Received: 6 October 2019 | Revised: 3 January 2020 | Accepted: 4 February 2020

DOI: 10.1002/2050-7038.12360

REVIEW ARTICLE

WILEY

A comprehensive review on day-ahead electricity market and important features of world's major electric power exchanges

Devnath Shah[1] | **Saibal Chatterjee**[2]

[1]Department of Electrical Engineering, NERIST, Nirjuli, Arunachal Pradesh, India

[2]Department of Electrical and Electronics Engineering, NIT, Aizawl, Mizoram, India

Correspondence
Devnath Shah, NERIST, Room No-2084, Brahmaputra Hostel, Nirjuli 791109, Arunachal Pradesh, India.
Email: devnath.nitap@gmail.com

Peer Review
The peer review history for this article is available at https://publons.com/publon/10.1002/2050-7038.12360.

Summary

Restructuring to the existing electric power system has transformed the conventional method in which electric power is traded around the globe. Now private players and entities having distributed generators can actively participate in restructured electricity market. It brings competition among different market players and leads to an overall fall in electricity prices. To further enhance competitiveness and bring transparency in the electric power trading mechanism, a common platform called power exchange (PX) has been established in many countries of the world. PX is a common internet-based online platform where various market players submit their offers/bids for selling/buying electrical energy or services. As in today's restructured electricity market, significant percentage of short-term electric power is traded through day-ahead market (DAM) of PX, the study of DAM is very important. Therefore, this article presents a comprehensive review of day-ahead electricity market and other important features of world's major electric power exchanges. It mainly focused on PX products, trading mechanism, DAM design issues, world's major PX, comparative analysis of DAM of world's major PX and future challenges.

KEYWORDS

day-ahead market, electricity market, intraday market, market-clearing price, power exchange, restructuring

1 | INTRODUCTION

Restructuring in electric power industry brings major changes to the way electrical power has been traded all over the world.[1] It paved the way for unbundling of generation, transmission, and distribution so that various private players

Abbreviations: ACP, area clearing price; ATC, available transfer capacity; BSP, Borzen Slovenian Power; CERC, Central Electricity Regulatory Commission.; CROPEX, Croatian Power Exchange; DAM, day-ahead market; DSO, distribution system operator; EPEX Spot, European Energy Exchange Spot; EPX or PX, electric power exchange; ESC, energy saving certificates; EXAA, Energy Exchange Austria; EXIST, Energy Exchange Istanbul; GME, Gestore dei Servizi Energetici; HUPX, Hungary Power Exchange; IBEX, Independent Bulgarian Energy Exchange; IEX, Indian Energy Exchange; IM, intraday market; IPEX, Italian Power Exchange; JPEX, Japan Electric Power Exchange; MAR, minimum acceptance ratio; MCP, market-clearing price; MCV, market clearing volume; MIC, minimum income condition; OKTE, short-term electricity market operator; OMIE, Operador Mercado Iberico Energia; OPCOM, Power Market Commercial Operator; OTE, Czech Electricity and Gas Market Operator; PCR, price coupling regions; PJM, Pennsylvania-New Jersey-Maryland; PUN, Prezzo Unico Nazionale; PXIL, Power Exchange India Limited; RAM, remaining available margin; REC, renewable energy certificates; TAM, term-ahead markets; TSO, transmission system operator.

and entities having distributed generators can actively participate in power trading. Under deregulated power market, consumers have the autonomy to select their own suppliers according to their specific requirements. Electricity is considered as tradable commodity instead of service with certain market value in power market. Restructuring in power sector brings competition among private players and lead to overall fall in electricity price. To further enhance competitiveness and bring transparency in electric power trading mechanism, a common platform called power exchange (PX) or electric power exchange (EPX) has been established in many countries of the world.[2] An Exchange means a platform in which different buyers and sellers come together for transaction of products or services. It does not represent a market but acts as host to the market whose core function is to ensure fair and transparent transactions between its stakeholders. Similarly, EPX or PX is an internet-based online platform where various market players submit their offers/bids for selling/buying electrical energy or services. The main objective of any PX is to provide a mechanism for robust, transparent, and reliable price formation. Although a very large portion of today's electric power is still traded through long term bilateral contracts, still there exists a significant percentage of short-term electric power which is traded through PX. Evolution of PX around the world depends on experiences and lessons learned from different PX with time. Design of PX varies among countries and also among different exchanges in the same country. In the last two decades, a number of countries around the world established their own EPXs for providing different market players a platform for competitive power trading. Some of the world's major PX includes Nord Pool, European Power Exchange Spot, Japan Electric Power Exchange (JPEX), Italian Power Exchange (IPEX), Indian Energy Exchange (IEX), and so on. Nord Pool is one of the earliest successful functioning PX in the world and is being considered as an ideal model for standard design. A general PX provides the following services to its market participants[2,3]: (a) online market interface for power trading; (b) market clearing and deal settlement; (c) accounting and billing of spot market products; (d) information needed to its market participants; and (e) addressing financial risk. Apart from these, PX also provides a market platform for ancillary services trade which includes regulation market, reserves market, and so on. It also ensures physical delivery of all electric power traded through PX. For any PX, there must exist synchronization between the operation of transmission system operator (TSO) and PX. TSO provides technical clearance to PX for transacting power over transmission grid. Power trading through PX has the following advantages: (a) PX ensures fair and transparent formation of market clearing price (MCP) for all PX products. All market participants were ensured that they will get the best possible deal based on their preferences and constraints. (b) Trading through PX enables market players to find the optimum buyer or seller for power trade. (c) PX stands in as a counter-party so that market participants can trade without considering risk-profile of other market players. (d) PX offers wide range of portfolios (offer/bid types) to its market participants so that they can trade in flexible quantities and variable number of hours. (e) PX ensures rational distribution of transmission loss. (f) PX improves the market environment and provides electricity price signals to the market which leads to increased competition in power market. Over the years, power trading through PX significantly increases which is crucial for the success of any PX. Success factor of any EPX can be measured with the following parameters[4]: (a) total number of participants; (b) liquidity in the market; (c) market growth in terms of traded volume, and (d) fee structure competitiveness. In any PX, the total number of market participants (buyers and sellers) indicates its respective strengths. Large number of participants are always desirable for any PX. With a small number of participants, the market behaves more like an oligopoly market with little competition.

The working mechanism of a generalized PX is shown in Figure 1. Power Sellers can submit their sell offers to PX between some pre-specified time intervals. Also, Buyers having industrial loads, domestic loads, commercial loads, Retailers and Power Brokers can submit their buy bids to PX between some pre-specified time intervals. The PX then processes all submitted supply offers and buy bids simultaneously and clears the market on the basis of supply-demand equilibrium at a common price called MCP. The sum of all cleared offers or bids is called market clearing volume (MCV). If there exists congestion in the transmission grid, then the entire market splits into a number of small markets which is cleared separately at a different price called area clearing price (ACP). Generally, small consumers like domestic and commercial consumers indirectly participate in power trading through PX via appropriate settlement and deal with retailers and power brokers. The direction of power flow is shown in Figure 1 which flows from power generator to the transmission grid. Large consumers like big industries can directly take power from transmission grid or via a low voltage distribution grid. Small consumers like domestic and commercial loads receive power through a low-voltage distribution network. The figure also shows the direction of money flow from different consumers to PX. It is possible for large consumers to directly pay money to PX via associated banks. However, small consumers generally make payments via retailers and power brokers. Then, the PX transfers these amounts to the respective sellers which is proportional to their respective cleared volume during the market clearing process. The direction of information flow is also indicated in Figure 1. Coordination of PX with different entities by exchanging various information is very crucial for

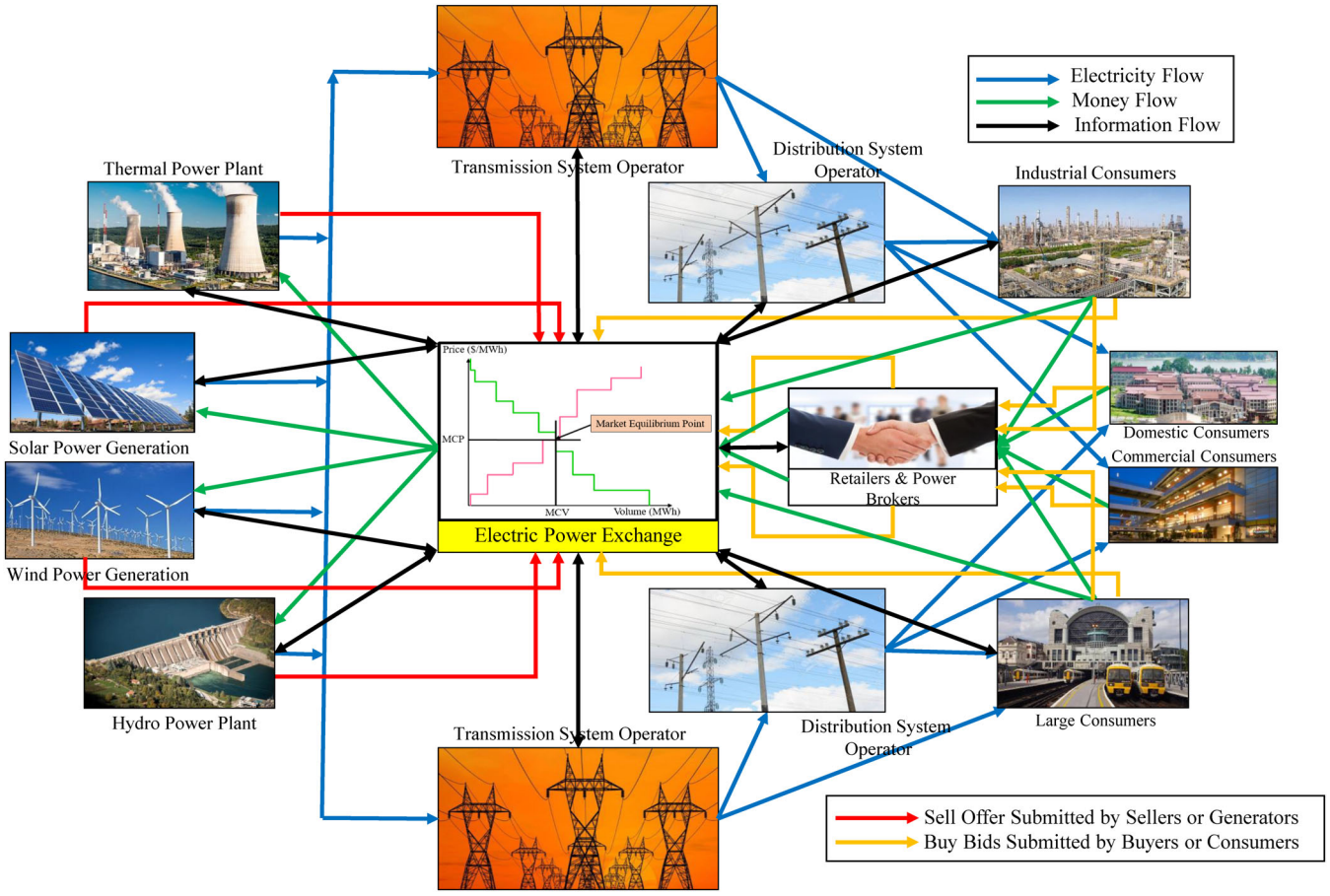


FIGURE 1 Generalized power trading with electric power exchange

efficient, robust, transparent and fair working of any PX. The PX regularly exchanges various information bidirectionally with Electric Power Generators, TSO, distribution system operator (DSO), Large Consumers, Retailers and Power Brokers for its proper functioning. With Power Sellers/Buyers, PX exchanges information related to cleared offer/bid volume, uncleared offer/bid volume, MCP (or ACP), transmission congestion status, dispatch schedules, sell/buy amount, and so on. Likewise, with TSO and DSO, PX shares information regarding dispatch schedules from various generators, cleared power demand for various loads, congestion rent, transmission loss allocation, and so on. Retailers and Power Brokers also exchange similar kinds of information with PX. Market clearing in any PX involves a number of steps and the basic sequence of the steps is shown in Figure 2. As evident from Figure 2, the first step is bidding in which all sellers and buyers submit their hourly/half-hourly volume-price offers and bids between pre-specified time intervals. For example, IEX allows submission of quarter-hourly volume-price offers and bids between 1000 hours to 1200 hours. The next step is matching in which PX aggregates all sell offers/bids and plots cumulative supply/demand curve on volume-price plane. Based on the market equilibrium point obtained by intersection between cumulative supply and demand curves, the PX clears the market and determines MCP and MCV. In the next step, PX runs a power flow algorithm and checks the transmission congestion status. If there exists any transmission congestion then the entire market is disintegrated into a number of small markets which is cleared with different ACP. Here PX also ensures that there exists sufficient balance in buyers account to perform requisite transaction safely. If there exists an insufficient balance in the buyer's account then the market is cleared again by eliminating their respective bids. After that, the PX announces the final results on ACP, MCP, cleared sell offer volume, cleared buy bid volume and transmission congestion status. Finally, the PX sends the respective schedule to generators, TSO and buyers for final power delivery by Central Load Dispatch Centre and Regional Load Dispatch Centre.

As in today's restructured electricity market, significant percentage of short-term electric power is being traded through PX, therefore a comprehensive review of important features and working mechanisms of major PX around the world is crucial. In literature, very few work exists which provides a qualitative review on features and working of major PX around the world. Quite a few works exist on the working of some specific PX. Various experiences learned

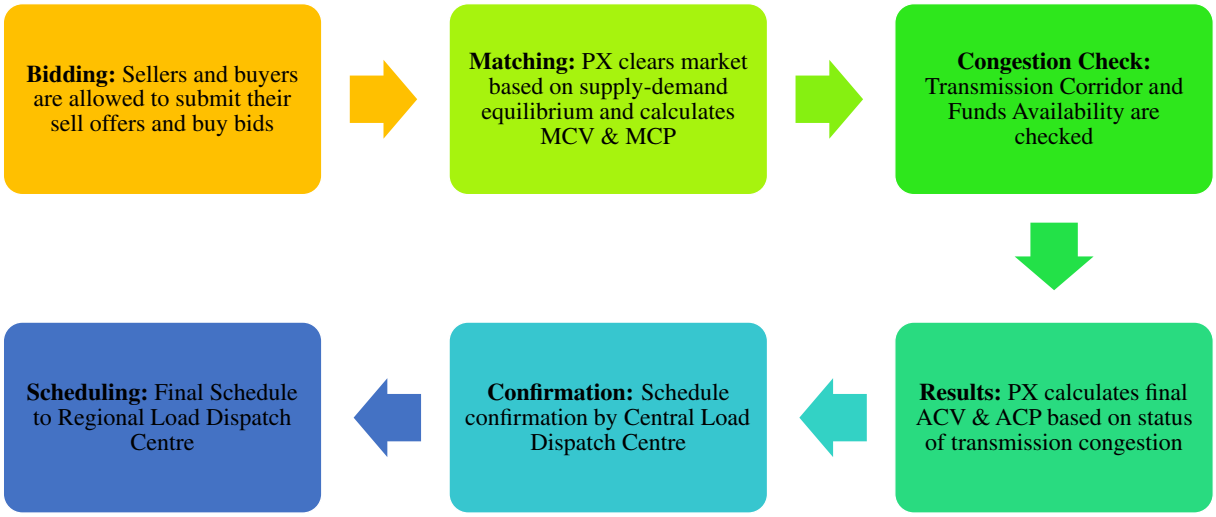


FIGURE 2 Market clearing steps in electric power exchange

from design and implementation of Nord Pool are presented in Reference 5. Mediratta et al[6] discusses the theoretical and empirical perspective of exchange-based spot market trading of electric power in Western Europe. A systematic comparison on the pricing mechanism of the European Electricity market with different European PX is presented in Reference 7. Important PX from North America, Europe, and Australia along with their operational aspects is summarized.8 In Reference 9, the author discussed the power sector reforms in the Indian electricity market along with working of India's first PX viz IEX. The role of different European PX in wholesale electricity market is studied in Reference 10. A brief review on different aspects of PX along with a summary of important features and working of some important PX around the world up to 2010 is presented in Reference 2. It covers working principle of basic PX, their design issue and few lessons learned from international experiences. Alam et al11 focused on working of two important PX viz. IEX and Australian Energy Market Operator. Some effects of PX in the Indian electricity market is analyzed in Reference 12. Rademaekers et al13 analyzes market data of different PX between 2002 and 2007 and also give crucial information about different PX around the world. An overview of working mechanism and types of products offered in Japan Electric PX is presented in Reference 14. A comprehensive overview of European PX and their market design is presented in Reference 15. Mayer and Trück[16] examine wholesale electricity spot prices for 28 market regions in 19 countries and compare these markets regarding their price variations and market structure. Trading arrangements of Indian and some developed electricity markets are discussed in Reference17. A brief study regarding emergence of major PX are presented in Reference 18. A recent assessment on electric power trading through PX in India is presented in Reference 19. Broad implication of Brexit on electricity market of Great Britain is analyzed in Reference 20. Electricity market design within the European Electricity Market for Croatia along with some recommendations is presented in Reference 21. Impact of integrated European Electricity Market on the Iberian Electricity Market is investigated in Reference 22. Effect of introducing block order on computational time, Prezzo Unico Nazionale (PUN) level and paradoxically rejected offers/bids number for Italian Day-Ahead Electricity Market is presented in Reference 23. A study on developing advanced algorithm for market clearing in integrated European Intraday market is presented in Reference 24. Kolcun and Rusek,[25] analyzes clearing price behavior in Polish Power Exchange. Stet[26] presents the highlight of the electricity market in Romania. Some recent studies on the Indian restructured electricity market can be found in References 27 and 28. It is evident from this literature that most of the existing works consider only one or two PX at a time. To the best of our knowledge, there exists no paper which gives a detailed review of different features and working of world's major PX. There is a need for a comprehensive literature review on different features and working of world's major PX. Also, most PX around the world at least provides day-ahead market (DAM) to its market participants apart from intraday market (IM), renewable energy certificates (REC), energy-saving certificates (ESC), and so on. in which PX allows trading of simple hourly offer/bid, block offer/bid and complex offer/bid accounting for the most part of power traded through PX. Hence, the study of Day-Ahead Electricity Market of PX is very important. Therefore, this article presents a comprehensive review of Day-Ahead Electricity Market and other important features of world's major EPXs. It mainly focuses on PX products, trading mechanism, DAM design issues, world's major PX, comparative analysis of DAM of world's major PX and future challenges. IM, REC and ESC are also briefly discussed.

The rest of the paper is organized as follows: Major PX products are discussed in Section 2. Trading mechanism in PX is given in Section 3. Various design issues of DAM of PX are briefed in Section 4. Important features of world's major EPX are presented in Section 5. Comparative DAM analysis of world's major EPXs based on different aspects are presented in Section 6. Section 7 focusses on future challenges for DAM of current PX. The final conclusion is drawn in Section 8.

2 | PX PRODUCTS

PX around the world offers wide range of power products to its market participants for fulfilling their market requirements. Most PX at least provide DAM and IM as PX products. DAM allows trading of power contracts through online auction for the next 24 hours of a day ahead of its physical delivery while IM allows continuous trading of power contracts ranging from same day up to few days in advance. Apart from these PX products, some PX also offers products like RECs and ESCs (REC). These products are plotted in Figure 3.

