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Review of real-time electricity markets for integrating Distributed Energy Resources and Demand Response

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HIGHLIGHTS

- This paper reviews typical RTMs in the North America, Australia and Europe.
- The successful RTM experiences are summarized and discussed in three groups.
- Technical overview of the RTMs integrating DER and DR is presented.

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ABSTRACT

The high penetration of both Distributed Energy Resources (DER) and Demand Response (DR) in modern power systems requires a sequence of advanced strategies and technologies for maintaining system reliability and flexibility. Real-time electricity markets (RTM) are the non-discriminatory transaction platforms for providing necessary balancing services, where the market clearing (nodal or zonal prices depending on markets) is very close to real time operations of power systems. One of the primary functions of RTMs in modern power systems is establishing an efficient and effective mechanism for small DER and DR to participate in balancing market transactions, while handling their meteorological or intermittent characteristics, facilitating asset utilization, and stimulating their active responses. Consequently, RTMs are dedicated to maintaining the flexibility and reliability of power systems. This paper reviews advanced typical RTMs respectively in the North America, Australia and Europe, focusing on their market architectures and incentive policies for integrating DER and DR in electricity markets. In this paper, RTMs are classified into three groups: Group I applies nodal prices implemented by optimal power flow, which clears energy prices every 5 min. Group II applies zonal prices, with the time resolution of 5-min. Group III is a general balancing market, which clears zonal prices intro-hourly. The various successful advanced RTM experiences have been summarized and discussed, which provides a technical overview of the present RTMs integrating DER and DR.

Contents

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1. Introduction

In the last decades, the restructuring and deregulation of power system change the basic structure of system operation and planning. In the new deregulated environment, electricity and corresponding prices are determined and traded in the markets, respectively. There are different categories of electricity market architectures and pricing schemes prevalent in the power systems around the world according to their local economical characteristics and infrastructure conditions.

The current development tendency is that, industrialized countries increasingly penetrate their power systems by renewable energies, such as wind energy and photovoltaic for the purposes of low-carbon emissions and environmental protections, while expecting to increase the asset utilization of high electrification of transportations and efficient heating facilities, e.g., Electric Vehicles, Heat Pumps, Combined Heat and Power System (CHP) [1]. These factors will have high impacts on power systems' operation and planning, especially influencing the distribution grids where connecting most of the small Distributed Energy Resources (DER) and end-consumers possibly acting as Demand Response (DR) [2]. The recent rapid development of communication technologies on telemetry and remote control, e.g., smart meters, has established the foundation of Real-time electricity markets' (RTM) implementation [3].

One of the main functions of RTMs in modern power systems is to build an efficient and effective transaction platform for small DER and DR to actively provide balancing services during power system operations [4]. Small-size DERs and DR integrated via aggregators have the potentials to provide faster (e.g. 5 min) balancing services than the large conventional generating units, which usually provide balancing services within 15–20 min. Simultaneously, the RTM can also coordinate with the conventional Manual Reserve Market, which provides sufficient reserve capacity for supporting the real time balancing e.g., tertiary reserve according to the UCTE's (Union for the Coordination of the Transmission of Electricity) definition [5]. DER can help lessen peak-load, reduce reliance on large central fossil fuel generation, improve asset utilization, and accelerate interoperability. DR enables advanced demand management, encourage customers' active participations, and boosts digital communication technologies [6,7]. The prosumers, who possibly perform as both DER and DR alternatively, respond to real-time electricity prices by means of Information and communication technology systems (ICT), will bring the flexibility of power system operations and change the structure of electricity markets [8].

This paper reviews advanced typical RTMs coordinated with the relevant ancillary service markets, which maintain reliable and secure operation of power systems, respectively in the North America, Australia and Europe. In this paper, RTMs are generally classified into three groups:

(1) RTM Group I: the RTMs apply nodal prices by Optimal Power Flow (OPF) implementation, which clear energy prices every 5 min, represented by PJM.
(2) RTM Group II: the RTMs apply zonal prices, with the time resolution of 5 min, represented by AEMO.
(3) RTM Group III: the general Balancing Markets (BM), which clear zonal prices intro-hourly, e.g., 45 min, which are applied by most European markets.

The RTM architectures and corresponding incentive policies for integrating DER and DR in electricity markets are described and discussed in the paper.

2. Basic implementation of RTM

2.1. Basic market architecture

The basic architectures of electricity markets are relatively similar around the world. The general function of electricity markets is a non-discriminatory and transparent transaction platform for electricity commodities such as energy, various ancillary services. The motivations of electricity markets normally consider three perspectives [9]:

(1) Market Operators: to improve economic efficiency.
(2) System Operators: to ensure the system reliability, stability and security.
(3) Green Policies: to increase the utilization of Renewable Energy Sources (RES).

