)
2) The coordination between the operation of distribution system and market
3) The coordination between distribution network investment and distribution network access management
4) The coordination between distribution system planning and distribution system operation

The engagement level of DSO is diverse under different market structures in the actual industrial structure evolution. DSO may undertake one or more roles according to the actual structure requirement. The extreme situations of DSO maximum engagement and the DSO minimum engagement are discussed in this paper, to further analyze the application of DSO under typical stages in the distribution-level market transition pathway. The maximum engagement of DSO under any market structure means DSO taking entire four roles, when DNO undertakes emerging roles and transfers to DSO. DSO is only in charge of the coordination as an individual entity for its minimum engagement, when other distribution system activities are under the control of DNO or other entities. The detailed roles and functions of DSO under three typical structures are explored in the following discussion.

# 7.5 The DSO engagement in the distribution electricity market under the maximum and minimum levels

## 7.5.1 DSO under the central-control dominated market structure

The majority of the electricity demand in the system is satisfied by transmission-level generators under the central-control dominated market structure, where the electricity system operator (ESO) is in charge of meeting the capacity requirement of the system. The national electricity market, locating at the transmission level, involves the majority activities of market including energy transactions, system balancing and ancillary services delivery. The distribution-level market here is responsible for promoting the connection and outputs of DERs in the system.

Suppliers procure power from both the markets of wholesale and the local DER under this central-control dominated structure, and sell them to consumers through the retail market. Individual customer themselves could also look for power providers directly in the local DER market. The local energy, which could be generated and traded within regions, occupies obvious low-price advantages that they reduce or even remove the connection cost of DERs. Being an important index for energy, the cost of connection affects many components in the electricity system supply chain including costs of distribution infrastructure upgrading, distribution system operating, transmission balancing and transmission operating. The vested interests of local low power prices make profit by purchasing cheap intermittent energy resources through flexible price settlement in local energy market, rather than by evading distribution charges and taxes and sacrificing the other users' interests. This localized energy absorption forms a virtuous cycle that further lowering the prices of intermittent energy resources in the local distribution market.

The vast of suppliers come from the transmission-level suppliers in the national market although local DERs are more advantageous in terms of costs, because of the limitation volume of flexibilities under central-control market structure. The distribution-level energy market in this scenario could only run as the affiliate market of national wholesale electricity market, the trading result of whom would impact the net demand of upper-level market and balancing strategies of ESO. For local ancillary service market, the restricted DERs could only offer basic network capacity services to ensure the sufficiency of distribution system. Although this is a solution with no need for additional network investment, the distribution network and planning are still the primary solution towards network congestions as local ancillary market could only bring little effects to the distribution network operation.

The exploration of DSO launches through discussing the extreme cases, which are the minimum and the maximum engagement. DSO under the minimum engagement situation only takes the responsibility of coordination. The coordinator here links the local ancillary service market and local energy market, as DSO under the scenario does not involve operation because of the limited DERs volume. Being a neutral market facilitator, DSO should gather the information of customers while providing privacy protection. The maximum two-way benefit would be gained through information delivery between ancillary service market and local energy market, that DSO would promote decision making within supply and requisitioning parties.