2.1 | DAM or spot market

Spot Market is the most common type of PX product allowed in any PX. In Spot Market, PX allows trading of hourly power contracts for the next 24 hours of a day. Hourly contracts are submitted by supplier and buyers in terms of multiple volume-price pairs which basically represent the willingness of supplier/buyer to sell/buy a certain volume of power at a price equal to or higher/lower than their respective specified price. Both electric power sellers and buyers were allowed to submit volume-price offers and bids for each hour in PX. Multiple volume-price pairs representing different segments of sell offer and buy bid from two sellers and two buyers were shown in Figure 4. It is evident from Figure 4 that seller S-1 submit, three volume-price pair plotted in increasing order of their offer price. It basically represents the willingness of seller S-1 to sell power up to volume $Q^S1(S\text{-}1)$ at a price equal to or higher than $P^S1(S\text{-}1)$. For volume between $Q^S1(S\text{-}1)$ and $(Q^S1(S\text{-}1) + Q^S2(S\text{-}1))$, seller S-1 is expecting a price equal to or higher than $P^S2(S\text{-}1)$ and so on for other segments. From buyer's side, buyer B-1 submit two volume-price pair plotted in decreasing order of their bid price. It basically represents the willingness of buyer B-1 to buy power up to volume $Q^D1(B\text{-}1)$ at a price equal to or lower than $P^D1(B\text{-}1)$. For volume between $Q^D1(B\text{-}1)$ and $(Q^D1(B\text{-}1) + Q^D2(B\text{-}1))$, buyer B-1 is willing to pay a price equal to or lower than $P^D2(B\text{-}1)$. For example, Nord Pool in its DAM allows trading of hourly contracts. PX like JPEX allows half-hourly contracts instead of hourly contracts while PX like IEX allows quarter-hourly (or 15 minutes)

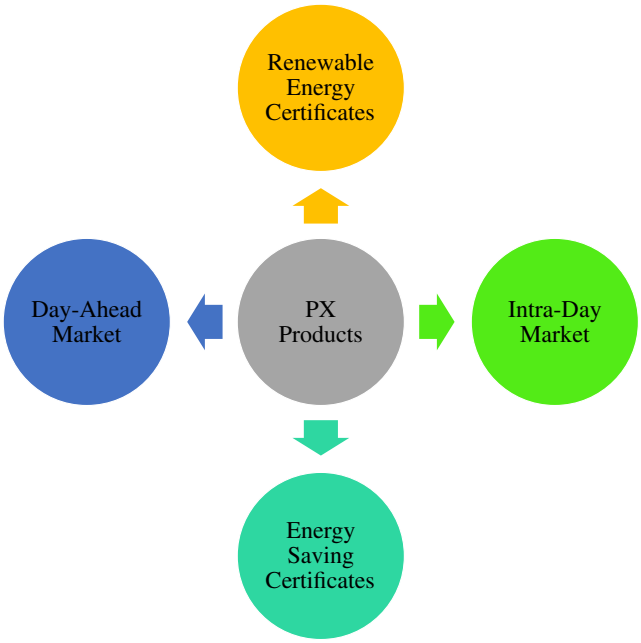


FIGURE 3 Products offered in electric power exchange

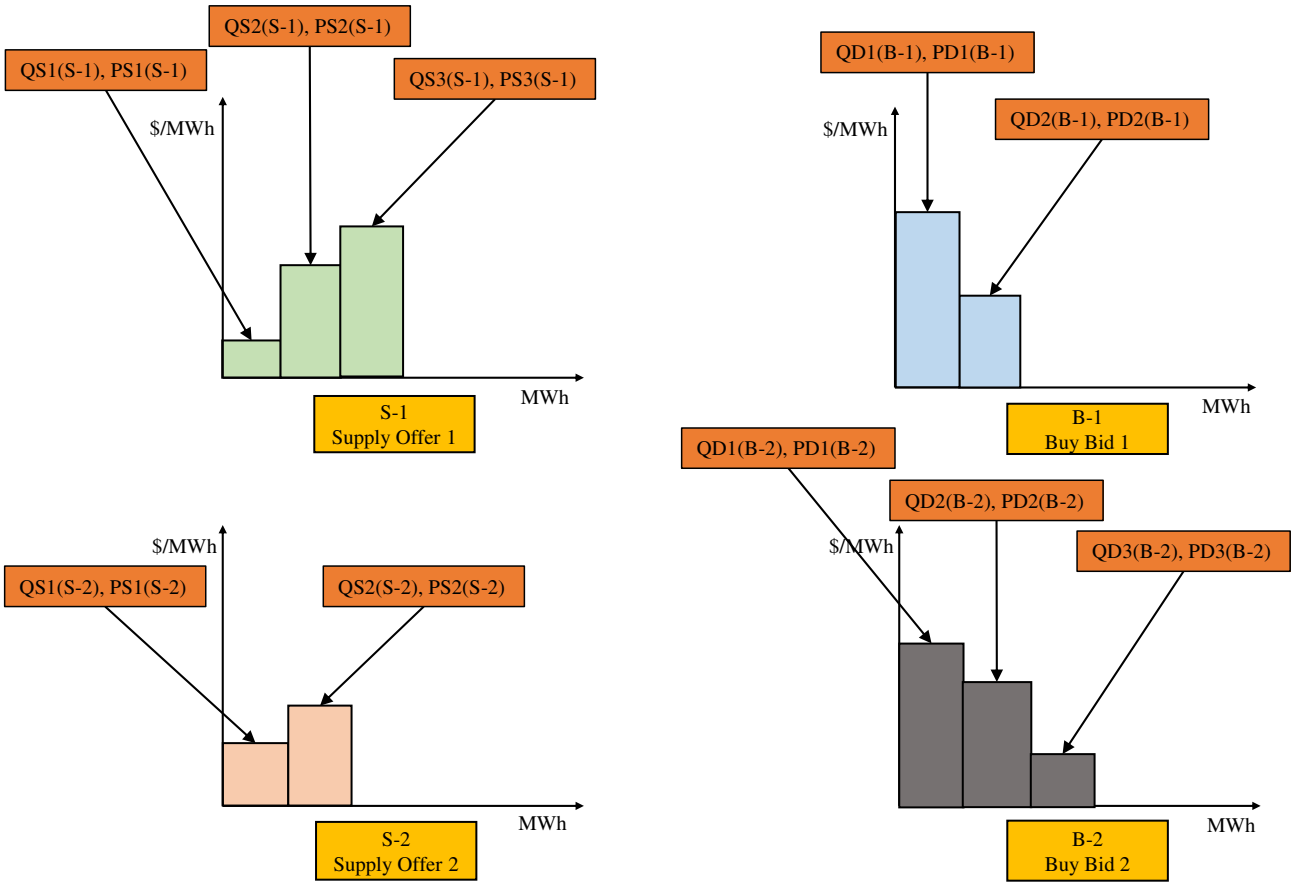


FIGURE 4 A typical representation of hourly sell offer and buy bid submitted in DAM

contracts. Apart from simple contracts, Spot market also allows trading of block products in which trader specifies a fixed (or variable) volume, fixed price and consecutive time slot in which the block offer/bid is to be delivered if cleared. Block products include regular block product, linked block product, curtailable block product, profile block product, and exclusive block product. This is particularly useful for supplier's having thermal generators with high startup and shut down costs. Wide ranges of complex offer/bid exhibiting complex execution conditions were also allowed in different PXs around the world. Figure 5 shows typical timeline for Spot Market or DAM in IEX. It starts by initial margin check at 0930 hours and from 1000 hours to 1200 hours, offers and bids are allowed to submit from sellers and buyers. Between 1200 hours and 1300 hours IEX calculates initial MCP and check funds availability for each seller and buyers. Between 1300 hours to 1400 hours National Load Dispatch Centre (NLDC) check for any possible congestion in delivering the cleared volume. By 1430 hours buyers pay to IEX and by 1500 hours IEX calculates MCP (or ACP in case of congestion) and send a scheduling request to NLDC. By 1730 hours NLDC confirms acceptance and IEX sends a detailed schedule to State Load Dispatch Centre (SLDC). By 1800 hours SLDC incorporates collective transactions in the daily schedule. Finally, by 1400 hours in the next day, IEX makes payment to sellers. Spot Market of most of the EPX has more or less similar framework.

2.2 | Intraday market

Apart from DAM, IM, or Term-Ahead Market is the most common type of PX product offered in any PX. This platform allows continuous trade of a wide range of power contracts for a duration from 1 hour to few days. In IM, market participants were allowed to negotiate power contracts up to 1 hour before its actual delivery. Intraday trading is particularly useful for adjusting unforeseen changes in power production and consumption to its market participants. On contrary to uniform price market clearing in DAM where last accepted bid sets price for all transactions, the prices in intraday trading were set in a "pay-as-bid" process. IM in Nord Pool allows trading of following offer/bid types[29]:

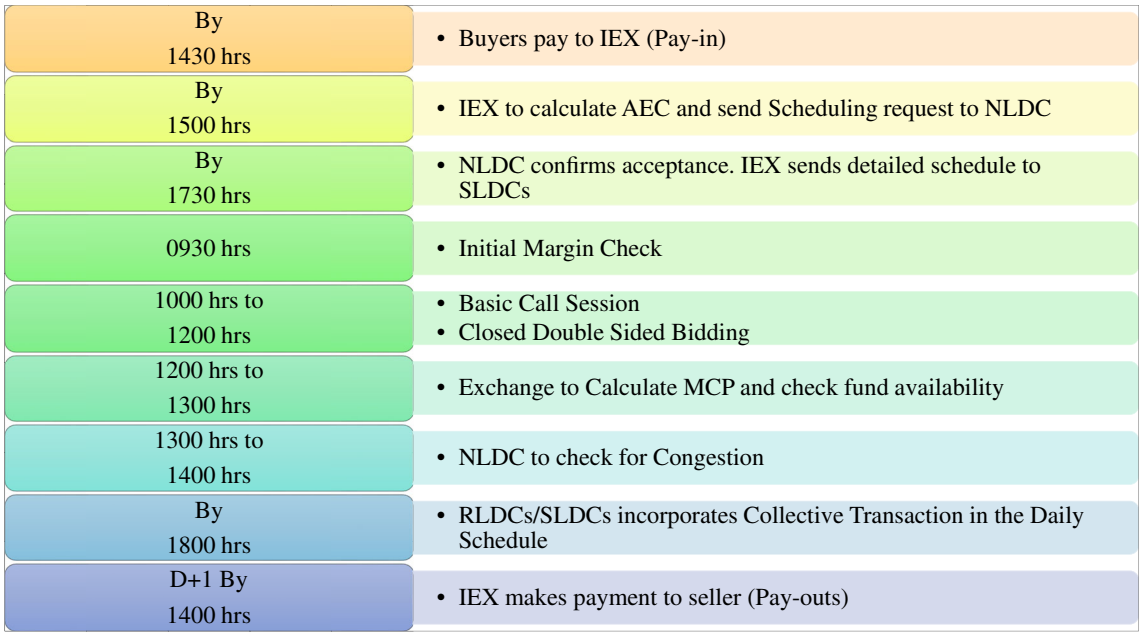


FIGURE 5 Typical timeline of DAM in Indian Energy Exchange[30]

(a) Limit offer/bid: It is a sell offer or buy bid having a specified price limit. The buy limit bid is cleared at a price equal to limit price or lower and sell limit offer is cleared at a price equal to limit price or higher. Partial execution of limit offer/bid is also possible. (b) User-defined block offer/bid: It is a block offer/bid consisting a set of consecutive hourly offer/bid with its length and execution time defined by users. (c) Predefined block offer/bid: These are block offer/bid with fixed execution time and length set by Nord Pool. (d) Iceberg offer/bid: It is a type of limit offer/bid, with a large volume. It is divided into number of small segments called Clips. Similarly, term-ahead market (TAM) of IEX allows trading of following power contracts: (a) Intra-day, (b) Day-ahead Contingency, (c) Daily, and (d) Weekly contracts. Details regarding these products were shown in Figure 6.

2.3 | Renewable energy certificate

REC is a tradable and nontangible energy commodity which represents a proof that 1 MWh of electricity was generated from an eligible renewable energy resource and injected into the transmission grid.[30] REC provide a mechanism for purchase of renewable energy which is injected to or extracted from transmission grid. A supplier having renewable power generation, solar or non-solar, is credited with one REC for every 1 MWh of electricity it produces and injected into transmission grid. The accompanying REC can then be sold on open market. Under REC mechanism, a generator can generate electrical energy through renewable energy sources in any part of the country by buying certain number of REC from PX or entity selling these certificates. As electric power generation from renewable power sources is expensive in nature, many big firms/buyers were obligated to buy some part of their energy from suppliers having renewable resources. Big firms/buyers can fulfill their Renewable Purchase Obligations (RPO) by buying appropriate number of REC certificates from entities offering REC trade. Some PX around the world like **IEX**, Energy Exchange Istanbul (**EXIST**), **Power Market Commercial Operator (**OPCOM), and so on offers a market platform for fair and transparent trade of REC certificates. REC trade through PX is similar to that of power trade in DAM. Sellers and buyers were allowed to submit their respective offer and bids to PX between some specified time intervals and then PX clears the market based on supply-demand equilibrium. Uniform price auction scheme is generally used for market clearing. Through PX, the obligated entity can purchase these RECs to meet their RPO from any part of the region/country. REC are of two types solar and nonsolar. Solar REC accounts for electrical energy generated from solar energy. Nonsolar REC accounts for electrical energy generated from nonsolar renewable sources like wind energy, tidal energy, and so on. Some recent studies on REC were presented in References 31-36.

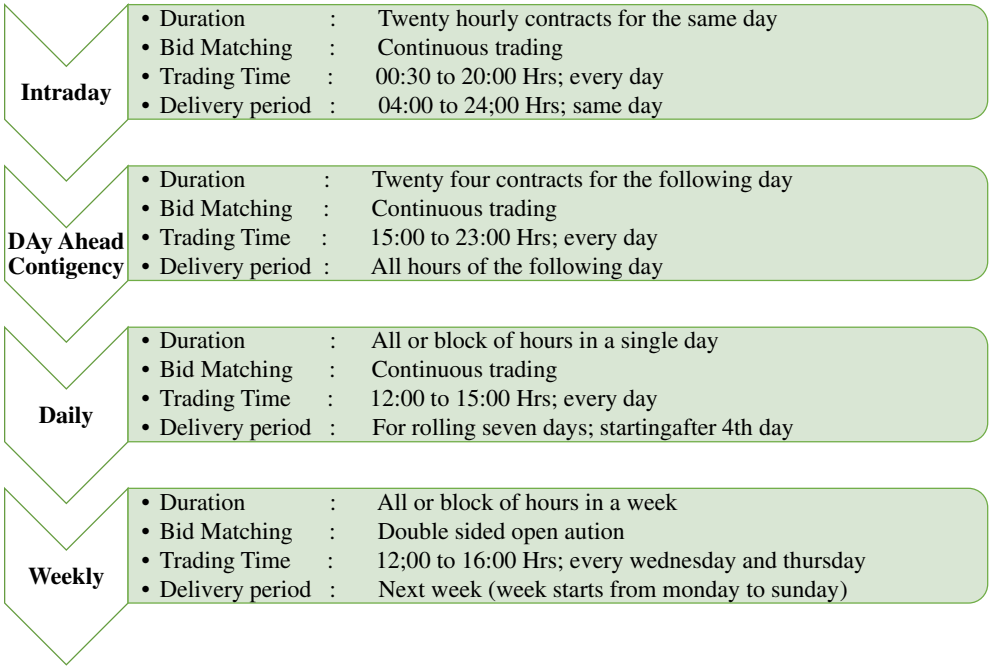


FIGURE 6 Different products traded in Term-Ahead Market of Indian Energy Exchange[30]

2.4 | Energy-saving certificate

ESC is similar to REC.[30] It is also called energy efficiency certificates (EEC) and tradable white certificates. It is a tradable certificates representing 1 MWh of energy savings from efficiency projects. Central governments or policymaker asked energy-intensive industries or organizations to reduce certain percentage of their energy consumption through efficiency measures. The industries or organizations over-achieving their efficiency targets were issued certain number of ECS depending on their total energy savings. These certificates are tradable document in any open market. The under-achieving entities can fulfill their energy-saving obligation by buying appropriate number of ESC from open market. PX like **IEX**, **IPEX**, and so on provide suitable market platform for trading of ESC. Trading of ESC through PX is similar to that of REC. Some recent studies on ESC can be found in References 37-39.

3 | TRADING MECHANISM IN PX

Most PX around the world uses either auction or continuous trade for executing fair, transparent and efficient power trade through PX. In power trade through auction, market participants were allowed to submit their sell offers and buy bids between prespecified time intervals and then PX clears the market based on supply-demand equilibrium. On the other hand, in power trade through continuous trade, submitted supplier's sell offers were continuously matched with opposite buyer's buy bids during trading hours. Power trading through auction can be either single-sided or double-sided auction. Single-sided auction allows either seller or buyer to submit their sell offer and buy bid, respectively, whereas double-sided auction allows both seller and buyer to submit their offer and bid respectively. Auction process can also be classified into open type auction and closed type or sealed auction. Open type auction allows its market participants to change their offer and bid according to the rival's bid behavior while in close type, offers and bids were submitted in a sealed format and not disclosed to other market participants. Most PX adopt double-sided closed auction scheme for offer/bid submission. A brief review of power trade through uniform price closed auction and continuous trade was presented next.

3.1 | Uniform price auction

As PX around the world uses a sophisticated online internet-based means for power trading, online auction provides the best way for its market participants for exploring the entire market and make better deals among them. Most PX at

least provide DAM in which trading is allowed through double-sided closed auction scheme. Uniform price closed auction scheme is adopted for power trading in DAM in which sellers and buyers were asked to submit their hourly (or half-hourly or 15 minutes) offers and bids for all 24 hours of the next day (D + 1) between fixed time intervals a day ahead of its physical delivery. For hourly, half-hourly and quarter-hourly (or 15 minutes) DAM, total number of periods is 24, 48, and 96, respectively. Then, PX separately clears the market for each period based on supply-demand equilibrium. For market clearing, a PX first aggregates all supply offers and buy bids separately for each periods and then clears the market on the basis of supply-demand equilibrium. Initially, PX aggregates all supply offers separately and plot the cumulative supply curve for each period on quantity-price plane. The process is demonstrated in Figure 7. After that, the PX also aggregates all buy bids separately and then plots cumulative demand curve for each period on same quantity-price plane as shown in Figure 7. Then, PX find intersection points between all cumulative supply and demand curves. For any period, the intersection point (or points) is called market equilibrium point. At market equilibrium point, supply demand are equal. The PX clears the market at this market equilibrium point. A typical intersection point between cumulative supply and demand curves is show in Figure 8. Price at market equilibrium point is called MCP and volume at market equilibrium point is called MCV. In any uniform price DAM, the market is cleared at this MCP. Only those sell offers were cleared whose offer price are equal to or less than MCP and only those buy bids were cleared whose bid price are equal to or higher than MCP. The rest of the offers/bids were either rejected or remains in order book until matched or expired. Social Welfare maximization is the primary objective for market clearing through uniform price auction in PX. Social Welfare is defined as sum of buyer's and supplier's surplus. Supplier's surplus is defined as product of quantity and price difference between the MCP and offer price. Buyer's surplus is defined as product of quantity and price difference between bid price and MCP. Buyer's surplus is also called Consumer's surplus and Supplier's surplus is also called producer's surplus. Consumer's surplus and supplier's surplus is shown in Figure 8. PX in this way, through online uniform price closed auction, discovers best price in DAM and arranges good deals for its market participants. Apart from DAM, other PX products traded through uniform price closed auction scheme include REC and ESC. Power trading through continuous trade is presented next.