Generally, the wholesale electricity market comprises three market places according to different time scales [10]:

(1) Day-ahead market (DAM): for the settlement in a given hour of operation for the following day.
(2) Intraday market (IDM): for the settlement hour-ahead before operation.
(3) RTM or BM: for the system balance during the operational hour, in some places, e.g., the Nord pool, called Regulating Market.

The basic market architecture in modern power systems is illustrated in Fig. 1. Note that, besides conventional large generating units with high ramping rates, e.g., hydro-power units, the RTM in modern power systems is also focusing on providing balancing services via the aggregations of small distributed generators and flexible demands.

2.2. Ancillary services

Ancillary Services are critical for maintaining power systems' security and reliability during operation. Large system imbalance between load and generation can cause high frequency deviations and may lead to system collapse. Minor imbalances can also threaten the system's secure operation. Some emergency schemas will be activated for system outages, e.g. inter-tripping schema will disconnect some generations or loads for preventing system collapse. If the power system collapses, the black start generations (hydro power plants, small diesel generators and batteries) will be utilized for system restoration.

For the reasons above, according to the definitions of the FERC (United States Federal Energy Regulatory Commission) [11,12] the general ancillary services are classified into six groups:

(1) Scheduling and dispatching.
(2) Energy imbalance.

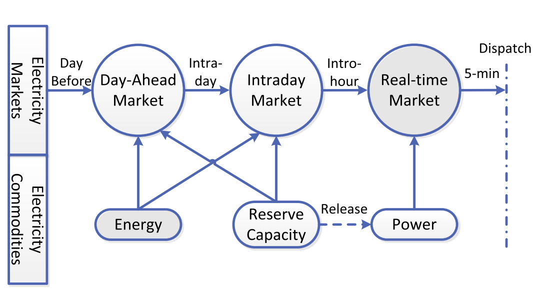

Fig. 1. Basic market architecture in modern power systems.

(3) Reactive power/voltage control.
(4) Loss compensation.
(5) Load following.
(6) System protection.

Specifically, for energy imbalance and frequency control service, there exist different kinds of reserve products in the markets. Generally, these reserve products are classified referring to their technical characteristics such as responding time scales and controlling mechanisms. The FERC definitions of reserves applied in North American markets are represented as [13]:

(1) Regulation reserve: for fast frequency control.
(2) Spinning reserve: respond simultaneously to a contingency within minutes.
(3) Non-spinning reserve: rapid start up to a contingency.
(4) Replacement reserve: to substitute the faster and more expensive reserves so as to reduce regulating cost.

The UCTE definitions on 'Load–Frequency Control and Performance' [14], applied in Europe, defines three types of reserves:

(1) Primary reserve: automatically and instantly activate within 15 s or within a linear time limit of 15–30 s over instantaneous.
(2) Secondary reserve: intend to keep system frequency stable in the time frame of seconds up to typically 15 min.
(3) Tertiary reserve: manually activate within a predefined time frame, usually 15 or 20 min, to replace the primary and secondary reserves in order to release them for the next contingency.

Fig. 2 illustrates the general ancillary services in modern power systems. The voltage control, loss compensation and load following are continuous services. The system protection services (rather than device protection) include the reliability based spinning reserve (fully available within 10 min) and the supplemental operating reserve (fully available within 30 min). The scheduling and dispatching services are equivalent to the unit commitment and economic dispatch which determined in the Day-ahead market,

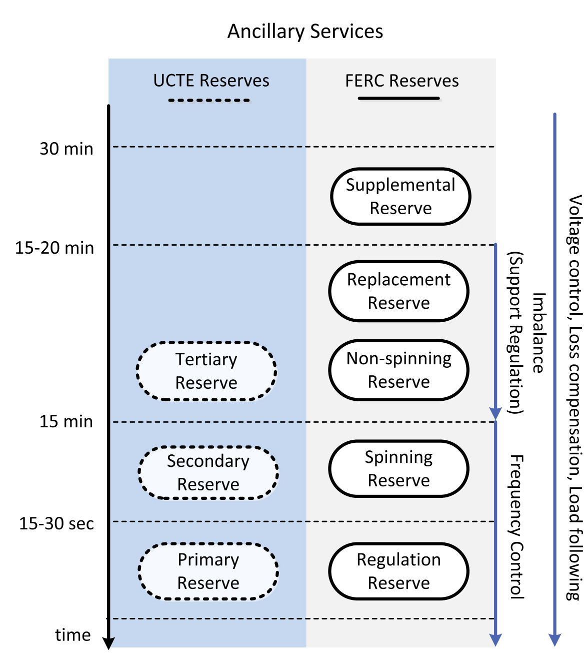

Fig. 2. General ancillary services in modern power systems.

thus not include in Fig. 2. Note that, the tertiary reserve refers to UCTE's definition, the replacement reserve and non-spinning reserve refer to North American definition, they are manually activated reserves used to replace the faster reserves (e.g., the primary and secondary reserves are used by UCTE, the regulation and spinning reserves by North America), so as to release these faster reserves for the next imbalance contingency. These manual reserves are supporting the power system regulation, coordinated with the RTM.