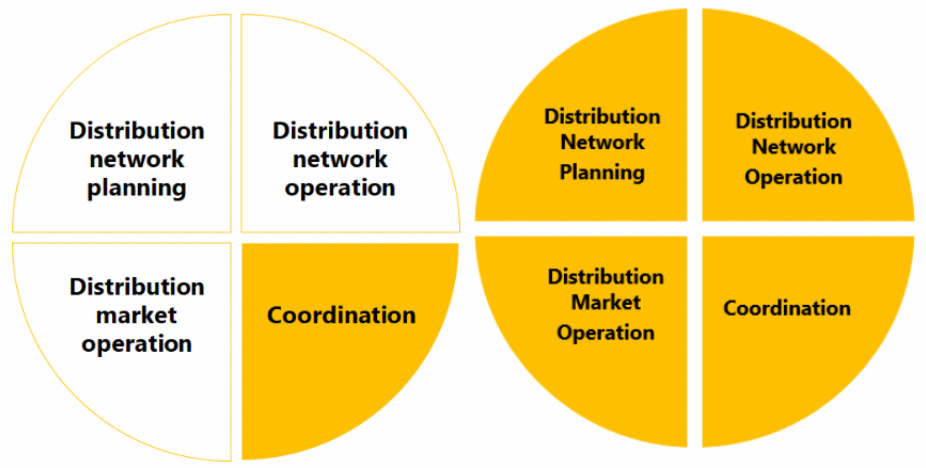


Figure 7- 4 DSO involvements under central-control dominated market structure

The DSO maximum engagement undertakes entire roles of the current DNO, including distribution system planning, distribution system operation, and emerging market operation. Furthermore, the responsibility of DSO also involves the coordination between local energy market and ancillary service market. The conflicts between entire system operation and local markets rarely exist here because of the small-scale DERs, thus the coordination position DSO is standing focus on the internal distribution system. The coordination within energy market and ancillary service market locally would facilitate the sufficiency of DERs.

### 7.5.2 DSO under the region-control dominated market structure

The distribution system under this structure is in a semi-autonomous situation. The national ESO is still responsible for satisfying total system capacity, while demand belonging to regional power is satisfied equally by both the local DERs and the transmission-level generations. More diverse market activities would be involved in this distribution system aligning with the increasing DERs. The relationship between the utility grid and its connected micro-grids could be drawn an analogy with that between the transmission system and the distribution system. More transactions rather than only the energy market are transferred to the distribution level, ancillary services market is a typical example.

A dynamic market operation is required due to the more comprehensive products and more vibrant market activities. A sufficient distribution management should consider many perspectives, including the fluctuation of renewable energy outputs, requirements of ancillary services at both the transmission level and the distribution level, and the changing expectations from customers. A key settlement strategy is to conduct multiple distribution regions. The continuation of consumption and the economy of electricity supply could be guaranteed when DERs participating their belonging regional distribution market. The interaction between DSO and ESO in this structure aims at providing reserve services and prevents the regional interruption. The boundaries between distribution system and transmission system are much different compared with the current DNO architecture.

The minimum engagement of DSO under this structure is the coordinator. The coordination is required between the interaction of distribution system operation and market operation, as well as that between distribution system operation and distribution market operation. Being a neutral market facilitator and a coordinator, DSO helps with the transparency of the liberalized regional market by acquiring and transferring information within market participants. The exchanges of market strategies are also carried out within market operators, network operators and DSO, mobilizing dynamic responses and reducing market conflicts and network constraints brought by market activities.

The maximum engagement of DSO takes the entire four roles. Due to the characteristics equipped for local energy markets and ancillary services market of multi-layer, multi-type and multi-timescale, the complexity of market operation role increases significantly compared to the maximum engagement of DSO under central-control market structure. Rather than only playing as a coordinator, DSO here is responsible for the overall regional distribution system. DSO is expected to achieve the optimized dispatching of DERs across different market, with further operation coordination between distribution system and distribution market.

### 7.5.3 DSO under the community-control dominated market structure

Local DERs would meet the local power demand with a further penetration of DERs, when distribution system is operated independently. Transmission-level generators in this scenario only takes responsibilities to a small part of electricity market by offering limited capacity services and ancillary services to assure the electricity system reliability and security. The transmission-level generation here is applied to maintain the system frequency and settle the potential issues that might be brought by the fluctuate renewable energies. The individual distribution system is considered as independent one, that the communities are the places to complete the transaction and delivery of bulk energy. The distribution communities themselves are autonomous for power balancing, where the ancillary services and generation planning happen within the communities.

The local network capacity market would take the place of the traditional transmission-level -network capacity market under this community-control market structure, achieving the balance of power supply and demand. The increasing dynamic of local energy market offers system with high economic efficiency that the adequate DERs and fully-functional local ancillary service market guarantees the power supply reliability and security. The local ancillary service market here could be considered as a middle market, which connects local market participants to the national frequency response market. Most supply in the local energy market is provided by DERs under this structure, and the transmission-level market is applied to take after the intermittency of local renewable energies as the position. Local consumers are charged from local users, showing the highly independent market scenario.