3.2 | Continuous trade

Apart from DAM, IM is the most common PX product offered by any PX around the world which allows power trading through continuous trade. Although some offer/bid types in IM were also traded through uniform price closed auction

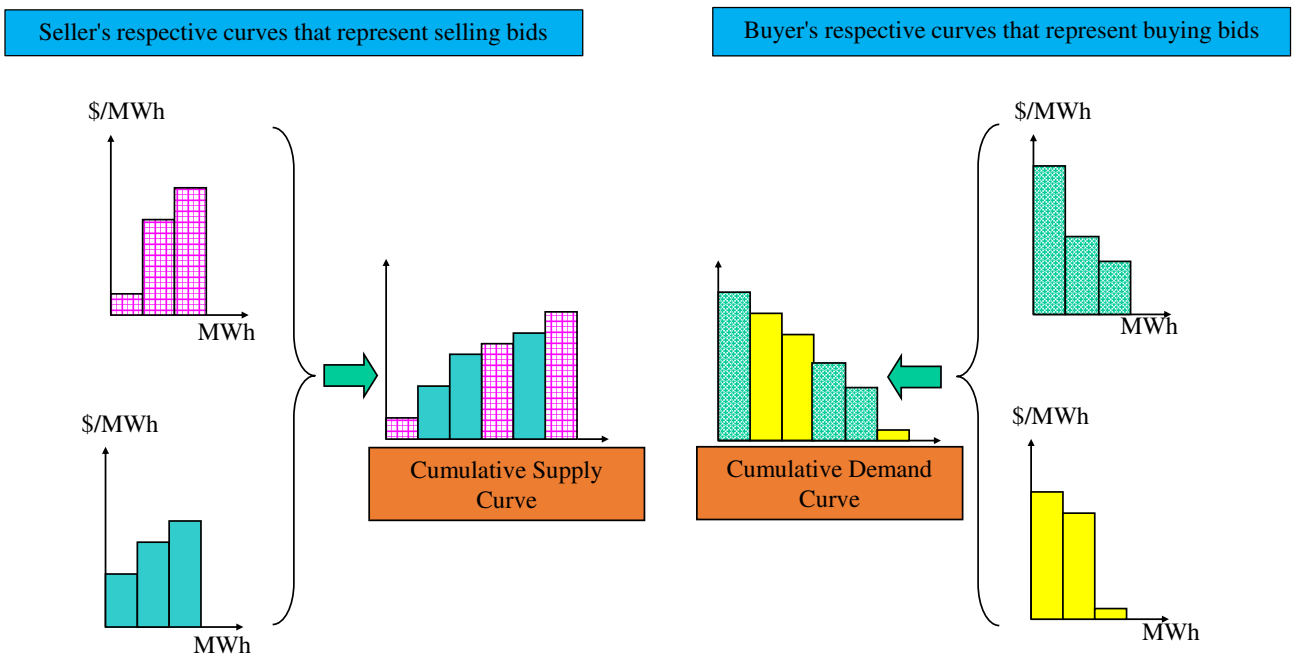


FIGURE 7 Offer and bid submission of sellers and buyers

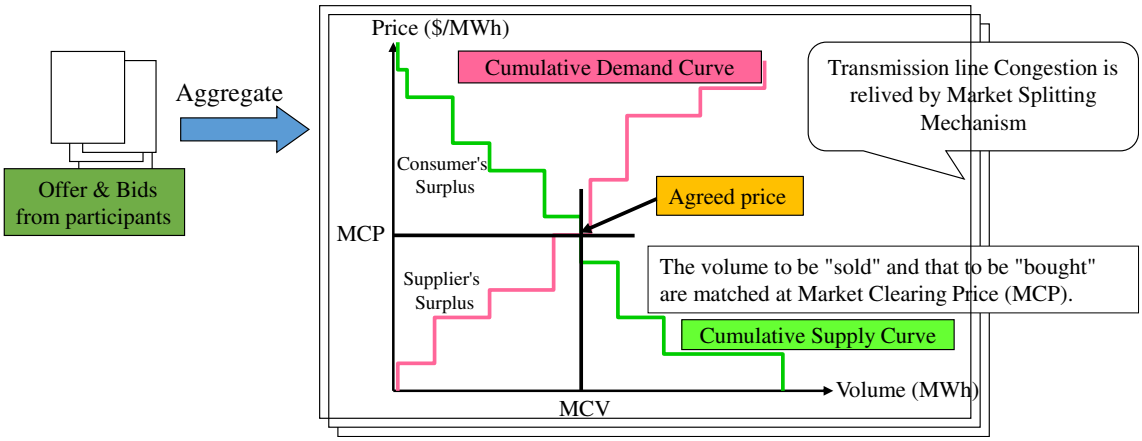


FIGURE 8 Market clearing, consumer's surplus, and supplier's surplus

scheme but most of them were settled through continuous trade. In continuous trading, market participants were allowed to submit their sell offer and buy bid on a continuous basis throughout the entire trading session. Supplier's sell offers were continuously matched with opposite buyer's buy bids with price-time priority. Supply offer with minimum offer price and buyer bid with maximum bid price were considered as best sell offer and best buy bid. If bid price of best buy bid is higher than or equal to offer price of best sell offer, then they were matched and results into contracts. Such matching continues throughout the entire trading session. In case, bid price of best buy bid is less than offer price of best sell offer, they will not results into any contracts and both sell offer any buy bid remain in the order book till it expired. Design issues of DAM of general PX were presented next.

4 | DESIGN ISSUES OF DAM OF PX

As volume of power traded through DAM of PX is very high, study of different aspects of DAM of any EPX is important.[2] This section presents a brief introduction of some important design issues related DAM of any PX. It mainly focuses on five design issues namely Bid Types, Execution Condition, Market Clearing Types, Transmission Congestion Management, and DAM Coupling. As ancillary services (AS) are very crucial for stable and reliable operation of any power system network, a brief review of AS trade through PX is also included.

4.1 | Offer/bid types

Types of offers/bids allowed in DAM of any PX is crucial factor as suppliers have to model their generation cost according to the allowed offer/bid types. PX across the world allowed a wide range of offers/bids types due to market responses and innovations. Types of offer/bid offered in DAM is shown in Figure 9.

4.1.1 | Simple offer/bid

It is the most common and popular offer/bid types allowed in any PX. DAM of most PX allows market players to submit simple hourly (or half-hourly or 15 minutes) offers/bid. It defines the fixed hour (or execution time) and volume at which the supplier can sell power or buyer can buy power. Price in terms of $/MWh also needs to be specified along with their execution time and volume. Four simple bids with their fixed execution time and volume is shown in Figure 10. For example, Simple Bid-1 has execution time from 07.00 AM to 08.00 AM and fixed volume of 100 MWh. Likewise, Simple Bid-2 has execution time from 11.00 AM to 12.00 PM and fixed volume of 50 MWh. For example, Nord Pool allows simple hourly bid,[29] JPEX allows half-hourly bid[40] and IEX allows simple bid of 15 minutes duration.[30]

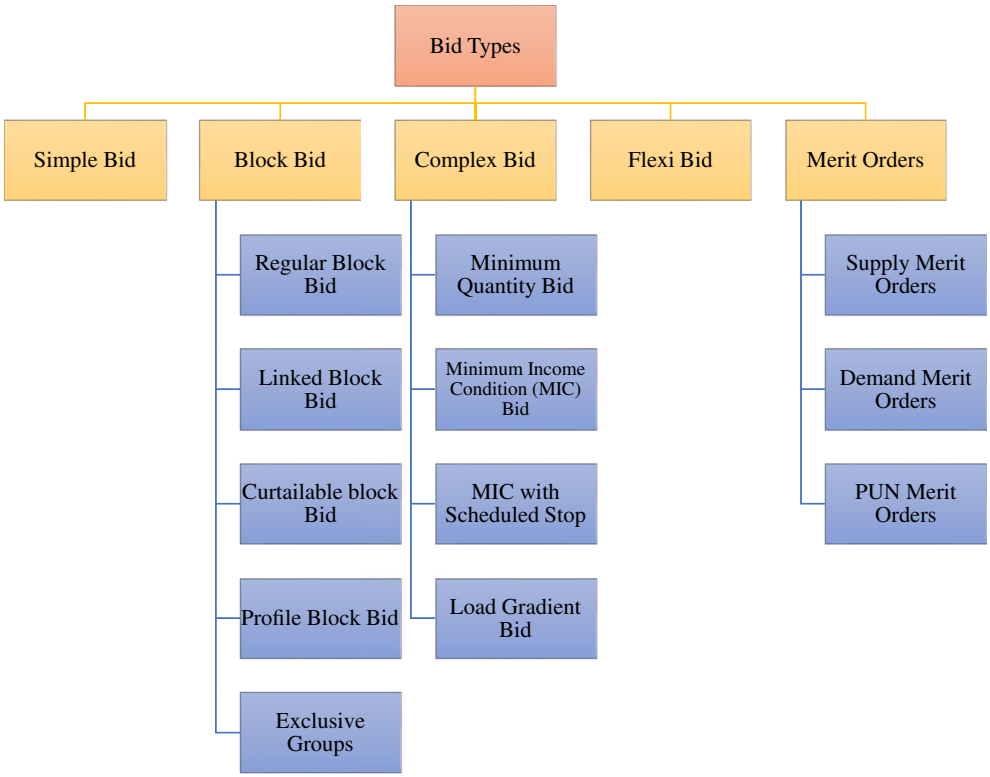


FIGURE 9 Bid types offered in day-ahead market of electric power exchange

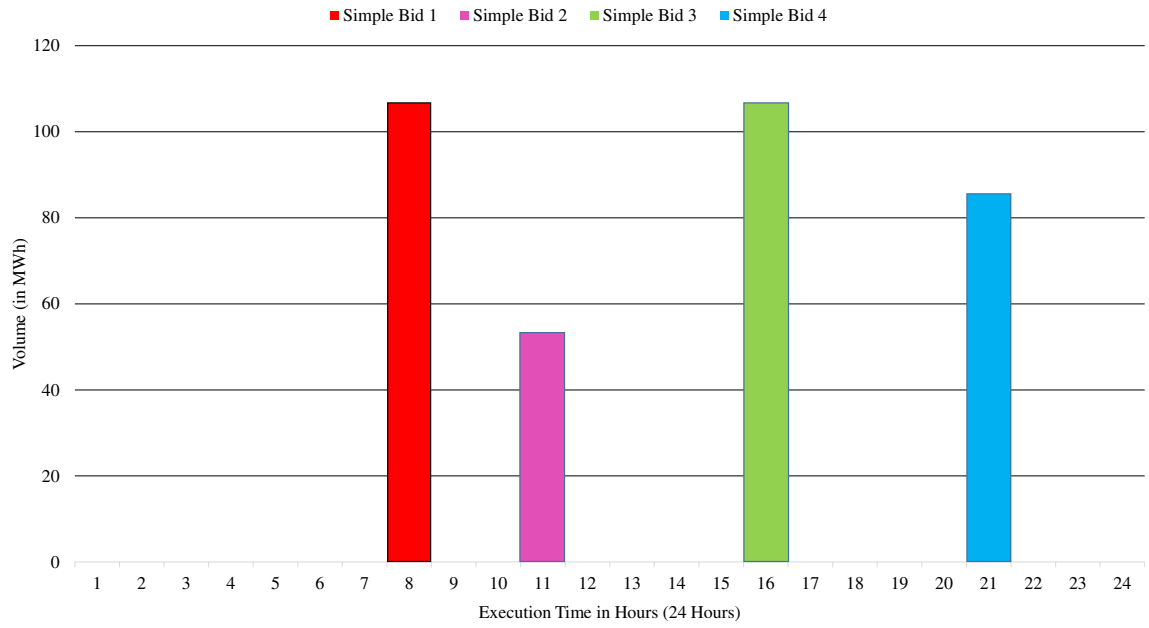


FIGURE 10 Volume execution time diagram of four simple hourly bids

4.1.2 | Block offer/bid

Electric Power suppliers having thermal generators with high startup and shut down cost are generally reluctant to submit hourly offers/bids as they feel hourly offer/bids to be economically inefficient. For example, if a seller submits hourly offers for 8 (say) consecutive hours and cleared only in alternate hours. Under this condition, the seller has to

run his generator for hour 1, then shut off for hour 2 and then again run for hour 3 and so on. Sellers having high startup and shut down cost may feel it be economically not viable. It is therefore economically efficient for them to submit offers in blocks of some consecutive hours say 4 hours. So, if it gets cleared for the first block and not cleared for the next block or vice versa, they can recover startup and shut down cost. This also helps them to submit offers at a lower price. The block products can be of standard and nonstandard types. Standard block offers have fixed length (number of consecutive hours) and execution time which is generally fixed by PX. Nonstandard block offers have user-defined length and user-defined execution time which is generally set based on some specified criterion. Number and length of block offers are generally restricted to some predefined standard as it complicates the market clearing mechanism. Five popular types of block offer/bid are discussed below.

1. *Regular block bid*: Regular block bid is a type of block bid which is most frequently used. In this type, the seller specifies a fixed a volume, fixed price, and consecutive time slot in which it is to be delivered if cleared. It is cleared if average MCP over operation time horizon is more than the specified price limit. It is either fully accepted or fully rejected. Partial execution is not possible. It is demonstrated in Figure 11 with two regular block bid. For example, Regular Block Bid-1 have fixed volume of 100 MWh and fixed execution time from 07.00 AM to 11.00 AM Some example of standard Block Bid (BB) from European Energy Exchange (EPEX) Spot is Base Load (BB 1-24), Evening (BB 19-24), Early Morning (BB 5-8), off-peak-1 (BB 1-8), and Sun Peak (BB 11-16).[41]
2. *Linked block bid*: Linked block bid represent set of block bids whose clearing are linked to each other. In other words, acceptance of a child block bid depends on the acceptance mother block bid. The child block can then only be accepted if the mother block bid is accepted. This is very useful for sellers having thermal generators with high starting and shutdown cost. Once the initial costs are covered from mother block, then the generator can generate at a lower marginal cost. A typical example of linked block bid is shown in Figure 12. Child-1 (C-1, C-2, and C-3) can only be accepted after parent is accepted and Child-2 (C-11, C-12, and C-13) can only be accepted once Child-1 (C-1) is accepted.
3. *Curtailable block bid*: It is same as regular block bid but can be partially executed as per user-defined parameter called minimum acceptance ratio (MAR). MAR represents the percentage of regular block bid which must be either fully accepted or rejected. Its value lies between [0 to 1] and [0% to 100%]. If MAR of any curtailable block bid is 0.5 (or 50%) then it is accepted only when at least its 50% of total volume is fully cleared at the specified time period otherwise fully rejected. If MAR of any curtailable block bid is 1 (or 100%) then it becomes a regular block bid with all-or-nothing execution condition.

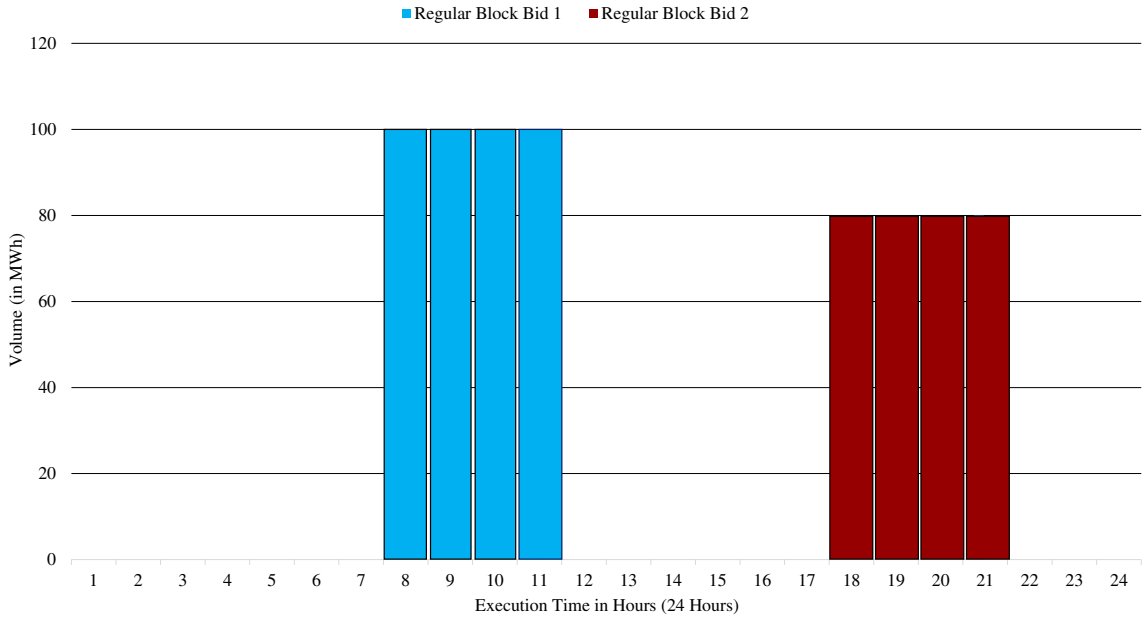
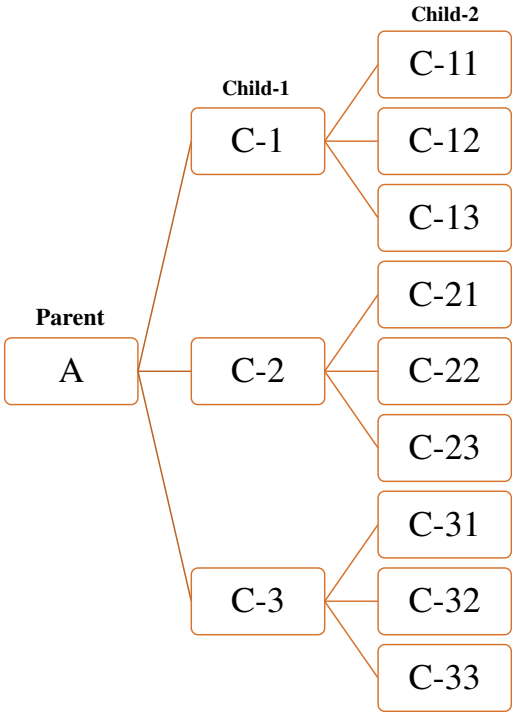


FIGURE 11 Volume execution time diagram of two regular block bids

FIGURE 12 Parent-child arrangement in linked block bids



4. *Profile block bid*: In this type, there is provision for entering same or different volume profile with time during bid submission. However, price would be same across all block period. For market-clearing block bid price is compared with weighted average price instead of average price. Typical representation of two profile block bid with varying quantity is shown in Figure 13. It would facilitate the variable distributed generators to model their bid according to the varying generation profile.
5. *Exclusive block bid*: Exclusive block bid is a member of exclusive group and is similar to simple block bid. Exclusive group is a cluster of large number of simple block bids among which at most one block bid is selected for execution. Execution constraint of Exclusive block bid is same as that of simple multi-period block bid. Only that exclusive block bid is selected which results into maximum social welfare.

4.1.3 | Complex bid

These are simple hourly (or half-hourly or 15 minutes) stepwise supply bids subject to some specified complex execution conditions and are cleared only if those condition get fulfilled otherwise rejected. These are of following types.

1. *Minimum quantity bid*: In this type, traders can set minimum acceptable quantity for clearing their bid. For a bid to be cleared minimum quantity condition must be fulfilled otherwise must be rejected. The balance quantity will be placed in multiple block bid as a subset of the entire bid. The introduction of Minimum Quantity Block Bid would optimize the selection of block bid and thereby minimize the chance of paradoxical rejection.[42]
2. *Minimum income condition (MIC) bid*: It allows market participants to place a bid with a requirement of minimum revenue condition. The bid should be out of the matching process entirely if the MIC is not fulfilled. It is defined with two components: fixed amount ($) and variable amount ($/MWh).
3. *MIC with scheduled stop*: It allows traders to specify scheduled stop condition along with MIC. As, if MIC bid is not selected then it may lead to abrupt shut down of generator. Schedule stop condition (SSC) would prevent the sudden shut down of generator by selecting few initial bids and hence gradually bringing the plant to shut down.
4. *Load gradient bid*: Here trader have to specify maximum gradient limit as some generation technologies cannot cope up with sharp variations of delivered power, it helps in restricting accepted volume in two adjacent periods. A load gradient offer/bid is shown in Figure 14. It has the following advantage: this bid type would benefit the ramping requirements of the power plants and would provide grid stability.