2.3. Pricing and settlement

Refer to the pricing and settlement schemes for the particular electricity commodities traded in DAM, IDM and RTM, the differentiation of geographical prices is necessary to be discussed. Basically, there are three types of geographical pricing schemes [15]:

(1) Uniform Marginal Pricing: the same price everywhere in the whole control area.
(2) Nodal Marginal Pricing: different prices at each transmission bus (node) based on the implementation of OPF.
(3) Zonal Marginal Pricing: the same price in a particular zone including several nodes, which is a tradeoff of UMP and NMP.

Note that OPF is the fundamental of nodal price based electricity markets. For the high voltage level transmission network, the line resistance is far less than the line reactance, thus, DCOPF is applied. DCOPF is solved to provide the active power and voltage angle of each bus, and the power flow on each transmission line in the power system. With advances in computing technology and solution algorithms, OPF can find a solution in reasonable time from long-term system planning to day-ahead, every hour, to even every 5 min [16].

Usually, the energy procurements in DAM and IDM are organized by auctions implementing portfolio offers-bids, with the pricing by marginal cost. The tertiary or replacement reserve capacity in reserve markets and corresponding balancing power in RTM are obtained by consecutive auctions or contractual obligations, with the pricing by the fixed price, pay-as-bid or marginal price.

For the settlement between BRPs (Balance Responsible Party) and the wholesale market, both spot price (i.e., day-ahead price) and real-time price are applied [17]. The real-time price is set by RTM Operator, usually the TSO takes the role. Balancing power (MW) is traded in RTM, but energy (MWh) is calculated when it comes to ex-post financial settlement.

Fig. 3 shows an example of the RTM settlements for both production and consumption sides, assuming that the real-time price is higher than the spot price. If a producer generates less than the day-ahead contract, it has to purchase some power from RTM to make up the difference, the energy purchased is settled by the real-time price. If a producer generates more than the day-ahead contract, it can sell the excess power to RTM, the energy is settled by the spot price. If a consumer uses less than the day-ahead contract, on the contrary, consuming less is equivalent to producing, thus it can sell the less consumption to RTM, the energy is settled by the real-time price. If a consumer uses more than the day-ahead contract, it needs to purchase extra power from RTM, the energy is settled by the real-time price.

Fig. 3 is a typical example for illustrating the RTM settlement. Different MOs may develop different settlement strategies for encouraging players to provide particular services. Hence, the real-time price could be higher or lower than, or equal to the day-ahead price (spot price) corresponding to different incentive policies.

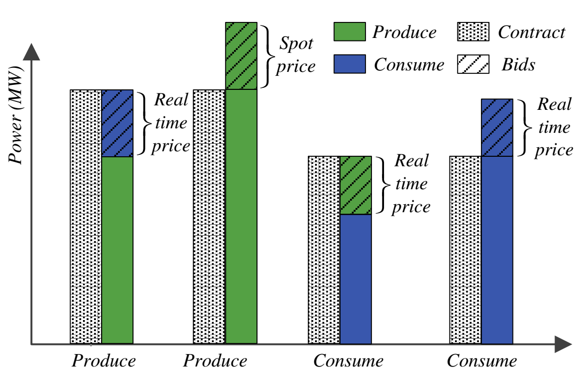

Fig. 3. An example of the RTM settlement.

2.4. Aggregators

In the current market structures, the participation of electricity markets must satisfy the minimum amount of bids, e.g., at least 10 MW per bid in the Nord pool regulating market. The current methods for small DER and DR participating in electricity market are the series strategies of aggregators or clusters. Generally, the aggregators can be categorized into three major types according to their collecting objects [18], as illustrated in Fig. 4:

(1) Production Aggregator: to group numbers of small generators so as to generate economies of scale in accessing the markets, e.g., Virtual Power Plant.
(2) Demand Aggregator: an intermediary between small consumers and other players (e.g., the retailers, or distribution companies) in the system, some of these consumers may have storage and/or production capacity.