The minimum engagement of DSO offers the facilitation and coordination for neutral market. The most prominent feature under this structure happens on the capacity market, which is totally transferring to the distribution level, with a larger market share of DERs, the increasing market dynamics and the expending of ancillary services market products. A fully functional distribution system is then conducted, guaranteeing the entire system's affordability, reliability, and security. Being a neutral market facilitator, DSO undertakes providing a liberalized commercial phenomenon and mobilizing the DERs. Being a market coordinator, DSO acquires all the market results and informs potential conflict information to market operators. The optimized market program is offered to achieve the whole-system benefit maximization under network constraints.

The maximum engagement of DSO includes entire four roles. The non-market network dispatch depends on the number and transaction amount of diverse services and ancillary service market respectively, being the most significant difference. The operation of market thus affects the types and scales of DSO distribution system operation. The different market could be considered as the replacement of network investment and reinforcement, cutting down the investment requirement towards network capacity. A large-scale coordination is expected under the maximum engagement of DSO, including the distribution system planning and operation coordination, market operation and distribution system operation coordination, and coordinating cross markets.

The roles that DSO is positioning in the future could be divided into two major categories: 1. Possessing the traditional roles and functions of ESO and DSO in the high-independent distribution level, taking responsibility of the system security, reliability, and sustainability. 2. Emerging functions to DSO the development of distribution system and distribution market. To guarantee the stable system operation, DSO in the future is required to undertake the network-related and technology-related functions including network access, network services and emergency reserves, as well as the economy-related functions of investment planning and network price charging. The completion of those functions is necessary for the stable operation of the distribution system, requiring an institute to take the responsibilities. The higher independent level the distribution system is under, the more information is settled at the distribution level, with more detailed messages describing the network and the market. The information and messages transferring between the transmission system and the distribution system would bring extra costs in information delivery and settlement, leading to low efficiency. From this perspective, it would be a rational option to make DSO taking the necessary functions in autonomous systems, aligning with both the cost and the efficiency.

The market operation and coordination (distribution system coordination and distribution market coordination) are the most typical emerging DSO functions, facing diverse costs including market management costs and information scheduling costs. The importance of DERs is increasing on the path of energy development in China, that their features of facing customers directly and offering supply according to the demand would mitigate even eliminate the unbalanced energy distribution. Then it is a have-to-discussed topic for the construction of distribution market. The potential benefits that the DER market would bring to the development of the whole system is unignorable although accompanying with costs. The roles and responsibilities taken by the DSO under divers market structures are detailly listed in table 7-1.