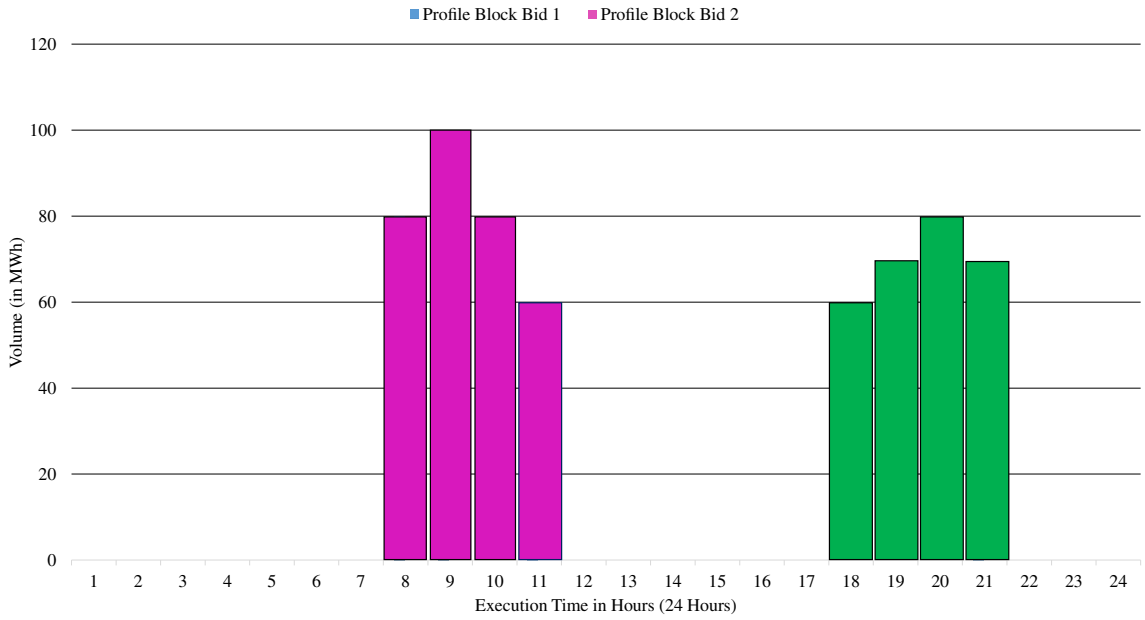


FIGURE 13 Volume execution time diagram of two profile block bids

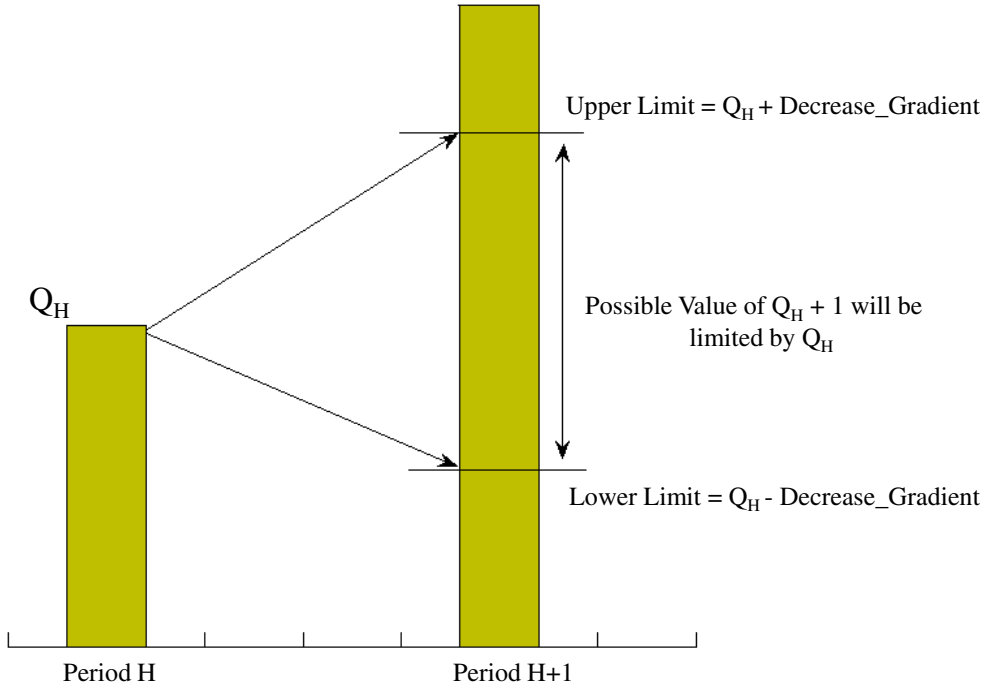


FIGURE 14 A load gradient offer/bid[42]

4.1.4 | Flexi bid

It is simple hourly bids with its execution time not defined. The execution condition is set during market clearing based on social welfare maximization. Typical example of four flexi bids is shown in Figure 15.

4.1.5 | Merit orders

It is a special type of order (or offers/bids) used in Spot market of EPEX.[41] They are individual step orders defined at a given period and is associated with a number called merit order number. A merit order number is a number used for ranking merit orders in different bidding zones containing same order types. It depends on period and order type. The

lower the merit order number, the higher the priority for acceptance. These orders belong only to the Gestore dei Servizi Energetici (GME) or IPEX market and are of following types.

1. *Supply merit orders*: These are sell offers which is cleared at ACP of the respective submarket.
2. *Demand merit orders*: These constitute all buy bids from different pumping units along with all buy bids from non-Italian national zones. These are also cleared at ACP of the respective submarket.
3. *PUN orders*[41]: PUN orders are a particular type of demand merit orders, in which they are cleared at the PUN price (single common price throughout IPEX) rather than ACP of that submarket. The PUN price is defined as the average price of the GME marginal market prices for the Italian bidding areas, weighted by the purchased quantity assigned to PUN orders in each bidding area.

4.2 | Execution conditions

As trader will be not present at the time of their bid execution in DAM, so PX asked sellers and buyers to specify their offer/bid's execution condition.[3] Execution condition specifies the type in which a seller or buyer wish to execute their submitted offer or bid. PX clears all offers/bids according to the specified execution condition. Popular execution conditions are:

4.2.1 | All-or-none

This execution condition implies that if it is possible to fully execute the submitted offer/bid then execute it or otherwise put it in the order book until its full execution or its expiry. For example, let a seller submits an offer of 100 MWh at a price of 50 $/MWh with All-or-None execution condition. Then the PX clearing mechanism can fully clear the offer any time before the expiry of the submitted offer. If it remains unexecuted for the entire validity period, it is fully eliminated from the list.

4.2.2 | Full-or-partial

Here partial execution of offer/bid is possible and the remaining quantity will remain in order book until matched or expired. For example, in 100 MW offer, the PX can clear the offer partially, say 80 MWh, in one time block and remaining, say 20 MWh in other time period.

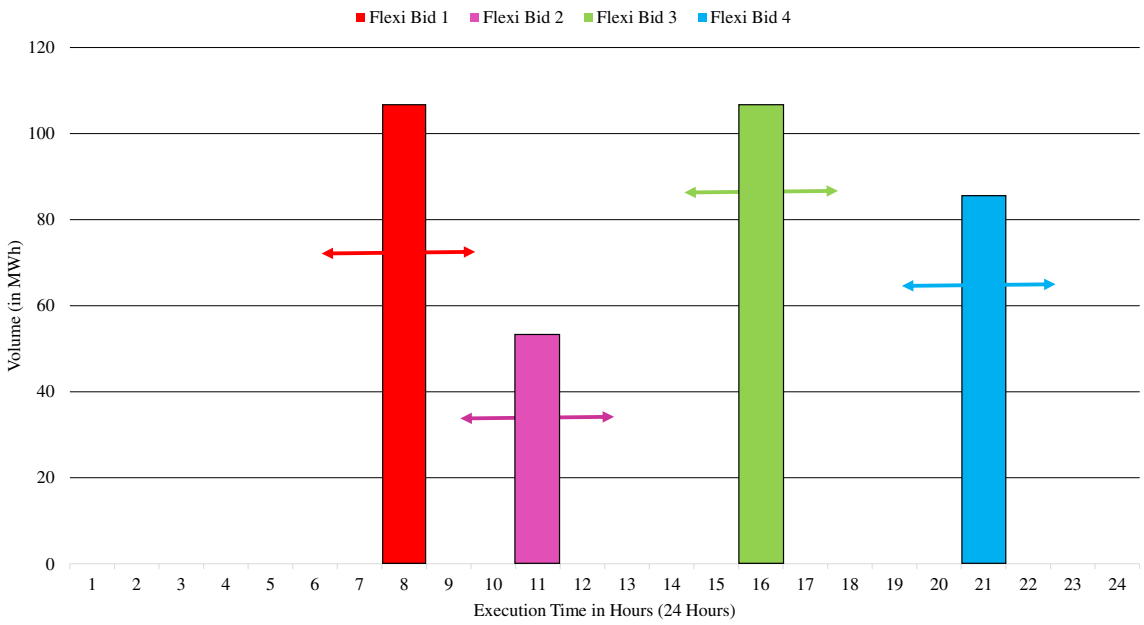


FIGURE 15 Volume execution time diagram of four flexi bids with flexible execution time

4.2.3 | Fill-or-kill

Here the sellers/buyers also specify desirable execution time for executing their offers/bids. The offer/bid is canceled immediately if the total quantity is not accepted at the specified price or better. This can be explained with the following example. Let a seller submit an offer of 100 MW at an offer price of 50 $/MWh with Fill-or-Kill execution condition. Then, the PX can fully clear the offer in a specified time block only otherwise it will be removed from the order book.

4.2.4 | Fill-and-kill

With this execution condition, the offer/bid is fully or partially accepted at the specified price and at specified execution time. Any remaining volume or quantity is discarded and not even placed in order book.

4.2.5 | Fill minimum or kill

This is an advanced execution condition and a hybrid of Fill-or-Kill and Fill-or-Kill. The bid is only cleared if some specified minimum is fully accepted and rest can be partially accepted otherwise fully rejected.

4.2.6 | Minimum income and maximum payment condition

This is another advanced execution condition in which sellers and buyers will specify their minimum income and maximum payment condition respectively with their offers and bids.[20] The MIC refers to the limiting price above which any offer must be cleared otherwise must be rejected and vice-versa for the buyer's bid.

These execution conditions can be graphically plotted in Time Flexibility—Volume Flexibility diagram as shown in Figure 16. Here positive *x*-axis represents time flexibility and negative *x*-axis represents time inflexibility. Similarly, positive *y*-axis represents volume flexibility and negative *y*-axis represents volume inflexibility. The execution condition "Full-or-partial" is shown in first quadrant where there is both time and volume flexibility. It means the offer/bid with "Full-or-Partial" execution condition can be executed anywhere between 1 and 24 hours and can be executed with any volume below its maximum volume limit. Likewise, the execution condition "Fill-And-Kill" is shown in second quadrant where there is time inflexibility and volume flexibility. It means the offer/bid with "Fill-And-Kill" execution condition can be executed at specified hours only with any volume below its maximum volume limit and so on for others.

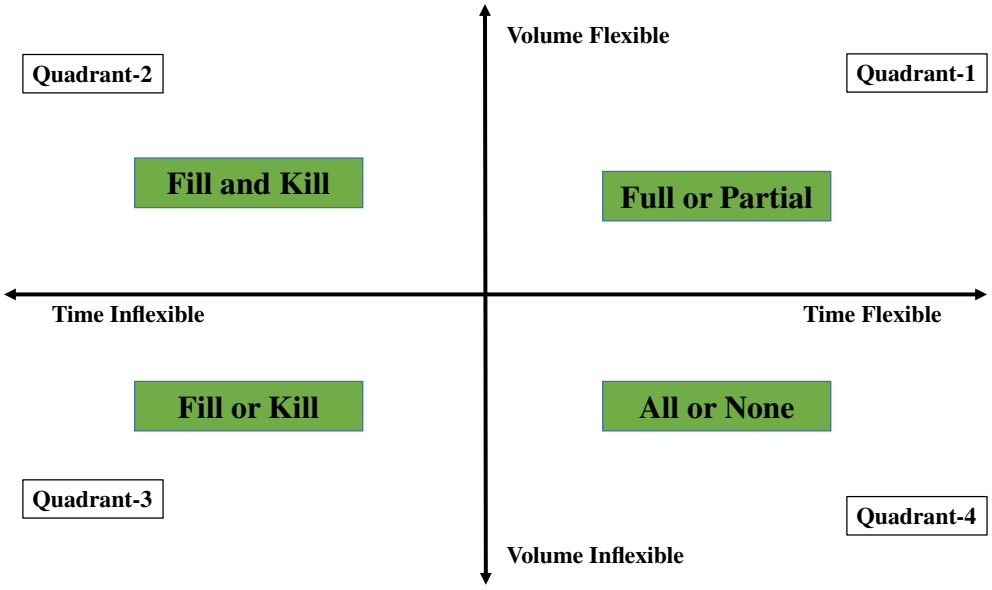


FIGURE 16 Execution condition types on volume-time flexibility plane

4.3 | Market clearing types

It represents the method used by the PX for market clearing in DAM.[3] Two popular methods, that is, step-wise clearing and piece-wise linear clearing are presented next.

4.3.1 | Stepwise clearing

In this type, the market operator first sort all supply offer in increasing order of their offer price and then buy bids in decreasing order of their bid price. Then, stepwise cumulative supply and demand curves were plotted on price-quantity plane using sorted supply offer and buy bids. Market equilibrium is obtained by finding intersection point between these cumulative supply and demand curves. Stepwise market clearing problem considering simple offer/bid only can be formulated as Linear Programming problem as given in References 2 and 43. When considering simple block bid also, it can be formulated as Mixed Integer Linear Programming problem. A typical example of stepwise clearing is shown in Figure 17. Market is cleared at MCP. All offers with offer price less than MCP and bids with bid price more than MCP gets cleared. In stepwise market clearing, there is possibility of getting multiple market equilibrium points. PX generally specifies additional conditions to deals with multiple market equilibrium points. Four different possible cases of intersection between cumulative supply and demand curves in stepwise market clearing is presented in Figure 17. In case-1 and case-2 there exist unique market equilibrium point. But, in case-3, there exist multiple market equilibrium points with more than one eligible MCP. PX have to specify additional set of condition to choose appropriate MCP. Generally, MCP with lowest price is selected. Similarly in case-4 there exist multiple eligible MCV and generally PX chooses MCV having the largest value. The stepwise clearing scheme is implemented in EPEX Spot,[41] IEX,[30] and so on.

4.3.2 | Piecewise linear clearing

Piecewise linear clearing method uses linear interpolation of cumulative supply and demand curve to obtain the market equilibrium point. This market-clearing method always gives unique market equilibrium point. A typical example of piecewise linear market clearing is shown in Figure 17. Market equilibrium point using linear clearing method for all four possible intersection condition is obtained and plotted in Figure 17. Clearly, there exist no multiple market

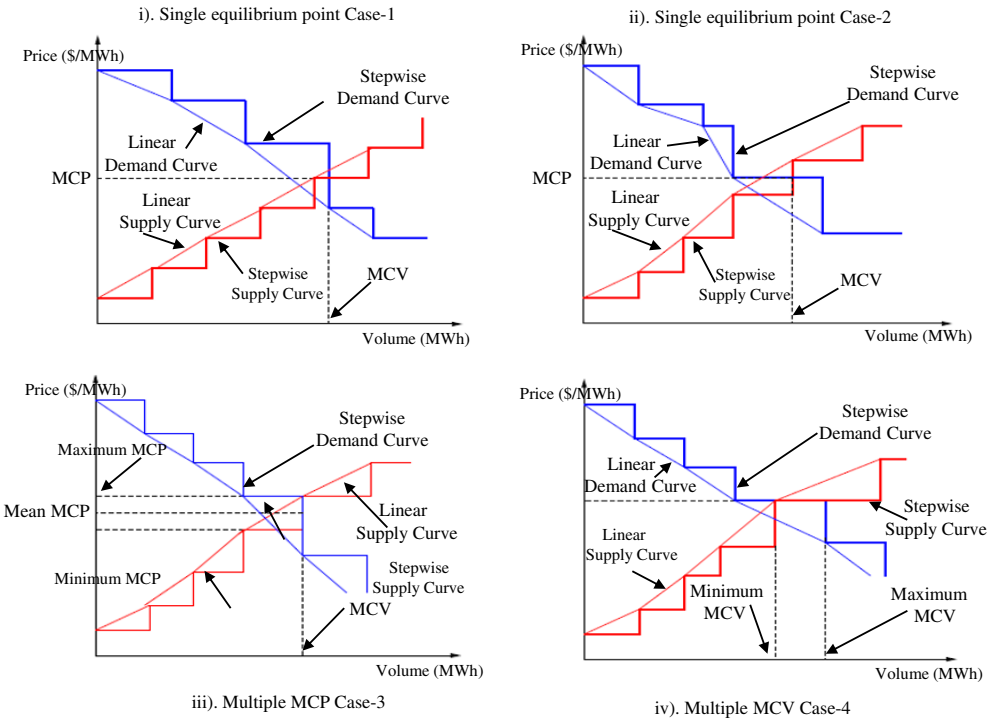


FIGURE 17 Different cases of intersection of cumulative supply and demand curves in stepwise and piecewise linear market clearing[2]

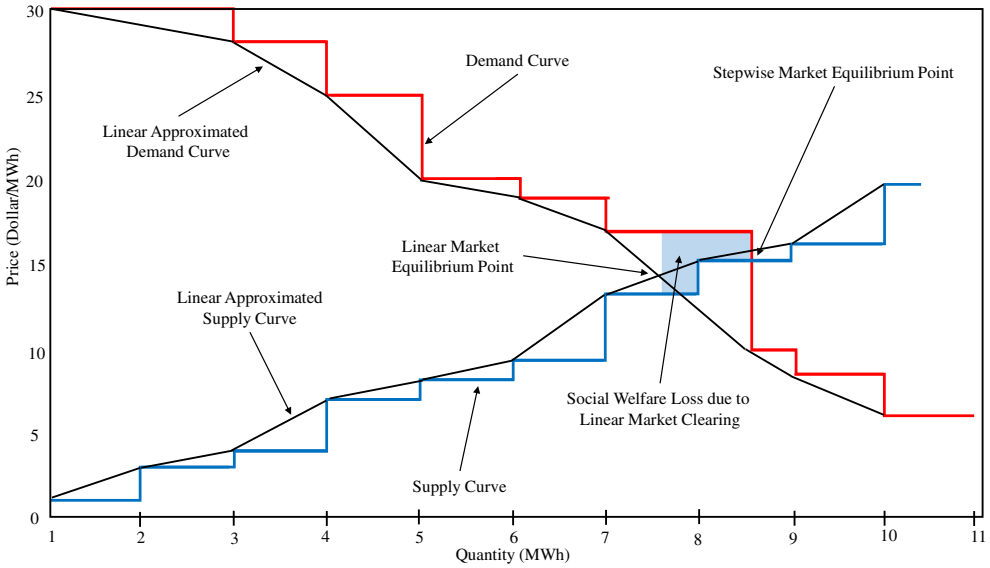


FIGURE 18 Surplus loss in piecewise linear market-clearing method

equilibrium points but there exist certain social welfare loss in all cases. Nord Pool power exchange uses this method for market clearing in DAM.[29] In Reference 44, different intersection cases with piecewise linear clearing results were investigated and compared. Piecewise market-clearing method results in a market equilibrium point which leads to some surplus loss. The study in Reference 44 concludes there exists some surplus (or social welfare) loss when market is cleared using piecewise linear market-clearing method. Social welfare loss due to piecewise linear clearing is demonstrated by shaded region in Figure 18.