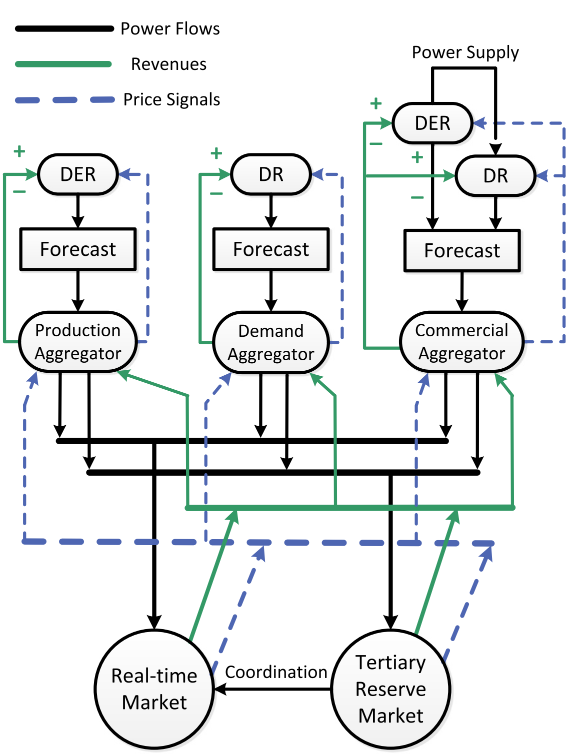

Fig. 4. Aggregators for Integrating DER and DR in RTM.

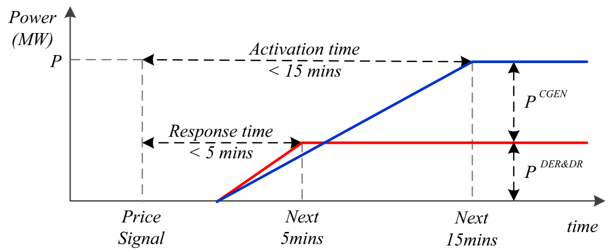

Fig. 5. Balancing service of DER and DR coordinating with large conventional generating units.

(3) Commercial Aggregator: balance responsible, energy supplier and buyer of the locally generated electricity.

In developed countries, particular policies have already been implemented for stimulating the green DER and DR aggregators.

2.5. Faster balancing service of DER and DR in RTM

Basically, DER and DR have faster response time than the large conventional generating units. Therefore, the aggregators of DER and DR have the potential to provide faster balancing service (e.g., 5 min) than the large generating units (usually provide balancing services within 15–20 min).

Fig. 5 illustrates the balancing service timeline coordination between DER/DR (noted by $P^{DER\&DR}$) and the conventional generators (noted by P^{CGEN}). When a contingency event happens, for example, a major generating unit trips, the TSO activates bids for totally $P = P^{CGEN} + P^{DER\&DR}$ MW additional power in RTM. Besides activating the conventional generators immediately to obtain balancing power in 15 min, the TSO also prefers a faster response from prosumers within 5 min. Therefore, a real-time price signal is published in the RTM for the following 5-min interval to obtain $P^{DER\&DR}$ MW balancing power from prosumers, then obtain the rest of the requirement P^{CGEN} MW balancing power from conventional generators [17].

2.6. RTM reform future for DER and DR

DER and DR can be cost-effective alternatives to traditional supply-consume market agents. Stakeholders expect the evolution of the RTM for achieving the goal of high economic efficiency and system reliability, mainly focus on the following issues:

(1) Bi-direction competitive bidding:

It can be customer-side distributed generations, responsive and interruptible loads, renewable energy curtailments. The aggregators associated with certain storage systems, provide positive or negative outputs for bi-direction biddings to RTM in different time intervals.

(2) Expansion of market participants:

To bundle DER and DR as a bidding resource in markets, e.g. aggregators, commercial entities, independent third parties.

(3) Co-optimizing strategies:

Basically, responsive loads can mitigate the renewable power variability; micro-units serve as the backup source for renewables in hybrid systems; large scale EV charging and associated battery storages serve for frequency regulation; heat pumps, electric boilers, and CHPs co-optimize the electricity-heating efficiency, etc. [19–22].

(4) Pricing and incentives:

The sub-dividing time-varying pricing is necessary for providing flexibility of system operation. Incentives for DER can be a mandatory or alternative tariff. DR may perform as Price-based (response to the price signal) or Incentive-based (response to the predefined incentive for system reliability) mode [23–25].

(5) Ancillary services:

DER and DR have the competence to provide fast and effective reserve capacity and balancing power in ancillary service markets.