Table 7- 1 Responsibility for DSO activities under diverse market structures

| | | Key activities for distribution system operation | Central-control dominated structure | | Region-control dominated structure | | Community-control dominated structure | |
|---|---|---|---|---|---|---|---|---|
| | | | Minimum DSO involvement | Maximum DSO involvement | Minimum DSO involvement | Maximum DSO involvement | Minimum DSO involvement | Maximum DSO involvement |
| Network planning | | Forecast long-term demand and DERs | DNO | DSO | DNO | DSO | DNO | DSO |
| Network planning | | Assess network investment and reinforcement | DNO | DSO | DNO | DSO | DNO | DSO |
| Network planning | | Consider DERs contribution in capacity planning | N/A | N/A | N/A | N/A | DNO | DSO |
| Network operation | | Forecast short-term outputs of DERs | DNO | DSO | DNO | DSO | DNO | DSO |
| Network operation | | Identify network constraints | DNO | DSO | DNO | DSO | DNO | DSO |
| Network operation | | Formulate timely restoration plans | DNO | DSO | DNO | DSO | DNO | DSO |
| Market operation | Energy market | Manage energy transaction mechanism between regions or communities within the distribution system | N/A | N/A | Third party | DSO | Third party | DSO |
| Market operation | Energy market | Enable settlement and monitor contracted energy produce delivery | Third party | DSO | Third party | DSO | Third party | DSO |
| Market operation | Energy market | Operate local balancing market to ensure whole system balancing | N/A | N/A | Third party | DSO | Third party | DSO |
| Market operation | Energy market | Manage day-ahead energy trading at the distribution level | Third party | DSO | Third party | DSO | Third party | DSO |
| Market operation | Energy market | Manage intra-day energy trading at the distribution level | N/A | N/A | Third party | DSO | Third party | DSO |
| Market operation | Energy market | Manage real-time energy trading at the distribution level | N/A | N/A | N/A | N/A | Third party | DSO |
| Market operation | Ancillary service market | Manage services transaction mechanism | DNO | DSO | DNO | DSO | DNO | DSO |
| Market operation | Ancillary service market | Procure network capacity services | DNO | DSO | DNO | DSO | DNO | DSO |
| Market operation | Ancillary service market | Procure reactive power services | N/A | N/A | DNO | DSO | DNO | DSO |
| Market operation | Ancillary service market | Procure security services | N/A | N/A | DNO | DSO | DNO | DSO |
| Market operation | Ancillary service market | Procure frequency response services | N/A | N/A | N/A | N/A | DNO | DSO |
| Market operation | Ancillary service market | Procure reserve services | N/A | N/A | N/A | N/A | DNO | DSO |
| Market operation | Ancillary service market | Enables settlement and monitor contracted service product delivery | DNO | DSO | DNO | DSO | DNO | DSO |
| Coordination | | Neutrally facilitate DER participation in distribution level and national markets | DSO | DSO | DSO | DSO | DSO | DSO |
| Coordination | | Coordinate distribution level and national energy markets | DSO | DSO | DSO | DSO | DSO | DSO |
| Coordination | | Coordinate distribution level energy market and ancillary service market | N/A | N/A | DSO | DSO | DSO | DSO |
| Coordination | | Coordinate distribution network operation and market operation | N/A | N/A | DSO | DSO | DSO | DSO |
| Coordination | | Coordinate distribution network planning and integrated network & market operation | N/A | N/A | N/A | N/A | DSO | DSO |

## 7.6 The rational engagement of DSO under transition pathway of distribution electricity market

The introduction scale of DERs and the vitality of distribution market are the two key influencing factors in the distribution system operation management.

The scale of DERs is very limited under the central-control market structure, where there are only distribution-level energy market and network capacity market. The operation and coordination of these emerging markets could be achieved by expanding current functions of DNO. The system operator under the central-control structure plays the role of satisfying distribution system requirement, while being in charge of current function including distribution system planning and distribution system operation. DSO could only play the coordination role, when collaboration is required between DSO and DNO in the distribution system management. The DNO in this situation is responsible for distribution system planning, distribution operation and distribution ancillary services market operation.

The penetration of DERs is growing under the region-control dominated market structure, with more diverse and dynamic market activities. The intra-day market is increased in the day-ahead only market, following the coming of local balancing market. The local ancillary service market under the structure would provide comprehensive services more than the network capacity market, such as reactive power services and security services. The DSO coordination under this structure covers two perspectives: the local energy market and local ancillary service market coordination, and distribution network and distribution market operational coordination.

The introducing scale of DERs under the community-control dominated structure is pretty high. The distribution system performs highly independently to the transmission system, with the high-dynamic distribution-level market activities. Each distribution community is in the charge of the independent market operator, and more than one community could be managed by one market operator. The neutrality of DSO guarantees the competitiveness, fairness and transparency of the market, ensuring the operational efficiency of all community markets.

The scale and complexity of distribution activities are increasing with the growing of distribution-level market liberalization. There is still incertitude in whether the DSO should cooperate with DNO in the distribution system, or the activities of DSO should include original DNO activities. Further research is expected to be launched on the relationship between DSO engagement level and the perspectives including DERs scale, market perfection, and distribution system connection structure.

## 7.7 Conclusion

The electricity industrial evolution brought by the developing DERs would influence the structure of future electricity system, especially the distribution system. To accommodate and utilize the large-scale DERs without launching network reinforcement and network investment, significant changes are required in the methods taken by DNO planning and operation. The transition from DNO to DSO is expected.