4.4 | Transmission congestion management

It is a mechanism to prioritize electric power transactions over transmission grid and determine such dispatch schedule which would not overload the transmission network.[1] Number of congestion management schemes exist in literature which is broadly classified into market-based and nonmarket-based methods. Market-based methods include: auctioning, market splitting, counter trading, rescheduling, load curtailment, nodal pricing and zonal pricing. Nonmarket based methods include: First come first serve and Pro-rata method. Most of the existing PX uses market splitting for relieving congestion in transmission grid. In market splitting, transmission congestion is relieved by splitting the existing market into two or more submarkets. MCP or more precisely ACP for each submarket is determined separately based on intersection between cumulative supply and demand curves of each submarket. ACP in areas or submarkets having surplus offer is decreased as compared to initial MCP and ACP in the submarkets having surplus bid is increased as compared to initial MCP. This price difference in different submarkets reduces electric power transaction over congested corridors and relieve congestion.

4.5 | DAM coupling

DAM coupling is a method to integrate different PX into one coupled market.[45,46] In the coupled market, energy transactions are not restricted to the local territorial scope. Buyers and sellers from different areas may also participate in collective energy transaction. It has the following advantages: increased market liquidity, high transparency, existence of less volatile electricity price across the globe and elimination of acquiring transmission capacity rights to carry out cross border exchanges. Market players have to submit their offers/bids, in their respective PX, which will be matched with other competitive offer/bids in any area involved, having in mind that network constraints are to be respected. Two important DAM coupling techniques include available transfer capacity (ATC) based method and flow-based method. In ATC based technique, different bidding zones were linked by fixed interconnectors and energy flow from one bidding zone to its neighboring zone only through these interconnectors and is limited by ATC of that lines. Flow-based market coupling technique is alternative to ATC based technique in which a more precise modeling of the physical flows is obtained by properly handling network constraints. Constraints are given by the means of remaining available margin (RAM) and power transfer distribution factor.[46] Currently,

market coupling is already established in European Electricity Market by price coupling region (PCR) Project which is initiated in 2009. PCR is a project resulting from the synergy of seven European PX to develop a single price coupling solution to calculate DAM price across Europe. One of the main features of the PCR project is the development of an algorithm, called EUPHEMIA,[45,47] which is used by all PX in order to provide efficient price coupling.

4.6 | AS trade through PX

AS refer to a set of services required to maintain stability and security of power grid. It includes operations like frequency support, voltage support, system restoration, energy balance, and so on. Traditionally it was managed by integrated utility and after restructuring in power sector it went to TSO. Today, there is trend to auction AS through PX. International experience on trading AS through PX reveals that market design options broadly differ based on market clearing and settlement mechanism. Most electricity market from Europe and Australia follow exchange-based trading of AS where PX carried out market operation and system operator handles system operation. Most US market always procure AS in the DAM or in the real-time market. A big advantage of such market is co-optimization of energy and AS market. In the next section, major PX around the world along with their important features are briefly discussed.

5 | MAJOR PX AROUND THE WORLD

Over the last two decades, many PX emerges all over the world. Design and characteristics of these PX varies from country to country. Study of important characteristics and features of these PX is very important. Therefore, this section briefly introduces important features of world's major PX. In this work, following major PX are considered: Nord Pool, EPEX Spot, GME, Pennsylvania-New Jersey-Maryland (PJM), Czech Electricity and Gas Market Operator (OTE), Croatian Power Exchange (CROPEX), Operador Mercado Iberico Energia (OMIE), EXIST, Hungary Power Exchange (HUPX), OPCOM, Borzen Slovenian Power (BSP) South Pool, EXAA, Independent Bulgarian Energy Exchange (IBEX), short-term electricity market operator (OKTE), JEPX, and IEX. Few other PX like Power Exchange India Limited (PXIL), HeNX, EMC, ECORT, and so on are not considered as characteristics and design aspects of these PXs are not much different.

5.1 | Nord Pool

Nord Pool is a pan-European PX which operates in Norway, Denmark Sweden, United Kingdom, Finland, and so on.[29] It is established in 2002 as an independent and licensed physical PX owned by the then four Nordic TSOs. It is considered a standard model for design of PX in many countries. Nord Pool is the world's first multinational PX which allows exchange based power trade to its market participants. It has about 360 trading customers in 20 countries. Nord Pool offers the following PX products to its market participants.

5.1.1 | Day-ahead trading

Here, Nord Pool allows day ahead auction for a range of order types including hourly orders, block orders, curtailable block orders, linked block orders, flexi orders, and exclusive group orders. It also offers access to coupled day-ahead auction in Nordics, Baltics, Central Western Europe, and UK regions. Total traded volume through DAM of Nord Pool in 2018 is 524 TWh.

5.1.2 | Intraday trading

This market segment allows continuous trading of 15-minute, 30-minute, hourly, and block products which provides an added flexibility for its market participants to fulfill their instantaneous trading requirement. The following order types were allowed in Nord Pool's Intraday market: Limit order, user-defined block order, predefined block order, and iceberg order.

Apart from these products, Nord Pool also offers wide ranges of services which simplifies their customer's issues for easy power trading. It offers market data services along with consulting services. Other important features of Nord Pool along with world's major PX were listed in Tables 1–3.

5.2 | EPEX Spot

EPEX Spot operates organized short-term electricity markets for Central Western Europe and Great Britain and is established in 2008 by the merger of spot markets of Powernext and EPEX.[41] In 2015, EPEX Spot integrated its business with former Amsterdam Power Exchange group, which operated the power spot markets in Belgium, Netherlands, and United Kingdom. It has about 270 trading customers in different countries and total traded volume through DAM and IM of EPEX Spot in 2018 is 567 TWh. This PX provides the following market products.

5.2.1 | Day-ahead trading

EPEX Spot offers day-ahead trading in Austria, Belgium, France, Germany, Luxembourg, the Netherlands, Switzerland and Great Britain. Standard hourly, half-hourly and block orders were allowed to trade through double-sided closed auction scheme once a day for each day of a year. Block order types include big block orders, loop block orders, curtailable block orders, linked block orders, and exclusive block orders. Big block order is similar to regular block order with its maximum volume up to 1300 MW and suitable for covering large production capacities. Loop block order is a families of two block order which are executed or rejected together. They allow to bundle buy and sell blocks to reflect storage activities. Total traded volume through DAM and IM of EPEX Spot in 2018 is 485 TWh.

5.2.2 | Intraday trading

Intraday trading market of EPEX Spot offers both continuous and auction trading of various power contracts. Intraday continuous allows continuous trade of hourly, half-hourly and 15 minutes contracts. These contracts were executed as soon as the two entered orders match in Intraday Continuous Trading platform. EPEX Spot also operates one 15 minutes intraday auction for German market, two 30 minutes intraday auction for Great Britain market and one 60 minutes intraday auction for Switzerland market. Total traded volume through IM of EPEX Spot in 2018 is 82 TWh.

Apart from these two PX products, EPEX Spot also provide French Capacity Market, Physical Fulfilment Services and Local Flex Trading. Other important features of this PX were listed in Tables 1–3.

5.3 | Gestore Mercati Energetici[48]

It simultaneously operates electricity, gas, and environment market in Italy. It is established on 2000 and its electricity market is also known as IPEX. Power trade through IPEX is divided into Spot Electricity Market and Forward Electricity Market. Spot Electricity Market allows following PX products.

5.3.1 | Day-ahead market

It allows trading of hourly power contracts for next day using double-sided closed auction scheme. Total traded volume through DAM of IPEX in 2018 is 296 TWh.

5.3.2 | Intraday market

In this platform, traders can modify their respective schedules submitted in DAM by submitting additional supply offers or demand bids. It takes place in seven sessions.

TABLE 1 Details of major power exchanges around the world[29,30,40,41,48-60]

Power exchange parameters	Nord Pool	EPEX Spot	GME	PJM	OTE	CROPEX	OMIE	EXIST
Involved countries	Denmark, Germany, Finland, Latvia, Lithuania, Norway, Sweden, UK	Austria, Germany, Belgium, Luxembourg, UK, France, Netherlands Switzerland	France, Austria, Italy, Greece, Slovenia, Malta, Switzerland	United States of America	Czech Republic	Croatia	Spain, Portugal	Turkey
Headquarter	Lysakar, Norway	Paris, France	Rome, Italy	Audubon, USA	Prague, Czech Republic	Zagreb, Croatia	Madrid, Spain	İstanbul, Turkey
Date of foundation	2002	2008	2000	2002	2001	2014	1997	2015
CEO	K. E. Thørud	R. Danielski	P. M Putti	A. L. Ott	A. Tomec	S. Brkić	A. Trindade	A. Türkoğlu
Traded volumes in 2018	524 TWh	567 TWh	325.3 TWh	—	22.89 TWh	2.38 TWh	276 TWh	152.32 TWh
PX websites	nordpoolgroup.com	epexspot.com	mercatoelettrico.org	pjm.com/	ote.cz	cropex.hr	omie.es	epias.com
Shortest trade unit	1 hour	1 hour and 1/2 hours in Great Britain	1 hour	1/12 hours	1 hour	1 hour	1 hour	1 hour
Currency	NOK, SEK, EUR, GBP	EUR	EUR	USD	CZK	EUR	EUR	Turkish Lira
Participation	Voluntary	Voluntary	Except ancillary services all voluntary	Compulsory for DAM	Voluntary	Voluntary	Voluntary	Voluntary
Participants in 2018	360	289	269	—	113	20	700	747
Market offering	Day-ahead trading and intraday trading	Day-ahead, intraday, French capacity, physical fulfillment services, and local flex trading	Day-ahead, intraday, daily products, environment market and ancillary services market	Day-ahead spot, real-time balancing, capacity credits market	Day-ahead, intraday, block and balancing market	Day-ahead market and intraday market	Day-ahead market and intraday market	Day-ahead market, intraday market, balancing power market, and ancillary service market
Bidding type	Double-sided	Double-sided	Double-sided	Double-sided	Double-sided	Double-sided	Double-sided	Double-sided
Adjustment market	Intraday trading	Intraday trading	Daily products and forward	Bid-quantity can be changed till gate closure	Intraday market	Intraday market	Intraday market	Intraday market
Real time/balancing market	Intraday continuous trading	Intraday continuous	Daily products market	Deviations are traded in real-time	Balancing market segment	Intraday market	Intraday market	Balancing power market
Pricing rule	Zonal pricing	Zonal pricing	Zonal pricing	Nodal pricing	Zonal pricing	Zonal pricing	Zonal pricing	Zonal pricing
Pricing type	Ex-ante	Ex-ante	Ex-ante	Ex-post	Ex-ante	Ex-ante	Ex-ante	Ex-ante
Risk management	Forward, future, option	—	—	Bilateral OTC, virtual bidding,	Financial security	Bank guarantee	Payment guarantee	Bank guarantee
Congestion management	Market splitting	Market splitting	Market splitting	Security constrained economic dispatch	Market splitting	Market splitting	Market splitting	Market SPLITTING
Transmission losses	Included in zonal price	Included in zonal price	Included in zonal price	Included in LMP	Included in zonal price	Included in zonal price	Included in zonal price	Included in zonal price

Power exchange	HUPX	OPCOM	BSP South Pool	EXAA	IBEX	OKTE	JEPX	IEX
Involved countries	Hungary	Romania	Austria, Italy, Slovenia	Austria, Germany	Bulgaria	Slovak Republic	Japan	India

(Continues)

TABLE 1 (Continued)

Power exchange	HUPX	OPCOM	BSP South Pool	EXAA	IBEX	OKTE	JEPX	IEX
Headquarter	Budapest, Hungary	Bucharest, Romania	Ljubljana, Slovenia	Vienna, Austria	Sofia, Bulgaria	Bratislava, Slovakia	Tokyo, Japan	New Delhi, India
Date of foundation	2007	2000	2008	2001	2014	2011	2003	2008
CEO	P. Tóth	V. Ionescu	K. P. Persolja	J. Wahl	K. Konstantinov	M. Cabala	T. Murakami	R. Srivastava
Traded volumes in 2018	19.91 TWh	22.70 TWh	7.47 TWh	7.9 TWh	6.05 TWh	13.50 TWh	208.64 TWh	51.37 TWh
PX websites	hupx.hu	opcom.ro	borzen.si	exaa.at	ibex.bg	okte.sk	jepx.org/english/	iexindia.com/
Shortest trade unit	1 hour	1 hour	1/4 hours	1/4 hours	1 hour	1 hour	1/2 hours	1/4 hours
Currency	EUR	EUR, RON	EUR	EUR	BGN	EUR	JPY	INR
Participation	Voluntary	Voluntary	Voluntary	Voluntary	Voluntary	Voluntary	Voluntary	Voluntary
Participants in 2018	58	374	—	73	72	—	—	6238
Market offering	Day-ahead market and intraday market	Day-ahead, intraday, universal service, and green certificates market	Day-ahead market, intraday market, balancing, and long term auction	Spot market and green power market	Day ahead, intraday, and centralized market bilateral contract	Day-ahead-market and imbalance market	Day-ahead market and forward market	Day-ahead market, term-ahead market, REC, ESC and G-TAM (proposed)
Bidding type	Double-sided	Double-sided	Double-sided	Double-sided	Double-sided	Double-sided	Double-sided	Double-sided
Adjustment market	Intraday market	Intraday market	Intraday market	—	Intraday market	—	—	Term-ahead market
Real-time/balancing market	Intraday market	—	Balancing market	—	Bilateral market	Imbalance market	—	Deviations are subjected to UI changes
Pricing rule	Zonal pricing	Zonal pricing	Zonal pricing	Zonal pricing	Zonal pricing	Zonal pricing	Zonal pricing	Zonal pricing
Pricing type	Ex-ante	Ex-ante	Ex-ante	Ex-ante	Ex-ante	Ex-ante	Ex-ante	Ex-ante
Risk management	—	Bank guarantee	Financial guarantees	—	Bank guarantee	Bank guarantee	Bank guarantee	Bank GUARANTEE
Congestion management	Market splitting	Market splitting	Market splitting	Market splitting	Market splitting	Area splitting	Market splitting	Market splitting
Transmission losses	Included in zonal price	Included in zonal price	Included in zonal price	Included in zonal price	Included in zonal price	Included in zonal price	Included in zonal price	To be purchased by participants

TABLE 2 PX products offered in major power exchanges around world[29,30,40,41,48-60]

PX Products	DAM	IM	REC	ESC	Additional exchange specific product
Nord Pool	Yes	Yes	No	No	Data along with consulting services
EPEX Spot	Yes	Yes	No	No	French capacity, physical fulfillment services, and local flex
GME	Yes	Yes	No	Yes	Forward, derivatives, and ancillary services market
PJM	Yes	Yes	No	No	Real-time balancing and capacity market
OTE	Yes	Yes	No	No	Block market and balancing market
CROPEX	Yes	Yes	No	No	—
OMIE	Yes	Yes	No	No	—
EXIST	Yes	Yes	No	No	Balancing power market and ancillary service market
HUPX	Yes	Yes	No	No	—
OPCOM	Yes	Yes	Yes	No	Universal service market and green certificates market
BSP South Pool	Yes	Yes	No	No	Long term auction
EXAA	Yes	No	No	No	Green power market
IBEX	Yes	Yes	No	No	Centralized market for bilateral contract
OKTE	Yes	No	No	No	Imbalance market
JEPX	Yes	No	No	No	Forward market
IEX	Yes	Yes	Yes	Yes	Green term-ahead market proposed

5.3.3 | Daily products market

It allows continuous trade of daily products with two clearing conditions namely "unit price differential" and "full unit price". In the first case price determined after trading phase is equal to differential price compared to PUN price (common exchange price) while in second case price determined after trading phase is equal to a unit value of price in electricity exchange.

5.3.4 | AS market

It is a trading platform which provides market platform for trading of all AS. Pay-as-bid method is used for clearing all submitted offers/bids for providing AS.

In forward electricity market, power traders were allowed to trade forward electricity contracts with certain delivery and withdrawal obligation. Apart from these products, GME also provide environmental market in which it is possible to form various market participants to sell or buy energy efficiency certificates. Other important features of this PX were listed in Tables 1–3.

5.4 | Pennsylvania-New Jersey-Maryland Interconnection[49]

It is a regional transmission organization and part of the Eastern Interconnection grid in the United States. It started short-term power trading from the year 2000.[18] It operates day-ahead, real-time, regulation, and monthly financial transmission rights auction market.[6] Other important features of this PX were listed in Tables 1–3.

5.5 | Czech electricity and gas market operator

It jointly operates short-term electricity and gas market in Czech Republic.[50] It is established in 2001. It starts day-ahead electricity market in 2002 and intra-day and block markets were added in later years. Till December 31, 2018, total

TABLE 3 PX offer/bid types in International Power Exchanges[29,30,40,41,48-60]

Bid Types	Single Bid	Regular Block Bid	Linked Block Bid	Profile Block Bid	Curtailable block Bid	Flexi Bid	Minimum Quantity Bid	MIC Bid	MIC with Scheduled Stop	Load Gradient Bid	Merit Bid	PUN Bid
Nord Pool	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No	No	No
EPEX Spot	Yes	Yes	Yes	Yes	Yes	No	No	Yes	Yes	Yes	Yes	Yes
GME	Yes	Yes	No	Yes	No	No	No	No	No	No	Yes	Yes
PJM	Yes	Yes	Yes	No	No	No	No	No	No	No	No	No
OTE	Yes	Yes	No	No	No	No	No	No	No	No	No	No
CROPEX	Yes	Yes	No	No	No	No	No	No	No	No	No	No
OMIE	Yes	Yes	No	No	No	No	No	Yes	Yes	Yes	No	No
EXIST	Yes	Yes	Yes	No	No	Yes	Yes	No	No	No	No	No
HUPX	Yes	Yes	No	No	No	No	No	No	No	No	No	No
OPCOM	Yes	Yes	Yes	No	No	No	No	No	No	No	No	No
BSP South Pool	Yes	Yes	Yes	No	No	No	No	No	No	No	No	No
EXAA	Yes	Yes	Yes	No	No	No	No	No	No	No	No	No
IBEX	Yes	Yes	No	No	No	No	No	No	No	No	No	No
OKTE	Yes	Yes	Yes	No	No	No	No	No	No	No	No	No
JEPX	Yes	Yes	No	No	No	No	No	No	No	No	No	No
IEX	Yes	Yes	Yes	Prop*	No	Prop*	Prop*	Prop*	Prop*	Prop*	No	No

Abbreviation: Prop*, Proposed.

number of registered market participants in short-term electricity and gas market is 113 and 97, respectively. Its electricity market provides the following market products.

5.5.1 | Block market

It allows continuous trade of standard block products on specific trading days, namely, Base type (00:00-24:00), Peak type (8:00-20:00) and Off-peak type (0:00-8:00 and 20:00-24:00).

5.5.2 | Day-ahead market

The DAM allows trading of hourly products before 24-hour of next trading day through closed double-sided auction. Total traded volume through DAM of OTE in 2018 is 22.89 TWh.

5.5.3 | Intraday market

IM allows market players to sell or buy continuous hourly power products. It allows trading before 60 minutes from the time of delivery or consumption.

5.5.4 | Balancing market

Balancing market allows market participants to sell or buy excess positive or negative hourly products whose delivery time could be very close to trading period that is, 30 minutes before power delivery. Other important features of this PX were listed in Tables 1–3.

5.6 | Croatian power exchange

It provide an online platform for short-term power trading in Croatia.[51] It acts as central counterparty between sellers and buyers and takes the risks of buying and selling electricity for all trades concluded on this trading platform. It is equally owned by Croatian Energy Market Operator Limited and Croatian Transmission System Operator Limited. It is established in 2014. It provides the following market products.

5.6.1 | Day-ahead market

DAM allows trading of standard hourly and block products for 24 hours of next day through double-sided closed auction. The total traded volume through DAM of CROPEX in 2018 is 2.38 TWh.