(6) Smart grid infrastructures:

The application of RTM integrating DER and DR rely on the implementation of Advanced Metering Infrastructure, ICT and Network Automation.

2.7. Effects of other Strategic Markets

Globally, the prices of electricity, natural gas, coal, and oil commodities are more or less correlated with the crude oil price. Therefore, the effects of other strategic energy markets on electricity market are worth to be observed.

- Crude Oil market:

The crude oil price has relatively strong positive correlation with coal and natural gas prices both for imported price and spot price. The electricity price depends dramatically on the fuel prices for power generation. Whereas, large scale RES penetration and DR may reduce the market share of fuel energies, thus weaken the impact of crude oil price. Consequently, except the countries which highly depend on oil for their electricity production, the Crude Oil market effect moderately on electricity market [26,27].

- Natural gas market:

As the market share of RES and DR increases, stakeholders may prefer to invest natural gas power in compared with fossil or nuclear power due to its flexibility and low investment cost. In addition, natural gas and electricity are alternative competitors for heating. Thus, the impact of Natural Gas market on electricity market depends on the interconnection and liquidity of the two markets. For electricity generation, the increase of RES power strongly decreases the natural gas power, since the RES power is cheaper than the gas power. For heating demand, the gas consumption is mainly caused by the temperature and the residential heating custom, does not significantly vary by the electricity price [28,29].

3. Group I–nodal price RTMs

In North America, some advanced wholesale electricity markets have implemented provision of accurate and timely price information to consumers [30]. Especially, the Northern U.S. markets are considered as advanced nodal wholesale electricity markets, with the real-time Locational Marginal Prices (LMP) calculated and announced for each 5-min operating interval. These typical markets are:

Table 1
Northern U.S. RTM pricing and settlement intervals.

American markets	Pricing interval	Settlement interval
ISO-NE	Ex-Post 5-min	Hourly
NYISO	Ex-Ante 5-min	Hourly
PJM	Ex-Post 5-min	Hourly
CAISO	Ex-Post 5-min	10-min

Note: To inform the real-time price: Ex-post – after the end of each time interval; Ex-ante – before each time interval.

- New England ISO (ISO-NE)
- New York ISO (NYISO)
- Pennsylvania-Maryland-New Jersey Interconnection (PJM)
- California ISO (CAISO)

The Real-time energy pricing and settlement resolution are summarized in Table 1. PJM is selected as the representative for a detailed description of the nodal price RTMs. Note that the ex-Ante means before the operation event, that is before the beginning of 5-min operational interval. The ex-post means after the operation event, that is after the end of each 5-munite operational interval. The ex-ante pricing ensures price responsive consumers to know what the price is before the purchase decision is made. This strategy is used to avoid anomalous price spikes.

3.1. PJM RTM mechanism

PJM operates the wholesale electricity market of the 13 states of U.S. and Columbia District. In PJM's market architecture, instead of IDM, the DAM connects directly to the RTM, cooperating with ancillary service markets. Fig. 6 illustrates the market architecture and strategies for PJM integrating DER and DR in both energy and reserve markets [31].

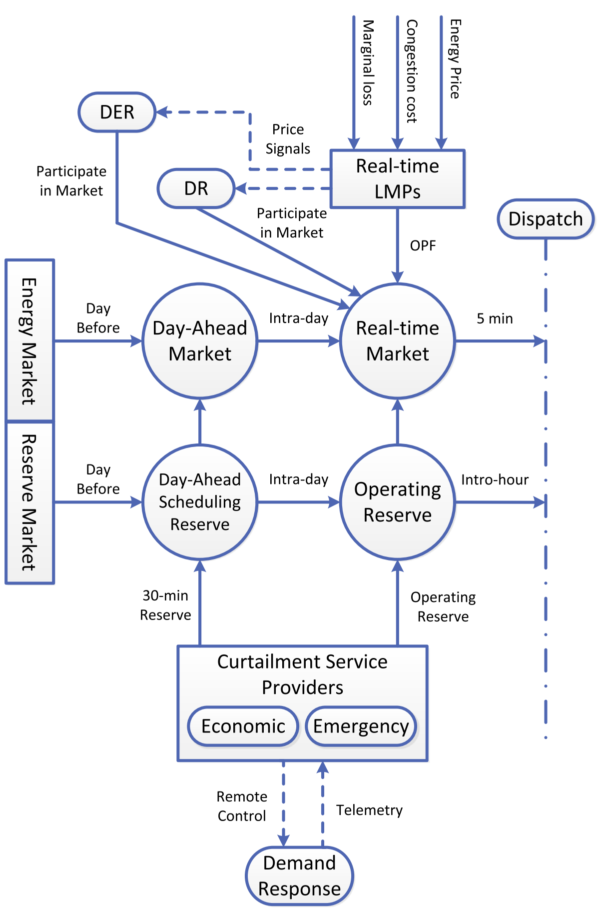

Fig. 6. Market strategies for PJM integrating DER and DR.