Three electricity market structures corresponding the three typical stages in the distribution system evolution are published in this paper. The three steps may coexist in China because of its unbalanced and reverse resource distribution. Four roles of future DSO are represented in this research based on the current t eight functions of

DSO, including system planning, network planning, market operation and coordination. The maximize and minimize engagement of DSO under each market structure is explored in this paper from the perspective of distribution system dynamic management. The responsibility assignment and collaboration method between DSO and other management entities are researched in the electricity market evolution, especially the cooperation between DSO and DNO.

# Chapter 8

# Conclusion

This chapter summarises the thesis by outlining the major contributions and findings from the research.

Promoted by the decarbonization policies, both the demand side and the supply side of the energy system in the U.K. is facing a low-carbon transition. Cooperated with the development of energy technologies, the electricity system is stepping into the future of decentralization, decarbonization and digitalization. The fundamental changes of the energy system, that is introducing unpredictable and unstable renewable energy resources and distributed energy resources, bring the tendency to the end-users that they are transferring from the passive energy procurements to the positive energy market participants. The opportunities are thus brought to the energy markets and business models to construct sufficient flexibility markets. The lowest-cost solutions are acquired respecting technical restrictions and network limitations, mobilizing the value of flexibilities.

Flexibility market trails are operating in the real world to face the penetration of new-developed energy resources. However, boundedness still exists in the current market: 1) The current flexibility markets stably operated are constructed aiming at network-related issues. Few flexibility markets are built to settle the demand-supply balance of the system. 2) Barriers are existed to the market, including market scale limitations brought by computing difficulties, irrational clearing mechanism, and low enthusiasm of market participants. It's still necessary to launch research towards distribution-level energy markets.

Three aspects are required to be considered in establishing distributed energy market based on the existing energy and technology forms: 1) Breaking down technical barriers, including energy barriers, connection hardware barriers and computing algorithm barriers. 2) Formulating appropriate market design, aiming at conducting appropriate operation rules and pricing and transaction roles. 3) Discussing sufficient market management-related issues, including laws and regulations reflecting market demands and the functions of market stakeholders.

The complete market-related issues are discussed comprehensively in this research from the macro to the detail, constructing a more rational and effective distributed energy market under the future trend of energy. The structure could reflect the commercial components in the distribution system visually, building a foundation to understand, construct and operate future distributed energy market. The non-technical market assessment criteria are then proposed, being the estimation benchmark of the general energy market and energy business models. Followed are market designs aiming at diverse development phases of energy infiltration. The market design to maximize clearing quantity is firstly presented for the massive introduction of renewable energy resources. The P2P market design which could offer automatic transactions to the individual end-users is then published, complying with the small-scale and privately-owned characters of distributed energy resources. Finally, considering the function changes when the market transferring from the transmission level to the distribution level, the roles and functions of market stakeholders under distributed energy market is explored.

The conclusions and findings of the research are:

## Multi-layer Electricity Market Structure in the Distribution Sector

The current electricity market structure only emphasizes single market component such as energy market or ancillary service market. Some industrial structures are also summarized, although being named as market structures. The demand towards a mature market structure which could illustrate complete commercial elements in the supply chain is crucial, to build up cognization to the electricity market concept and scope, with the understanding towards future market development.

A multi-layered electricity market structure is published in this chapter, expressing entire business factors in the electricity system. The proposed electricity market structure contains operation and management aspects, completely describing the entire process from energy trading, network delivery to the participants' cost recovery.

Three contributions are provided in this chapter:

- The market structure describing the current distribution system is described, providing a macroscopic perspective of market research.
- The future distribution market structure is projected, providing market circumstances with the penetration of new-developed energy resources.
- A comparison between the current and future market structures has been made, providing deep insight from not only the structure itself but also the active entities in the market.

## None-technology Market Assessment Criteria

The unitive assessment criteria of the sufficient market are necessary in the exploration of energy market and energy business models. Focusing on building and developing trading models or simulating the performances of current trading models facing the introduction of new-developed energies, the lack of benchmark estimation is shown in the research. Only the emphasized trading arrangement is discussed in the current research, failing to make the horizontal comparison of entire situations. The estimations of market design are often launched from technical-related issues including reliability, efficiency, and security. The market is expected to be understood from the economic application in the real world.