5.6.2 | Intraday market

It allows continuous trade of hourly, block and Iceberg orders. Other important features of this PX were listed in Tables 1–3.

5.7 | Operador Mercado Iberico Energia

It provides trading platform for short-term electric power trading in the Iberian Peninsula.[52] OMIE currently manages DAM and IM in Spain and Portugal. It is established in 1997. It offers the following market products.

5.7.1 | Day-ahead market

It allows trading of hourly products for next 24 hours of a day. Apart from volume and price, exchange also asked traders to specify the following characteristics of supply offer and buy bids: indivisibility condition, maximum allowed load gradient, minimum income, and scheduled stop Condition. The total traded volume through DAM of OMIE in 2018 is 276 TWh.

5.7.2 | Intraday market

It serves as a platform for its market participants to adjust their power schedules in real-time and currently structured in six auction sessions in the Iberian Electricity Market (MIBEL) field and a continuous European cross-border market. Other important features of this PX were listed in Tables 1–3.

5.8 | Energy Exchange Istanbul

After liberalization of electric sector in Turkey, Turkish Electricity Transmission Company (TEIAS) separated into two companies EXIST and TEIAS.[53] EXIST starts operating the electricity market while TEIAS is responsible for operating national grid. Currently, it jointly operates the electricity and natural gas market in Turkey. In the electricity market, it offers the following market products.

5.8.1 | Day-ahead market

DAM allows trading of hourly products for next day. Market participants can submit their offers from next day to 5 days later. Before market clearing, a collaterals check is performed in order to eliminate ineligible market offers in DAM. Total traded volume through DAM of EXIST in 2018 is 152.32 TWh.

5.8.2 | Intraday market

IM allows trading of power on hourly basis and allows trading 60 minutes before physical delivery of electrical power. Hourly and block products were allowed in IM with number of exchange specific execution conditions.

5.8.3 | Balancing power market

It provides the energy exchange market operator with redundant capacity for up to 15 minutes of real-time balancing. Apart from these products, EXIST also provide market platform for AS trade. Other important features of this PX were listed in Tables 1–3.

5.9 | Hungarian power exchange

As a part of liberalization of Hungarian electric sector, HUPX starts day-ahead power market in July 2010.[54] Currently, HUPX provides an online market platform for short-term power trade in Hungary. It offers the following market products.

5.9.1 | Day-ahead market

The DAM allows daily auction of hourly and standard block products for 365 days of year. It allows three predefined block order including block cord covering hour 1 to 24, block valley covering hours 1 to 8 and 21 to 24 and array peak

covering 9 to 20 hours. In addition to these predefined block order, arbitrary block offers consisting of continuous and discrete hours are also traded. Total traded volume through DAM of HUPX in 2018 is 19.91 TWh.

5.9.2 | Intraday market

IM allows continuous trade of number of exchange specific order types. It allows trading of following order types: local quarter product, local clock product, XBID clock product, local OTC clock product, and local OTC user-defined block product.

Apart from these PX products, HUPX also provides physical settlement of future trade in which weekly, monthly, quarterly, yearly base-load and peak-load contracts were traded between its market participants. Other important features of this PX were listed in Tables 1–3.

5.10 | Power market commercial operator

After liberalization of electricity market in Romania, Power Market Commercial Operator (OPCOM) was set up to manage the DAM.[55] It is established in 2000. Currently, it offers the following market products.

5.10.1 | Day-ahead market

DAM allows trading of standard hourly and block products for power delivery in the next day. Block products include both standard and linked block orders. The total traded volume through DAM of OPCOM in 2018 is 22.70 TWh.

5.10.2 | Intraday market

IM allows continuous trading of hourly products along with following order types: correlated offers, iceberg orders, and user-defined orders. It provides an additional flexibility for its market participants required for fulfilling their market requirements.

5.10.3 | Universal service market

It provides market platform for trading of power products having delivering period of 1 year, 6 months, 3 months, and 1 month.

5.10.4 | Green certificates market

It also provides market for green certificates trading. Other important features of this PX were listed in Tables 1–3.

5.11 | BSP South Pool

BSP South Pool is a daughter company of Borzen, a government-owned company which provides and facilitate coordinated operation of the Slovenian Electricity System.[56] Currently, BSP South Pool provides market platform for short-term power trade in Slovenia. It operates DAM, intra-day market and long-term auctions while Borzen deals with real-time balancing market. In 2018, volume traded through BSP South Pool was approximately 60% of total Slovenian yearly power consumption. A brief review of PX products allowed through BSP South Pool is as follows.

5.11.1 | Day-ahead market

It allows trading of standardized hourly sell offers and bids. Price ranges of hourly offer\bids were constrained in the following ranges (−558.74 $/MWh to 3352.41 $/MWh). Total traded volume through DAM of BSP South Pool in 2018 is 7.5 TWh.

5.11.2 | Intraday market

It is further divided into intraday continuous an intraday auction. Intraday continuous allows continuous trading of predefined and user-defined products which are matched on the basis of the price/time priority criterion. Predefined products include Base (00:00-24:00), Peak (08:00-20:00), Hourly product, and 15 min product. Intraday auction allows trading of two hourly contracts, that is, MI2 (H1-H24) and MI6 (H17-H24) through online auction scheme.

5.11.3 | Long term auctions

Long term auction trading is also allowed in BSP south pool. Other important features of this PX were listed in Tables 1–3.

5.12 | Energy Exchange Austria

It provides a platform for Spot Electricity and Environmental market in Austria.[57] It is established in 2001 and opened its Spot Market on 21st March 2002. Since then, EXAA has grown significantly for exploiting trading possibilities after the liberalization of energy market in Central Europe. A brief review of Spot Market and Green Power Market traded through EXAA is as follows.

5.12.1 | Spot market

It allows trading of hourly, quarter-hourly and standard block products for 24 hours of the next day. All 24 hours and 96 quarter hours of a day are defined as individual trading products which enables its market participants to fulfill their market requirements in best possible manner. Total traded volume through Spot Market of EXAA in 2018 is 7.9 TWh.

5.12.2 | Green power market

EXAA offers Green power market to its market participants. It is also considered as first EPEX which allowed power trading which is exclusively generated from renewable water and wind energy resources.

EXAA also offers teem which is a training course for gas and power markets. Experts from different areas related to energy markets, energy law, energy technology, and so on come and shares their valuable ideas on a single platform. Other important features of this PX were listed in Tables 1–3.

5.13 | Independent Bulgarian Energy Exchange

It was established in 2014, as a fully-owned subsidiary of the Bulgarian Energy Holding and holds a 10-year license to organize a PX for electricity trade in Bulgaria.[58] Currently, it offers the following market products to its participants.

5.13.1 | Day-ahead market

IBEX started its DAM on January 19, 2016, with its trading platform provided by Nord Pool. Here, market participants were allowed to trade standard hourly products and the total traded volume through DAM of IBEX in 2018 is 6.05 TWh.

5.13.2 | Intraday market

IBEX started its IM on April 11, 2018, with its trading platform provided by Nord Pool. Here, continuous trading of hourly, peak (09.00-20.00) and base (00.00-24.00) products were traded.

5.13.3 | Centralized market bilateral contract

It also provides a centralized market for bilateral products which provides all market participants to trade products having varying delivery periods in a transparent and nondiscriminatory manner. Other important features of this PX were listed in Tables 1–3.

5.14 | Short-term electricity market operator

Currently, it manages short-term electricity market in Slovak Republic.[59] OKTE was established in 2011 and authorized to act as a OKTE in the Slovak Republic. It organizes and evaluates short-term electricity market and provides clearing of imbalances to its participants. It offers the following market segments.

5.14.1 | Short-term electricity market

This segment of OKTE is responsible for organizing short-term electricity market including market participants' registration, orders submission, order matching, and deal settlements. The total traded volume traded through short-term market of OKTE in 2018 is 13.50 TWh.

5.14.2 | Imbalance settlements

This segment of OKTE is responsible for clearing and settlement of imbalances based on data provided by electricity market participants.

Furthermore, OKTE is currently in the process of extending the scope of its activities, especially related to the renewable energy support scheme and trading of guarantees of origin. Other important features of this PX were listed in Tables 1–3.

5.15 | Japan Electric Power Exchange

It provides a single platform for short-term power trading in Japan.[40] It is established in the year 2005 as a part of electric sector liberalization process Japan. Currently, it offers the following market products to its market participants.

5.15.1 | Spot market

Spot market allows trading of half-hourly power products for next day. A total of 48 products are traded every 30 minutes in 24 hours of a day. The total traded volume through spot market of JEPX in 2018 is 208.64 TWh.

5.15.2 | Forward market

In the forward market, participants freely post matters related to electricity trading. Other important features of this PX were listed in Tables 1–3.

5.16 | Indian Energy Exchange

It is the first Indian Power Exchange established in 2008 under the guidance of Central Electricity Regulatory Commission (CERC).[30] IEX along with PXIL[60] operates short-term electricity market in India. IEX offers the following PX products.

5.16.1 | Day-ahead market

It allows trading of quarter-hourly and block products for next 24 hours of a day. The block products can be either regular linked or both. The total traded volume through DAM of IEX in 2018 is 51.37 TWh.

5.16.2 | Term-ahead market

It allows continuous trade of a ranges of products including intraday, day-ahead contingency, daily and weekly. Intraday products allows continuous trading of 20 hourly contracts for the same day. Day-Ahead Contingency allows continuous trading of 24 hourly contracts for the following day. Daily product allows continuous trading of all or block of hours in a single day. Weekly products allow trading through double-sided open auction of all or block of hours in a week.

5.16.3 | Renewable energy certificates

Industries and big consumers obligated with renewable purchase obligation and suppliers having renewable generations can trade their REC through this platform. Online double-sided closed auction scheme is used for REC trading in IEX.

5.16.4 | Energy-saving certificates

Here, market participants were allowed to trade ESC through double- sided closed auction scheme and organization having energy saving obligation can either sell or purchase required number of ESC.

Apart from these products, IEX also filed petition in CERC for allowing to start renewable term-ahead market. Both power from renewable resource and green attributes will be sold together and power sellers will be able to realize better their value. Other important features of this PX were listed in Tables 1–3.

6 | COMPARATIVE ANALYSIS OF DAM OF WORLD'S MAJOR PX

This section presents a comparative analysis of important features of world's major EPXs with a special focus on their DAM segment. Table 1 captures important characteristics and parameter of major EPXs around the world. Apart from basic information, Table 1 compares world's major PX in terms of allowed participation mode, market offering, bidding type, offered adjustment market, balancing market, adopted pricing rule, adopted pricing type, risk management technique, congestion management and transmission losses handling method. Further, different PX products offered in major PX around the world are listed in Table 2. From Table 2, it is evident that DAM is the most common type of PX offered in any PX offering market platform for trading hourly and block products. IM is also very common among PX which allows traders for continuous market adjustment. Apart from IEX, EXIST also allows trading of REC. IEX and IPEX also provide market platform for trading of ESC. In IPEX, ESC is called Energy Efficiency Certificates instead of ESCs. Offer/bid types allowed in DAM of world's major PX is presented in Table 3. From Table 3, it is evident that Nord Pool and EPEX Spot allows trading of most numbers of offers/bids types. Although, currently IEX does not allow trading most of complex offers/bids types, but it had already proposed through Petition No 218RC2018 in CERC (dated July 17, 2018) to allow trading of most complex bid types.[30]

MCP in DAM of any PX is very important as it forms the basis of market prices for all power trade in both DAM and IM. Yearly average MCP in DAM of major power exchanges around the world are obtained from their respective websites[29,30,40,41,48-60] and plotted in Figure 19. Major PX considered includes Nord Pool, EPEX Spot, GME, PJM, OTE, OMIE, EXIST, HUPX, OPCOM, BSP South Pool, EXAA, IBEX, OKTE, JEPX, and IEX. From Figure 19, it is evident that yearly average MCP of Nord Pool for 2015 is 23.08 $/MWh which increases to 29.60 and 32.35 $/MWh in 2016 and 2017, respectively. In 2018, there exist a sharp increase in MCP from 32.35 to 48.30 $/MWh which is about 49.58% increase from 2017. In EPEX Spot, yearly average MCP decreases from 40.42 $/MWh in 2015 to 40.41 $/MWh in 2016. It eventually increases to 49.48 $/MWh in 2017 and 55.21 $/MWh in 2018, respectively. Yearly average MCP in 2018 for EPEX Spot is 14.09% higher as compared to Nord Pool. From Figure 19, it is clear that for most PX yearly average MCP decreases from 2015 to 2016 including EPEX Spot, GME, PJM, OTE, HUPX, OPCOM, BSP South Pool, EXAA, JEPX, and IEX. For HUPX, OPCOM, BSP South Pool, IBEX, and JEPX, yearly average MCP for 2017 and 2018 almost remains unchanged. Very sharp increase in average yearly MCP is observed from 2017 to 2018 in EXAA and IEX. In EXAA, it rose from 37.92 to 50.92 $/MWh whereas in IEX yearly average MCP rose from 42.28 to 55.10 $/MWh from 2017 to 2018, respectively. JEPX shows the highest average yearly MCP among all EPXs around the world. After JEPX, GME has the second highest average yearly MCP of 68.20 $/MWh in 2018. In 2015, average yearly MCP for JEPX is 90.86 $/MWh and in 2018 it remains at 90.76 $/MWh. In IEX, average yearly MCP is 39.48 $/MWh in 2015 which reduces to 33.61 $/MWh in 2016. It eventually increases to 42.28 $/MWh in 2017 and it further increases to 55.10 $/MWh in 2018. Price differences in these EPXs could be due to different competition and different market designs as evident from Table 1.

Furthermore, to get a significant idea about recent price behavior in DAM of world's major PX, average monthly MCP from January 2018 to July 2019 are obtained from their respective websites[29,30,40,41,48-60] and plotted in Figure 20. From Figure 20, it is evident that monthly average MCP in DAM for major PX around the world mostly varies between 25 to 80 $/MWh with an exception of JPEX where average monthly MCP is as high as 136 $/MWh. EXIST has lowest average monthly MCP for almost all months as compared to other PX. Average monthly MCP for JPEX is highest as compared to all PX for all months. A unique observation in average monthly MCP for all PX in 2018 and 2019 is that in 2018 there exist a gradual increase in average monthly MCP from January 2018 to December 2018 while it shows gradual decrease from January 2019 to June 2019. On the other side, monthly average MCP in JPEX shows gradual decrease from January 2018 to July 2019 with a little exception in July and August 2018. Average monthly MCP for other PX are more or less same with little variation as compared to other PX. Moreover, to get a significant idea regarding recent hourly MCP in DAM of world's major PX, hourly MCP for October 2, 2019, are obtained from their respective websites[29,30,40,41,48-60] and plotted in Figure 21. Seven major PX, in terms of traded volume, were considered including

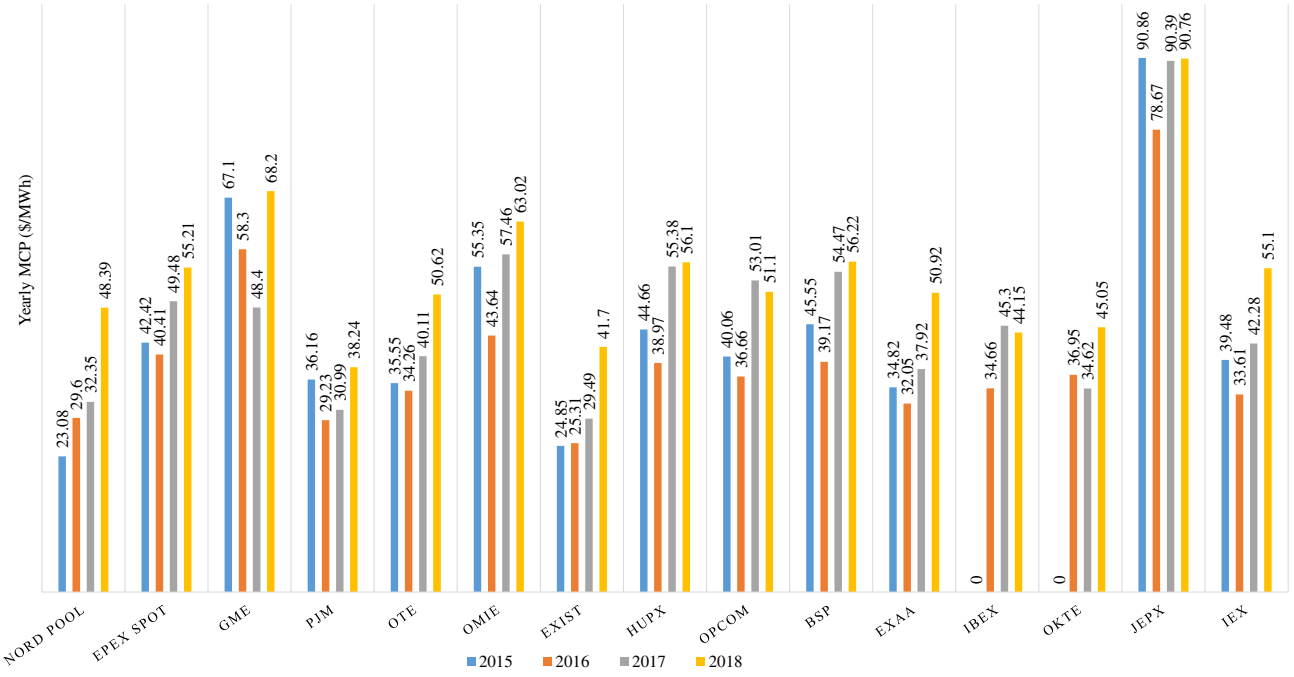


FIGURE 19 Yearly average MCP (in $/MWh) in DAM of major PX around the world[29,30,40,41,48-60]

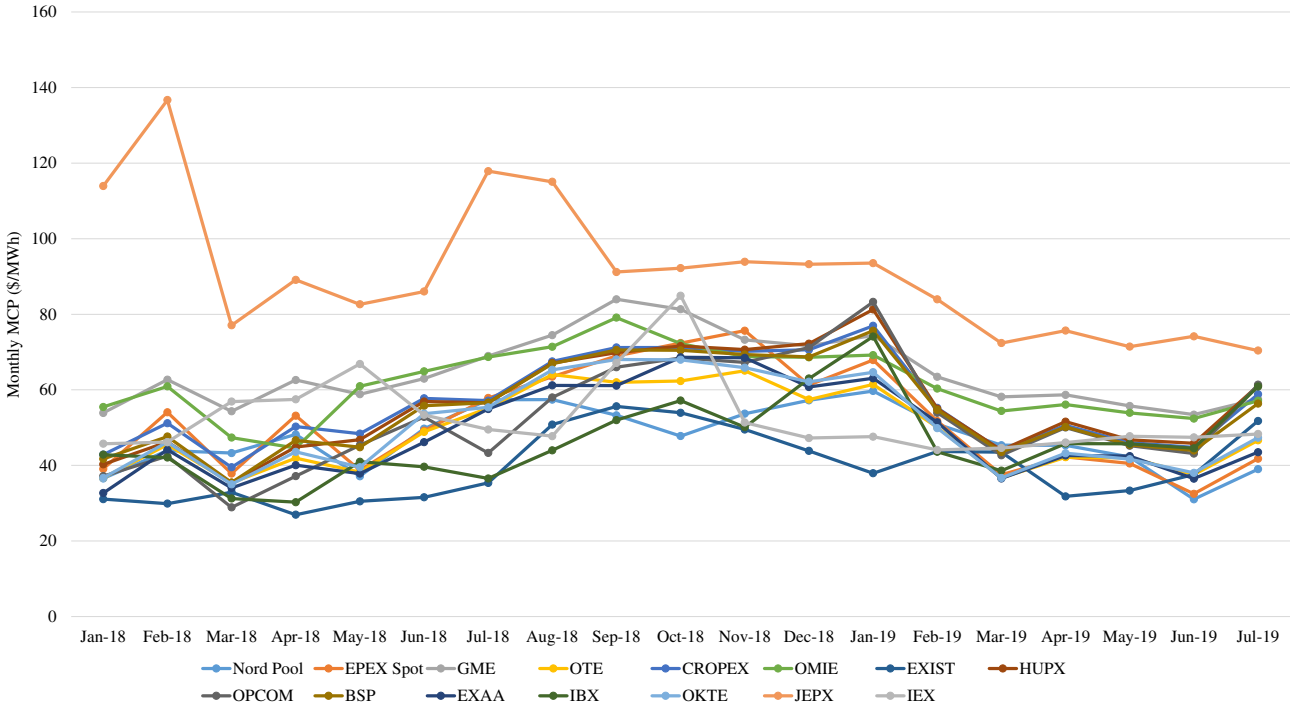


FIGURE 20 Monthly average MCP (in $/MWh) in DAM of major PX around the world (for the last 19 months)[29,30,40,41,48-60]