PJM's RTM is an energy transaction market, where LMPs (nodal prices) are calculated and announced every 5 min [32]. The real-time energy procurements deal by offers-bids auctions [33]. The pricing scheme considers three respects [34]:

- Energy purchase and sale in the market.
- Transmission congestion costs.
- Marginal losses on the bulk power grid.

If there are no congestion and transmission losses, the prices are theoretically the same for each bus or node. When congestion is taken into consideration, the prices will vary by locations. The marginal losses determined by penalty factors, also vary by locations. Consequently, LMPs change by locations on each node. The overall optimization objective is to minimize the production costs while respecting the constraints of transmission line capacity limits. OPF is applied for LMP calculation.

In PJM, there exist the Day-Ahead Scheduling Reserve Market and the Operating Reserve Market. The Day-Ahead Scheduling Reserve Market procures supplemental 30-min reserves on a day-ahead basis [35]. The Operating Reserve Market compensates the present imbalance in a very short-term forward dispatch [36,37].

3.2. PJM RES support mechanism

The 11 of 13 states of the U.S. and the Columbia District supplied by PJM develop a Renewable Portfolio Standard to offer Open-Access Transmission Tariff for RES [38]. Many other policies, protocols and programs have been developed for supporting RES and DER. For RES, no penalties are imposed on generation deviations if the wind output suddenly drops and differs from the scheduled value. For DER, any type of generators could self-schedule with a 20-min advance notice, which is suitable for DERs to adjust their uncertain outputs [39].

3.3. PJM DR support mechanism

DR is an important part of PJM markets with a variety of market products. There are five special trading platforms for DR [40]:

(1) DR Energy Market: where DR voluntarily responds to PJM LMPs by reducing consumption [41].
(2) DR Day-ahead Scheduling Reserve Market: where DR provides supplemental 30-min reserves [42].
(3) DR Capacity Market: where DR provides demand reduction as capacity resource in the forward capacity market [43].
(4) DR Synchronized Reserve Market: where DR dependably provides response within 10 min for the synchronized reserve ancillary service [44].
(5) DR Regulation Reserve Market: where DR helps adjust the generation to maintain the desired frequency [45].

The Curtailment Service Providers are the intermediate agents for DR resources participating in electricity markets [46]. The total amount of DR is limited less than 25 percent of the whole electricity procurement. There are two classifications of services for DR to select. A single electricity consumer may participate in either or both of the classifications [47]:

(1) Economic DR service: as a voluntary commitment, to receive a revenue stream by reducing their energy use when LMPs are high or shift their energy consumption to the periods when LMPs are lower.

(2) Emergency DR service: as a mandatory commitment, to reduce their loads or only consume under a certain limit, triggered by PJM when a supply shortage or emergency condition occurs. The mandatory commitment means penalties will be charged in case of non-compliance.

4. Group II–zonal price RTMs

The Australian National Electricity Market (NEM) is operated by the Australian Energy Market Operator (AEMO), applied zonal prices settled based on the Regional Reference Price (RRP) for five RRP zone areas: Queensland, New South Wales, Victoria, South Australia and Tasmania [48]. The NEM operates a 5-min real-time, security-constrained, economic dispatch energy market [49].

4.1. AEMO RTM mechanism

In AEMO, the RRP is the marginal cost of supply, based on offer prices at the regional reference node. The reference node is normally selected at a load center (large city). For the RRP calculation, AEMO performs distinctive demand definitions for inter-regional energy delivery [50]:

- Generated Demand: the Generation units' outputs.
- Sent out Demand: the power flow into the region and the transmission and distribution losses.
- Consumed Demand: the consumptions of transmission consumers and distribution consumers.
- Total Demand: the total electrical energy requirement at the exchange point with other regions.

Fig. 7 shows AEMO's Demand Definitions and Market strategies for Integrating DER and DR. The Total Demand in one region is the algebraic summation of the Generated Demand (+ scheduled generation, + semi scheduled generation), Send out Demand (+ flow into region, −transmission and distribution losses) and the Consumed Demand (− forecast transmission and distribution demands, − ADE). The Aggregate Dispatch Error (ADE) in Fig. 7 is to account the non-conformance of dispatched generating units for Regulating Frequency Control.