The benchmark market assessment criteria published in this chapter fills the gap of lacking uniform non-technical evaluation rules, and the comparison between typical trading methods applied in the existing transmission-level market is generated.

The main findings of this chapter are:

- The bilateral trading method possesses priorities in market liquidity, market signal provision and market manipulation.
- The pool model gains better performances in risk limits, transparency and market simplicity
- The number of benefits appears equal between the bilateral trading methods and the pool model, and more issues are involved deciding which is the better trading methods serving distributed energy communities including importance proportion and criteria preferences. Generally speaking, the bilateral trading methods are more applicable in dealing with close-zero bidding and ensuring the right of all market participants.

## Pay-as-bid Market Design to Increase Transaction Quantity

The existing market design, no matter adapting which kind of clearing method, essentially takes the equilibrium point of demand and supply curves. Although the maximum social welfare is reached by those market, the drawback in reliability may be brought to the system due to the unpredictability and intermittency of the renewable energy resources and distributed energy resources. The market model guaranteeing clearing quantity is thus expected for the demand-supply balance, reducing subsequent rely on the balancing market.

To address the above problem, market model which could increase the clearing quantity is proposed in this chapter. The actual bidding of Sylvania electricity market is discussed, with the simulation of renewable energy resources and distributed energy resources. Two scenarios are analyzed in this chapter, including the hybrid-energy market where renewable energy resources are traded together with conventional generators, and the renewable-energy-only market where the renewable energies are traded solely in a market. The two market scenarios are analyzed. The direct market results are firstly discussed, and the market assessment criteria proposed in chapter 4 are applied to estimate the performances of markets. The proposed market model is compared with traditional market models.

The main findings of this chapter are:

- The proposed market model possesses better performance in clearing quantity compared with the traditional market designs, leading to capacity guarantee facing the introduction of unpredictable and intermittent renewable and distributed energy resources.
- Higher average prices are gained by the improved pay-as-bid market model compared to the traditional models, indicating stronger benefit guarantee for individual suppliers with higher attractiveness.
- The proposed optimized market model shows quantitively increasing market liquidity and reducing market manipulation through the simulated operation of markets applied in the real world. Qualitatively speaking, the optimized market model possesses priority in risk, simplicity and feasibility.

## Uber-Airbnb Mixture P2P Automatic Trading Market Design

The infiltration trend of distributed energy resources and the small-scale and personal-owned features could foresee the needs of P2P market design in the future. Deficiency exists in the on-going P2P market project trails: 1) Individuals are only passive price takers in the market without motivating the enthusiasm of market participants. 2) The market remains inconvenience in accessing. 3) The flexibilities participating market are considered as single energy resource without being focused on their individual flexibilities. The more sufficient and simulative flexibility market is expected to be built.

A P2P platform serving the transaction of flexibility resources is proposed in this chapter, referring to the mature P2P business model. The proposed Uber-Airbnb model combines the pricing strategy of Airbnb business model and the matching strategy of Uber business model. The dynamic pricing strategy which could reflect the characteristic of distributed generations and flexible loads is also proposed, reflecting the market price fluctuation being closer to the pure commodity transactions. The segmentation needs of the proposed market are also explored under diverse levels of penetration. The non-technical market assessment criteria are also applied in the market estimation, the comparison between the integrated market and the segmented market is launched.

The main findings of this chapter are:

- The introduction of market segmentation to the P2P flexibility market applying dynamic price strategy could mitigate extreme prices. Any type of flexibility resources would not fall in trading due to the failure matching caused by extreme flexibility levels.
- The segmented distributed energy market possesses better performance in market value when considering energy products as pure commodities.
- The segmented market gains slight advantages in market liquidity and market manipulation from the real-world simulated operation perspectives. And in general, little difference is shown under the non-technical market assessment criteria

## Roles and Functions of Distribution System Operator

The sufficient market is required facing massive introduction of renewable energy resources and distributed energy resources to proceed energy transaction and mobilize energy value. Apart from discussing market design itself, the current and future roles and functions taken by stakeholders are required to be explored. The existing research exploring the projected management-related responsibilities of system operated bases on the premise that the entire functions of DSO could be completed at one time, falling to regard the DSO development as a dynamic progress. The cooperation and coordination between DSO and the management institutions in other levels are also required further research.