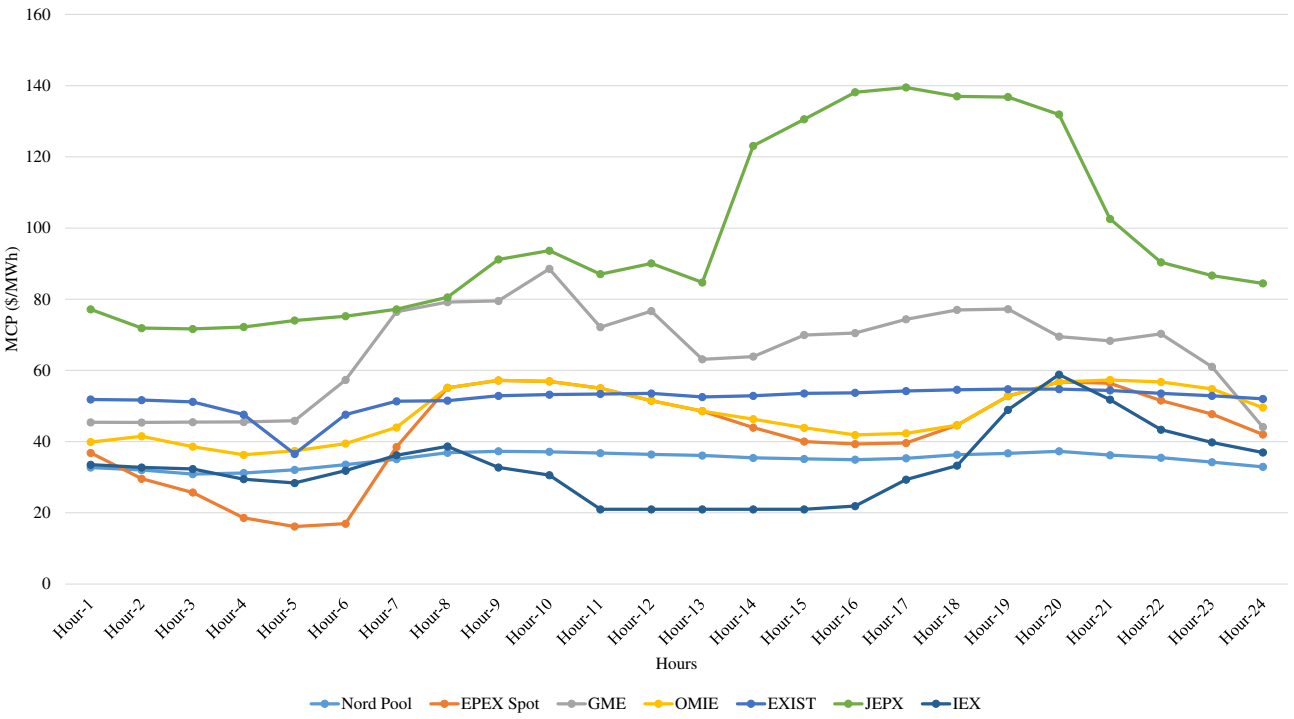


FIGURE 21 Hourly market clearing price in DAM of major PX around the world[29,30,40,41,48-60]

Nord Pool, EPEX Spot, GME, OMIE, EXIST, JEPX, and IEX. It helps in understanding recent price behavior of hourly MCP variation throughout the whole day (or 24 hours) in DAM. From Figure 21, it is evident that hourly MCP for Nord Pool shows very little variation from hour 1 to hour 24. Similar behavior is also observed in the case of EXIST. For JPEX, there exist a substantial increase in hourly MCP from hour 15 to hour 21. Its hourly MCP is also very high as compared to other PX. Similar kind of behavior is also observed in case of IPEX but with very little variations. For EPEX Spot and OMIE, the hourly MCP gradually decreases from hour 1 to hour 6 and then sharply increases from hour

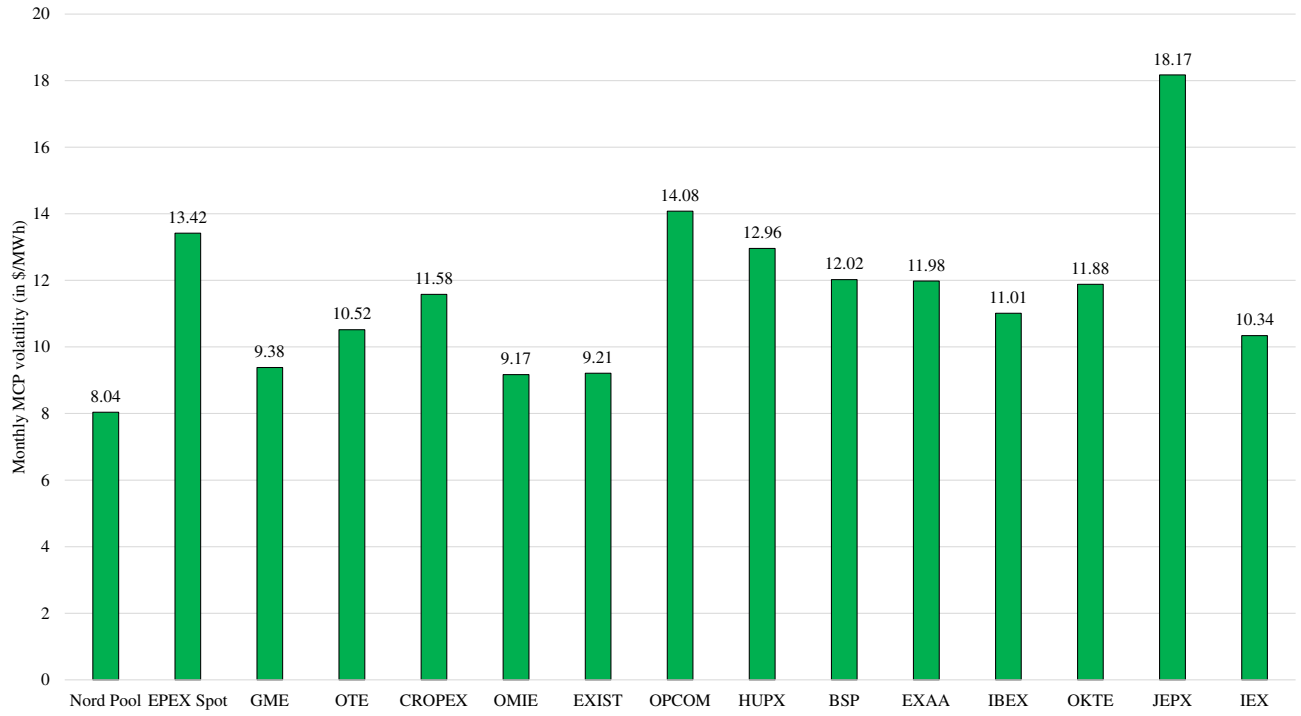


FIGURE 22 Price volatility in market-clearing price in DAM of major PX around the world[29,30,40,41,48-60]

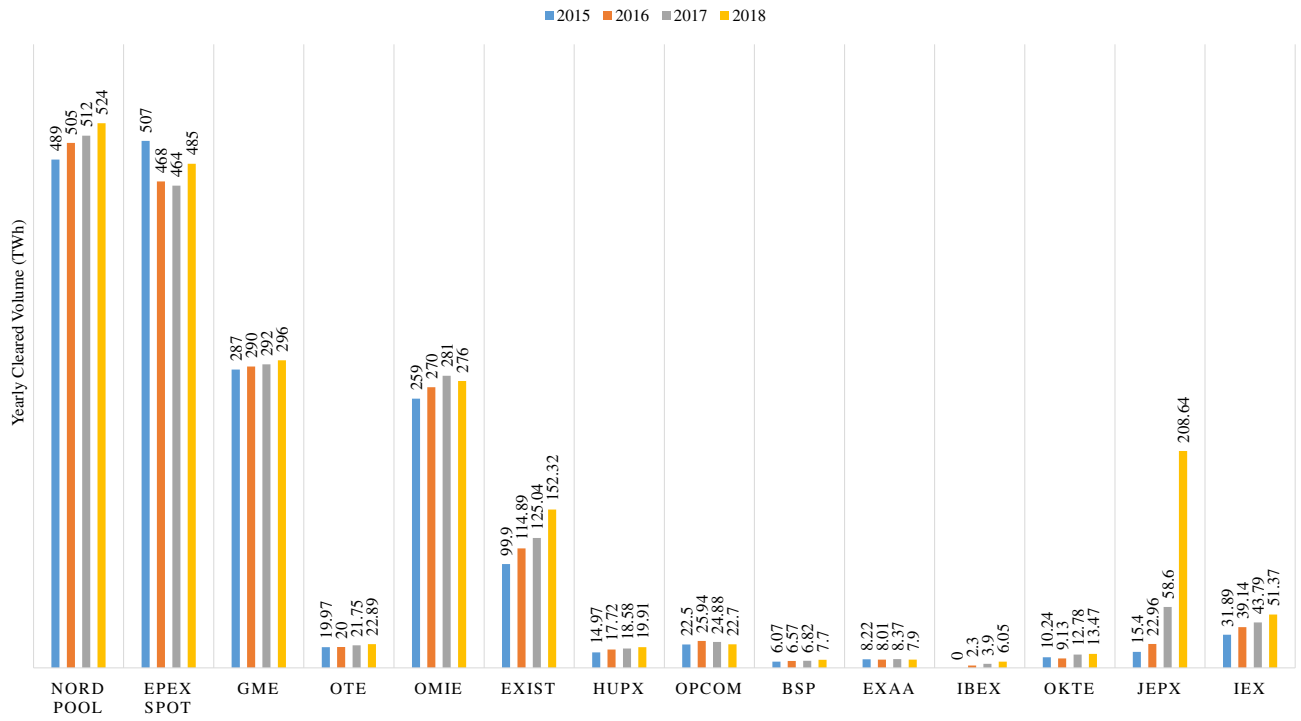


FIGURE 23 Yearly traded volume (in TWh) in DAM of major PX around the world[29,30,40,41,48-60]

6 to hour 9. It again gradually decreases from hour 9 to hour 17 and again increases from hour 17 to hour 20. Similar kind of behavior is also observed for IEX but with lower hourly MCP. Volitility in MCP of DAM is an important factor in decision-making process for suppliers and buyers in any PX. In general, increased MCP volatility in DAM also increases the risk involved in power trading for both suppliers and buyers. MCP volatility in DAM of world's major EPXs were obtained and plotted in Figure 22. From Figure 22, it is evident that volatility in MCP of DAM mostly varies between 8.04 and 14.08 $/MWh with a little exception of JPEX where volitility in MCP of DAM is as high as 18.17

$/MWh. Nord Pool has the lowest MCP volitility with its value of 8.04 $/MWh. Volitility in MCP of DAM remains more or less same for CROPEX, HUPX, BSP South Pool, EXAA, IBEX, OKTE, and IEX with their values ranges between 10.34 and 12.96 $/MWh. JPEX has the highest volatility in MCP of DAM with value of 18.17 $/MWh.

Total yearly traded volume through DAM of any PX is an important factor representing degree of success of any EPX. High traded volume through DAM is always desirable for any PX. Yearly traded volume in TWh for the last 4 years (2015-2018) through DAM of different PX around the world are obtained from their respective websites[29,30,40,41,48-60] and plotted in Figure 23. Yearly traded volume through DAM of Nord Pool Spot has the highest value followed by Epex Spot, GME, OMIE, EXIST, and JEPX. From Figure 23, it is evident that yearly traded volume through DAM of Nord Pool is approximately 489 TWh in 2015, it increases to 505 TWh in 2016. Yearly traded volume through DAM of Nord Pool in 2018 is 524 TWh which is 2.34% higher as compared to 512 TWh in 2017. For EPEX Spot, yearly traded volume through DAM in 2015 is 507 TWh which is highest among all PX in 2015. It reduces to 468 TWh and 464 TWh in 2016 and 2017 respectively. Yearly traded volume through DAM of EPEX Spot in 2018 is 485 TWh which is about 4.53% higher as compared to 464 TWh in 2017. For GME or IPEX, yearly traded volume through DAM remains more or less constant with its value of 287, 290, 292, and 296 TWh in 2015, 2016, 2017 and 2018 respectively. Similar kinds of behavior were also observed for OTE, HUPX, OPCOM, BSP South Pool, EXAA, and OKTE. For JEPX, yearly traded volume through DAM in 2015 is 15.4 TWh followed by 22.96 and 58.6 TWh in 2016 and 2017, respectively. In 2018, yearly traded volume through DAM of JEPX increases up to 208.64 TWh which is about 3.56 times to that traded in 2017. It is a very sharp increase in traded volume through JEPX. In the case of IEX, there exist a gradual increase in yearly traded volume through DAM with 31.89 TWh in 2015 to 39.14 TWh in 2016. It eventually increases to 43.79 and 51.37 TWh in 2017 and 2018, respectively.

7 | FUTURE CHALLENGES

Although PX had grown significantly over last the couple of decades, but still there exist few challenges. Today's PX have to overcome these hurdles to further increase total share of short-term power traded through PX. Survival of any PX needs continuous innovation in its market clearing mechanism, offer/bid types, and so on. Some major future challenges are:

7.1 | Development of advanced offer/bid structure

Types of offer/bid allowed in PX had grown significantly from hourly bid to block offer/bid and then to some advanced complex offer/bid as mentioned in Section 4. These complex offer/bid structures have their own merits and limitations. Recently, researchers were working on a generalized offer/bid types called “flexible profile offer/bid” which is somewhat similar to profile block order with flexibility in its execution time.[61,62] Typical example of a flexible profile offer with continuous duration of 10 hours is represented in Figure 24. Its execution time is decided by PX or market operator based on social welfare maximization. The adjustable profile block offers are cleared if the following condition are met[61]: (a) Fully cleared if offered price is less than weighted average MCP. (b) Partially cleared if offered price is equal to weighted average MCP. (c) Fully rejected if offered price is higher than weighted average MCP. For flexible profile bid, the clearing condition is the other way around. This is a generalized structure and can be reduced to a simple block bid with fixed execution time, simple block bid with fixed hourly volume. Although these types of advanced offer/bid has not been tested in any PX around the world but has tremendous potential to accommodate number of technical constraints of suppliers and buyers in offer/bid itself. PX needs to introduce these advance offer/bid structure in its DAM to provide its market participants an added flexibility for power trading. Few more new and innovative offer/bid types were discussed in References 63 and 64.

7.2 | Development of advanced market clearing algorithm

Earlier, most of the PX around the world accept only simple hourly and standard block offer/bids which created number of economic and technical hurdle to suppliers having thermal generators because of their high startup and shut-down cost. Some PX like Nord Pool, EPEX Spot, IEX, and so on. had introduced number of complex orders like Linked Block Bid, Profile Block Bid, MIC Bid, MIC Bid with scheduled off, Load gradient bid, Flexi Bid, and so on. Very few PX around the world had allowed these complex offer/bid types as it largely complicates the market clearing process. Some PX only

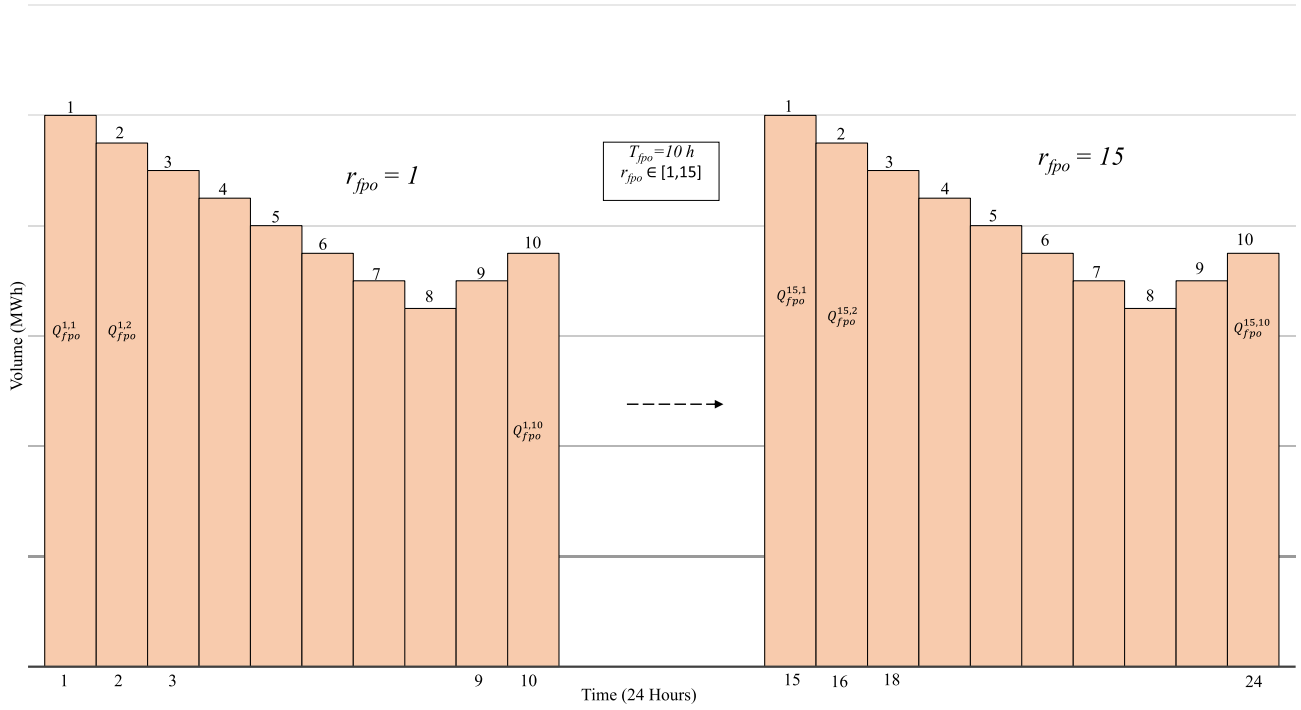


FIGURE 24 Typical example of a flexible profile offers/bid[61]

allow standard Block Bid from the suppliers' side to simplify the market clearing process. Also, the number complex bid a supplier can submit at a time is limited. Very few Flexi bids were allowed as its execution time is decided based on social welfare maximization which makes the market-clearing problem a NP hard combinatorial optimization problem. Few attempts to develop an advanced market clearing had been done recently. Biskas et al[65] presents an advanced market clearing algorithm for European Electricity market considering network congestion. A new method for market clearing using Mixed Complimentary Approach is presented in Reference 61 and the results obtained were compared with that obtained using Mixed Integer Linear Programming based method. Shah and Chatterjee[66] present an improvement in the current market clearing algorithm to improve social welfare distribution among suppliers and buyers. Although there is a significant development in the advanced market-clearing algorithm, still there is a restriction on number of allowed flexi offer/bids. Moreover, these market clearing algorithm are unable to handle large number of flexible profile offers/bids. There is a need of an efficient generalized market-clearing problem which is capable to handle large number of not only hourly flexi bid but also block flexi bid. In future, PX need to come up with a kind of generalized system which must be capable of providing market-clearing solution in reasonable amount of time. Study on some recent advanced in market-clearing algorithm and new software/program in DAM and IM can be found in References 67-70.