AEMO operates eight separate markets for Ancillary Services [51]. For each dispatch interval, AEMO's dispatch engine, called 'Scheduling Pricing and Dispatch', tenders for contracts, and calculates clearing prices for each of the eight markets, then settlements to determine payments to serve providers. The eight Ancillary Services markets could be classified in three categories by functions:

- Frequency Control Ancillary Services (FCAS).
- Network Control Ancillary Services (NCAS).
- System Restart Ancillary Services (SRAS).

For FCAS, both offers and bids can contain up to ten bands with non-zero MW capacity. Band prices must be monotonically increasing [52]. NCAS comprises two parts: Voltage Control and Network Loading Control. The former allows Synchronous Compensators to generate or absorb reactive power while not generating energy in the market. The latter controls the flow on interconnectors within short term limits through Automatic Generation Control. SRAS enables the system to restart following a complete or partial system black [53]. Both NCAS and SRAS are long-term contracts, and paid by the blending of Enabling Payment and Availability Payment.

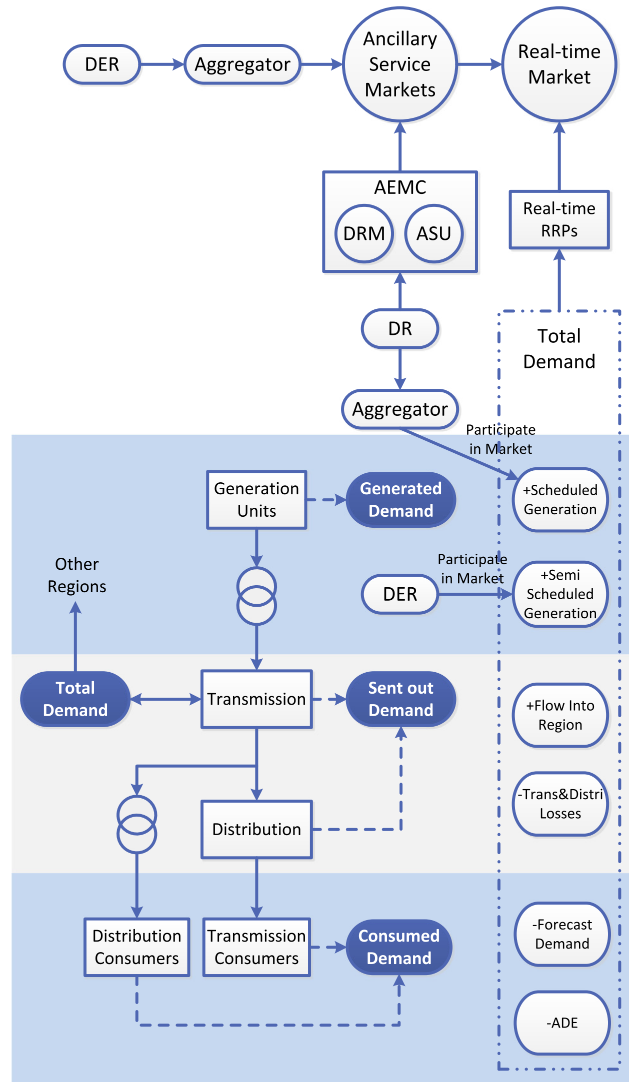

Fig. 7. AEMO's demand definitions and market strategies for integrating DER and DR.

4.2. AEMO RES support mechanism

In AEMO, the aggregators of small DER units and the aggregators of DR are allowed to participate in all the eight Ancillary Service Markets [54]. The ICT system contributes to measuring the amount of each DER or DR in an aggregator in the real time, both measuring power and frequency. The total amount of aggregated generation or aggregated load must be measured within 4 s.

The variation of renewable outputs may be huge [55]. Therefore, interconnectors need to operate at a lower limit in case of overload, which reduces the total available capacity of the power system. The AEMO's solution for this problem is to register RES or DER as semi generators. The Australian Wind Energy Forecasting System [56] is responsible for the forecast of wind and other renewable generations, enables RES to serve as semi-scheduled units to avoid system overload.

4.3. AEMO DR support mechanism

Two major recommendations have been implemented for DR participation in markets developed by the Australian Energy Market Commission [57,58]:

- Demand Response Mechanism (DRM).
- Ancillary Services Unbundling (ASU).

The DRM enables the Demand Response Aggregators (DRA) registered as the same as the other retailers or large generators in particular Demand Response Intervals. AEMO forecasts the energy baseline for each Demand Response Interval based on historic data and the data when demand reduction occurred. When approaching the settlement, the forecast energy baseline is compared with the actual energy consumption to investigate if DR schedule complies or not. DRAs will be paid or charged corresponding to the positive or negative difference between the energy baseline and the actual energy consumption. ASU unbundles part of DRs from their retailers, and establishes a third entity to group these DRs together to register as a DRA. Consequently, DRs' market behaviors will not be under control of their retailers [59,60].