This chapter proposes the management functions in the merging distributed energy market and explores the roles and functions of DSOs when considering the distribution system operator as a dynamic process.

The main findings of this chapter are:

- The distribution-level market transition pathway indicating three distributed market structure is proposed in this chapter, corresponding to the three typical stages of distribution system under the increasing penetration of DSRs
- Four roles of DSO are extracted based on the current research towards DSO, and the diverse detailed management behaviors under three typical market structures are illustrated to reflect the dynamics of DSO.
- The responsibility distinction and cooperation execution between DSO and other management institutions are discussed in this chapter.

# Chapter 9

# Future work

This chapter presents the potential future work to construct more appropriate distributed energy market

Comprehensive research has been launched in this thesis, exploring the distributed energy market under the penetration of renewable energy resources and the distributed energy resources. The research emphases analyzing the economy-related characteristics of the market, and further network-related features are expected to be discussed. Besides, more details of the diverse TSO-DSO coupling are required. including the measures of their cooperation and coordination.

The future work is majorly launched from two perspectives: 1). Considering network-related constraints of the market. The market would be discussed from the combined perspectives of technology and economy, whose network-related constraints are enlarged from the basic network capacity limits to other detailed essential issues. 2). Considering the coordination between TSO and DSO levels. The independent and autonomous distribution-level market future is introduced in this research, before which the transmission-level market would coexist with the distribution-level market for a long period. The dynamic coordination details between TSO and DSO under diverse coupling scenarios should be discussed.

## Discussing dynamic collaboration and coordination between DSO and TSO in the energy penetration progress

The collaboration between transmission-level market and distribution-level market requires exhaustive study, such as the priority between two markets or the interactive program serving urgent situations. First, the data interaction platform is needed to construction the sufficient flexibility certification and information activation. The existing EU SmartNet project proposes five TSO-DSO coordination solutions, affecting the procurement of local services and ancillary services. And the visual embedding serving the quantification and exchange of flexibilities requires appropriate platform as well.

Besides, the communication between TSO and DSO is essential to offer efficient flexibilities in the following operation periods. Those information exchange and interaction is also a crucial research direction. The condition information of the current and short-term distribution network operation is integrated when flexibility performing frequency control, that the ex-ante validation and pre-activation validation is included. DSO would estimate the technical feasibility of the frequency control scheme and their local restrictions in the distribution network in ex-ante validation. The advance-communication is needed between TSO and DSO in pre-activation validation serving the following modification.

The traffic light concept is considerable in the TSO-DSO information interchanging. The flexibility resources can be classified according to the influences on power grid operating conditions, that the green, yellow, and red flexibility resources can correspond to the total activation without technical matters, partial activation, and unable activation due to technical restrictions. And the different market stages could also be analogized under traffic light concepts. The safe network operation is represented with green phase, the local network services are introduced for projected future problems under yellow phase, and the DSO could interpose directly in the red phase.

### Conducting unified planning to market design and network technical limitations

Intaking the network constraints into the research of market design, the market clearing arithmetic is a significant element. The algorithm commonly to be applied to network inspection is the DC power flow algorithm, which is always be the first step in contemplating network constraints. The algorithm possesses advantages including being transparent for participants and fast solution speed to reduce computing difficulties of the clearing engine. There are limitations for DC algorithm although it is a key step in market design considering network constraints because of its advantage in containing power flow and network congestions.

First, the actual load flows may be error estimated because the reactance of distribution lines would not be much higher than the ohmic resistance. Furthermore, the calculation of reactive power flow is needed to be considered because of the voltage problems existing in the distribution network. The ideal reactive power transaction platform could be offered by distribution-level market, making it valuable to expand market designs. The flexibility management belonging to the DSO portends fundamental changes to the regulation framework. All the changes require the modification towards optimal power flow tools.

# Publication

**L. Shan,** C. Gu, and F. Li, " A Uber-Airbnb Mixture Flexibility Peer-to-peer Market in Integrated TSO-DSO Architecture " in IET Smart Grid, 2022. 1-19

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