7.3 | Ways to increase percentage volume trade through PX

Still, the volume of power traded through EPX is very low in some of the major PX around the world. Figure 25 gives details of a percentage of total volume transacted through IEX for the period from 2008-2009 to 2017-2018. In 2008-2009 IEX account for only 7.2% of total short-term volume traded which is very low.[42] Although it gradually increases from 7.2% to 36.21% in 2017-2018 but it is low and needs to increase its share further. These PX have to take series of steps like the introduction of complex bid types, efficient market clearing mechanism, and efficient loss allocation scheme, and so on to increase percentage of volume trade through PX.

7.4 | Incorporating emission trading within PX

As electric power sector are one of the major contributors of greenhouse gas emission, policy makers because of Kyoto Protocol[71] limits the maximum amount greenhouse gas emission from these utilities which is expressed in term of

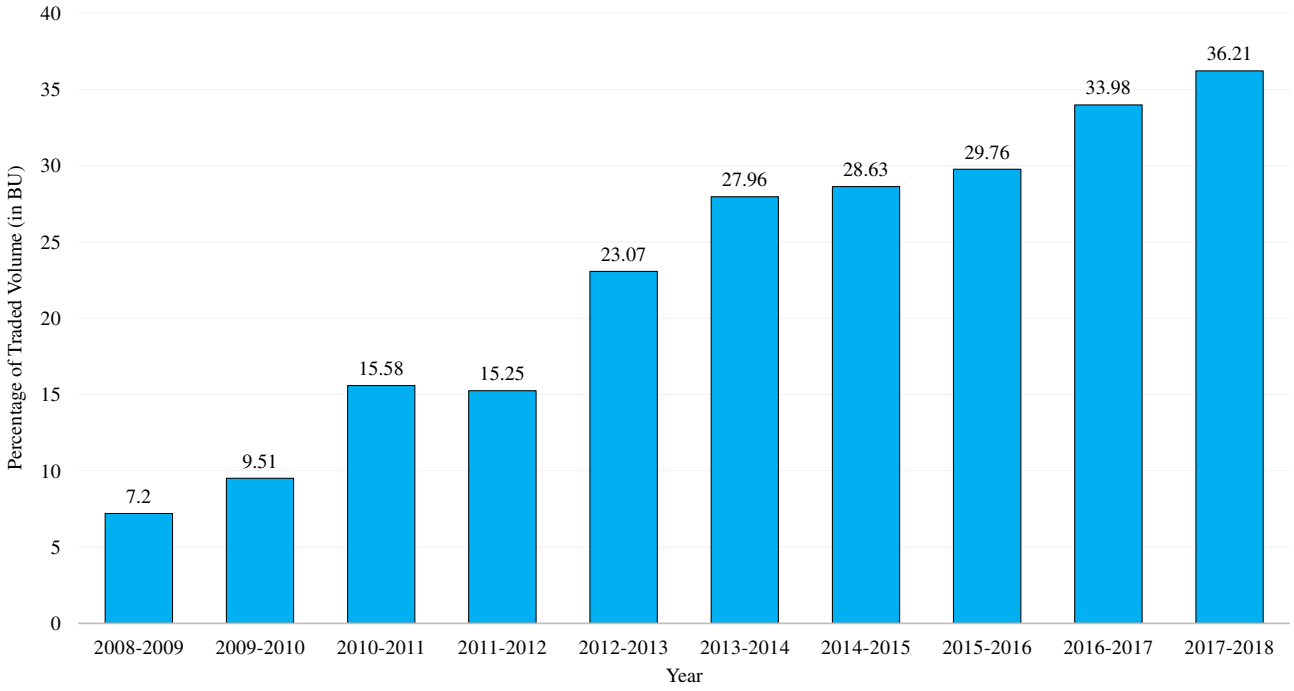


FIGURE 25 Percentage of total short-term volume (in BU) traded through Indian Energy Exchange[42]

number of Carbon Credit. One Carbon Credit allows power suppliers the right to emit one metric ton of carbon dioxide equivalent (CO_2E). Power suppliers require additional carbon credit for releasing extra emission and can buy additional carbon credit from separate emission market. Emission market also allows sell of unutilized carbon credit. Currently, power supplier separately participates in both electricity and emission market and requires accurate forecasting of MCP in both power and emission markets. Gajbhiye and Soman[72] proposed a new scheme which has the potential to integrate emission trading within PX. The proposed scheme not only provides a single trading platform for the traders, but also ensures that maximum benefit can be achieved to all market participants by optimally utilizing available carbon credits. Under this scheme, power suppliers can obtain additional surplus by selling those carbon credits for which carbon credit selling is profitable instead of utilizing it (costly power generation yields small surplus in power market). There is a need to integrate these two separate power and emission market and provide a common platform within PX where emission trading is also facilitated. Recent study on emission trading can be found in References 73-76.

7.5 | Measures to check market power abuse

Oligopolistic nature of current electricity market leads various market players to use market power for their individual benefits. Most of the PX around the world adopt a very little measure to restrict market power abuse. Karthikeyan et al[77] presents a comprehensive review on the estimation of market power in restructured electricity market using different indices. Few other research on market power analysis tool were presented in References 78-80. There is a need for the incorporation of an efficient method to detect and eliminate market power abuse by various market players.

8 | CONCLUSION

This article presents a comprehensive review of DAM and other important features of world's major PX. It mainly focused on trading mechanism, PX products, DAM design issues, world's major PX, comparative analysis of DAM of world's major PX and future challenges. Four popular PX products offered in PX include DAM, IM, REC, and ESC. Two trading mechanism in PX including auction and continuous trade were discussed. Design issue in DAM of PX including bid types, execution condition, market-clearing type, congestion management scheme, and Price Coupling of

Region were also presented. A systematic comparison of world's major PX in terms of different features were presented in Tables 1–3. A comparative analysis of DAM of world's major PX were presented in terms of average yearly MCP, average monthly MCP, MCP volatility and yearly traded volume. Finally, five major future challenges which today's PX need to overcome were identified including need of advanced bid structure, need of advanced market clearing algorithm, measures to increase percentage of traded volume through PX, procedure for incorporating Emission trading within PX and measure to check market power abuse. In future, further investigation is required for power trade through IM, REC, and ESC trade through PX, Green Term-Ahead Market, and so on.

ORCID

Devnath Shah https://orcid.org/0000-0002-6383-1982
Saibal Chatterjee https://orcid.org/0000-0003-1680-7565

REFERENCES

1. Ilic M, Galiana F, Fink L. *Power Systems Restructuring: Engineering and Economics*. New York: Springer Science & Business Media; 2013.
2. Bichpuriya Y Soman SA. Electric power exchanges: a review. Paper presented at: 16th National Power Systems Conference, 2010, pp. 115–120.
3. Shahidehpour M, Alomoush M. *Restructured Electrical Power Systems: Operation: Trading, and Volatility*. Boca Raton, FL: CRC Press; 2017.
4. Madlener R Kaufmann M. Power exchange spot market trading in Europe: theoretical considerations and empirical evidence. Paper presented at: OSCOGEN, Discussion Paper no. 5. 2002.
5. Flatabo N, Doorman G, Grande OS, Randen H, Wangensteen I. Experience with the Nord Pool design and implementation. *IEEE Trans Power Syst*. 2003;18(2):541-547.
6. Mediratta RK, Pandya V, and Khaparde SA. Power markets across the globe and Indian power market. Paper presented at: Fifth National Power System Conference (NPSC-2008), 2008.
7. Rademaekers K, Slingenberg A, Morsy S. Review and Analysis of EU Wholesale Energy Markets. Paper presented at: ECORYS Netherlands, EU DG TREN Final Report. 2008.
8. Srivastava AK, Kamalasadan S, Patel D, Sankar S, Al-Olimat KS. Electricity markets: an overview and comparative study. *Int J Energy Sect Manag*. 2011;5(2):169-200.
9. Singh A. Power sector reform in India: current issues and prospects. *Energy Policy*. 2006;34:2480-2490.
10. Penados CV. Role of the physical power exchanges in the electricity wholesale market. Universidad Pontificia Comillas, Madrid; October 8, 2008.
11. Alam F, Alam Q, Reza S, Khurshid-ul-Alam SM, Saleque K, Chowdhury H. Regional power trading and energy exchange platforms. *Energy Procedia*. 2017;110:592-596.
12. Singh A, Chauhan DS, Upadhdhyay KG. Effect of power exchange of India: an overview and key issues. *J Inst Eng Ser B*. 2013;94(3):207-214.
13. Rademaekers K, Slingenberg A, Morsy S. *Review and Analysis of EU Wholesale Energy Markets—Historical and Current Data Analysis of EU Wholesale Electricity, Gas and CO_2 Markets*. Rotterdam: ECORYS; 2008.
14. Hohki K. Outline of Japan electric power exchange (JEPX). *IEEJ Trans Power Energy*. 2005;125:922-925.
15. Ioannidis F, Kosmidou K, Makridou G, Andriosopoulos K. Market design of an energy exchange: the case of Greece. *Energy Policy*. 2019;133:110887.
16. Mayer K, Trück S. Electricity markets around the world. *J Commod Mark*. 2018;9:77-100.
17. Bajpai P and Singh SN, Electricity trading in competitive power market: an overview and key issues. Paper presented at: International Conference on Power Systems, ICPS 2004, Kathmandu, Nepal, 2004.
18. Girish GP, Vijayalakshmi S. Role of energy exchanges for power trading in India. *Int J Energy Econ Policy*. 2015;5(3):673-676.
19. Ahmad F, Alam MS. Assessment of power exchange based electricity market in India. *Energy Strategy Rev*. 2019;23:163-177.
20. Mayer P, Ball CS, Vögele S, Kuckshinrichs W, Rübbelke D. Analyzing Brexit: implications for the electricity system of Great Britain. *Energies*. 2019;12(17):3212.
21. Beus M, Pavicpavić I, Štritof I, Capuder T, Pandžić HP. Electricity market design in Croatia within the European Electricity Market—recommendations for further development. *Energies*. 2018;11:346.
22. Zalzar S, Bompard EF 2019. The Impacts of an Integrated European day-ahead and Intraday Electricity Market on Market Performance: The Iberian Region Case. Paper presented at: 2019 IEEE Milan PowerTech; 23-27 June 2019; Milan, Italy.
23. Savelli I, Giannitrapani A, Paoletti S, Vicino A, and Cornélusse B. Introducing block orders in the Italian day-ahead electricity market. Paper presented at: 2018 15th International Conference on the European Energy Market (EEM), 2018, pp. 1–6.
24. Le HL, Ilea V, Bovo C. Integrated European intra-day electricity market: rules, modeling and analysis. *Appl Energy*. 2019;238:258-273.
25. Kolcun M, Rusek K. Analysis of prices for electricity at the polish power exchange. *Polish J Manag Stud*. 2018;17:155-164.
26. Stet M. Characteristics of the Romanian energy market. Paper presented at: *IOP Conference Series: Materials Science and Engineering*, 2017, vol. 200, no. 1, p. 12067.

27. Sahoo NR, Mohapatra PKJ, Sahoo BK, Mahanty B. Rationality of energy efficiency improvement targets under the PAT scheme in India—a case of thermal power plants. *Energy Econ*. 2017;66:279-289.
28. Bhandari D, Shrimali G. The perform, achieve and trade scheme in India: an effectiveness analysis. *Renew Sustain Energy Rev*. 2018;81: 1286-1295.
29. Nord Pool. Available at: https://www.nordpoolgroup.com/.
30. Indian Energy Exchange (IEX). Available at: https://www.iexindia.com/.
31. Shereef RM, Khaparde SA. A unified REC market and composite RPO scheme for promotion of renewable energy in India. *Int J Sustain Energy*. 2017;36(6):606-618.
32. Zhao X, Zhou Y, Zuo Y, Meng J, Zhang Y. Research on optimal benchmark price of tradable green certificate based on system dynamics: a China perspective. *J Clean Prod*. 2019;230:241-252.
33. Linnerud K, Simonsen M. Swedish-Norwegian tradable green certificates: scheme design flaws and perceived investment barriers. *Energy Policy*. 2017;106:560-578.
34. Li W, Liu L, Zhang S, Zhang H. Will the tradable green certifications and renewable portfolio standard policy work well in China: a recursive CGE analysis. *J Renew Sustain Energy*. 2018;10:55904.
35. Frei F, Loder A, Bening CR. Liquidity in green power markets—an international review. *Renew Sustain Energy Rev*. 2018;93:674-690.
36. Currier KM, Rassouli-Currier S. Producer incentives in electricity markets with green quotas and tradable certificates. *Util Policy*. 2018; 55:59-68.
37. Aldrich EL, Koerner CL. White certificate trading: a dying concept or just making its debut? Part I: market status and trends. *Electr J*. 2018;31(3):52-63.
38. Di Santo D, De Chicchis L, Biele E. White certificates in Italy: lessons learnt over 12 years of evaluation. Paper presented at: International Energy Policy & Programme Evaluation Conference, 2018.
39. Harmsen R, Moth L, Kumar A. Applicability of energy saving obligations to Indian electricity efficiency efforts. *Energy Strateg Rev*. 2014; 2(3–4):298-306.
40. Japan Energy Exchange (JPEX). http://www.jepx.org/english/index.html.
41. European Energy Exchange (EPEX). http://www.epexspot.com/en/.
42. Indian Energy Exchange Annual report IEX_Report_2017–2018. https://www.iexindia.com/pdf/Annual_Report_FY_2017_18.pdf.
43. Gutierrez G, Quinonez J, Sheble GB. 2005. Market clearing price discovery in a single and double-side auction market mechanisms: Linear programming solution. Paper presented at: 2005 IEEE Russia Power Tech, St. Petersburg, 2005, pp. 1-5.
44. Meeus L, Purchala K, Belmans R. Implementation aspects of power exchanges. Paper presented at: Proceedings of the 40th CIGRE Conference, 2004.
45. NEMO Committee. Euphemia public description. PCR market coupling algorithm. 2016
46. NEMO Committee. EUPHEMIA public description—single price coupling algorithm. 2019.
47. Lam L, Ilea V, Bovo C. European day-ahead electricity market coupling: discussion, modeling, and case study. *Electric Power Syst Res*. 2018;155:80-92.
48. Gestore dei Servizi Energetici (GME) or Italian Power Exchange (IPEX). http://www.mercatoelettrico.org/En/Default.aspx.
49. Pennsylvania-New Jersey-Maryland Interconnection (PJM). https://www.pjm.com/.
50. Czech Electricity and Gas Market Operator (OTE). http://www.ote-cr.cz/.
51. Croatian Power Exchange (CROPEX). https://www.cropex.hr/en/.
52. Spain Electric Power Exchange (OMIE). http://www.omie.es/inicio/mercados-y-productos/conoces-nuestro-mercado-de-electricidad.
53. Energy Exchange Istanbul (EXIST). https://www.epias.com.tr/en/.
54. Hungary Power Exchange (HUPEX). https://hupx.hu/en/Pages/.
55. Spain Electric Power Exchange (OPCOM). https://www.opcom.ro/pp/home.php.
56. Borzen Slovenian Power Market Operator (BSP_South_Pool). www.bsp-southpool.com/home.html.
57. Energy Exchange Austria (EXAA). https://www.exaa.at/en.
58. Independent Bulgarian Energy Exchange. ibex.bg.
59. Short-term Electricity Market Operator (OKTE). https://www.okte.sk/en.
60. Power Exchange India Limited (PXIL). https://www.powerexindia.com/PXIL/insidepage.aspx?id=9.
61. Vlachos AG, Dourbois GA, Biskas PN. Comparison of two mathematical programming models for the solution of a convex portfolio-based European day-ahead electricity market. *Electr Pow Syst Res*. 2016;141:313-324.
62. Vlachos AG, Biskas PN. Adjustable profile blocks with spatial relations in the day-ahead electricity market. *IEEE Trans Power Syst*. 2013;28(4):4578-4587.
63. Sleisz Á, Divényi D, Raisz D. New formulation of power plants' general complex orders on European electricity markets. *Electr Pow Syst Res*. 2019;169:229-240.
64. Yörükoğlua S, Avşarb ZM, Kat B. An integrated day-ahead market clearing model: incorporating paradoxically rejected/accepted orders and a case study. *Electr Pow Syst Res*. 2018;163:513-522.
65. Biskas PN, Chatzigiannis DI, Bakirtzis AG. European electricity market integration with mixed market designs—part II: solution algorithm and case studies. *IEEE Trans Power Syst*. 2013;29(1):466-475.
66. Shah D, Chatterjee S. Improvement in social welfare division among buyer and supplier in LP based market clearing method in day-ahead electricity market. Taylor & Francis. *Aust J Electr Electron Eng*. 2019;16(4):237-249.

67. Koltsaklis N, Dagoumas A. Policy implications of power exchanges on operational scheduling: evaluating EUPHEMIA's market products in case of Greece. *Energies*. 2018;11(10):2715.
68. Mathieu S, Petitet M, Perrot M, Ernst D, Phulpin Y. SiSTEM, a Model for the Simulation of Short-Term Electricity Markets. http://hdl.handle.net/2268/215614. 2017.
69. Dourbois GA, Biskas PN, Chatzigiannis DI. Novel approaches for the clearing of the European day-ahead electricity market. *IEEE Trans Power Syst*. 2018;33(6):5820-5831.
70. Sensoy N, Ceyhan G. A genetic algorithm to solve day-ahead energy market clearing problem under network constraints. Paper presented at: 2018 15th International Conference on the European Energy Market (EEM), 2018, pp. 1–6.
71. Grubb M, Vrolijk C, Brack D. *Routledge Revivals: Kyoto Protocol (1999): A Guide and Assessment*. London: Routledge; 2018.
72. Gajbhiye R, Soman SA. Facilitating emission trade within power exchange: Development of conceptual platform. Paper presented at: Energy Market (EEM), 2010 7th International Conference on the European, 2010, pp. 1–6.
73. Dwivedi K, Kumar Y, Agnihotri G. Competitive bidding in electricity markets with carbon emission by using particle swarm optimization. Paper presented at: Proceedings of the IAENG International Conference Electrical Engineering. 2012.
74. Bao X, Zhao W, Wang X, Tan Z. Impact of policy mix concerning renewable portfolio standards and emissions trading on electricity market. *Renew Energy*. 2019;135:761-774.
75. Solaymani S. CO2 emissions patterns in 7 top carbon emitter economies: the case of transport sector. *Energy*. 2019;168:989-1001.
76. Turner O. Emissions Trading in the EU and China: A Comparative Study. 2018.
77. Karthikeyan SP, Raglend IJ, Kothari DP, Sahoo SK, Kumar KS. A comparison of NMRS with other market power indices in deregulated electricity market. In: Vijay V, Yadav S, Adhikari B, Seshadri H, Fulwani D, eds. *Systems Thinking Approach for Social Problems. Lecture Notes in Electrical Engineering*. Vol 327. New Delhi: Springer; 2015:409-428.
78. Borenstein S, Bushnell J, Knittel CR. Market power in electricity markets: beyond concentration measures. *Energy J*. 1999;20:65-88.
79. Ji Y, Yépez-García A. Market Power in Electricity Generation Sector: A Review of Methods and Applications. 2017.
80. Shukla UK, Thampy A. Analysis of competition and market power in the wholesale electricity market in India. *Energy Policy*. 2011;39:2699-2710.

How to cite this article: Shah D, Chatterjee S. A comprehensive review on day-ahead electricity market and important features of world's major electric power exchanges. *Int Trans Electr Energ Syst*. 2020;30:e12360. https://doi.org/10.1002/2050-7038.12360