5. Group III–zonal price BMs

This section introduces the coordination between general BM and the tertiary reserve markets (TRM) based on the Zonal Price, represented by most of the European electricity markets, from the perspective of their support mechanisms for RES and DR. Most of the European electricity markets have similar market architectures for integrating DER and DR. The Nord Pool for Denmark is selected as the example for describing the interconnection between BM and TRM.

5.1. Nord pool – denmark

The Nord Pool, which is a leading electricity market in Europe, covers entire North Europe regions including Western and Eastern Denmark, Norway, Sweden, Finland, Germany and Estonia [61,62]. The market architecture is composed of the DAM 'Elspot', IDM 'Elbas', BM (in Nord Pool, called regulating market) and an ex-post balancing market for the financial settlement after the operation [63,64]. In Denmark, Energinet.dk is the TSO. The Danish power system has been divided into two areas [65]:

- Western Denmark (DK1): synchronous with the continental Europe (UCTE), fulfill the ENTSO-E RG Continental Europe Operation Handbook.
- Eastern Denmark (DK2): synchronous with Nordic countries, fulfill the Joint Nordic System Operation Agreement and Energinet.dk's regulations for grid connection.

The reserves classification of Denmark according to UCTE definition is shown in Table 2.

The Energinet.dk purchases the expected capacity of the Manual Regulating reserve by daily auctions. The volume limitation of reserve bids is a minimum of 10 MW and a maximum of 50 MW, respectively. The accepted bids will be cleared for available capacity by marginal pricing. Furthermore, the corresponding BRPs of the accepted bids in the Manual Reserve market, must subsequently submit the power bids to the regulating market, and be paid by the balancing market settlement.

Table 2
Reserves classification in Denmark.

UCTE definition	DK1 (West)	DK2 (East)
Primary reserve	Primary reserve	FNR and FDR
Secondary reserve	LFC	–
Tertiary reserve	Manual regulating reserve	

Note: Load Frequency Control reserve (LFC); Frequency Controlled Normal operating reserve (FNR); Frequency Controlled Disturbance reserve (FDR).

The participation of the Manual Reserve market is not mandatory. BRPs can only submit power bids in regulating market for providing upward or downward balancing power. The regulating market applies a uniform price auction and closes 45 min before operation. The accepted bids in regulating market are activated based on the merit order. After each hour, the energy price for up and down regulation is determined by the marginal price, and the accepted bids are settled accordingly [66].

In Denmark, the balancing market is only an ex-post financial market place for the final imbalance settlement, which is not a physical BM as in the other European markets. BRPs have to participate in the balancing market if their actual productions or consumptions deviate with the scheduled values. The imbalance is settled by dual pricing for positive and negative deviations. Note that, there are two common mechanisms for imbalance settlement [67]:

- Single pricing: the deviation of every BRP is settled with one common price for each settlement period.
- Dual pricing: set only one price for positive deviations and one price for negative deviations in each settlement period, according to the forecast of consumption.

For supporting RES, especially the large scale of wind generation, Denmark adopts a feed-in tariff support scheme, according to which wind generation units on-shore or off-shore can receive a supplement to electricity production prices [68].

To support DR, at present, Electric boilers aggregated over a certain volume of 10 MW can participate in market bids [69].

5.2. Major European BMs

As represented by the Nord Pool for Denmark in the previous section, most of the European electricity markets adopt similar philosophies for market operation. The mechanisms of RTMs, i.e., the BMs in different European countries are almost the same, the main differences between each European market are reflected in the TRM. Therefore, the tertiary reserves are investigated. Table 3 summarizes several major European TRMs, imbalance settlement and their support policies for RES and DR [70].

5.3. RES and DR support mechanisms

This section provides a brief introduction of each major European electricity market and their support mechanisms for RES and DR.

5.3.1. EPEX

Germany adopts ex-ante fixed price for intermittent generations. There exist particular provisions for pumping units or other storage units participate in market bidding. In this provision, renewable storages will not lose their feed-in tariffs if they store their energy for later delivery [71–76]. France provides Fixed feed-in tariffs for most RES. For solar power, two types of feed-in tariffs for solar integrated into the building and for solar installed on the ground respectively [77]. The Swiss Energy Regulation stipulates feed-in tariffs for five different types of RES including small waterpower, photovoltaic, wind power, geothermal energy, and biomass [78].

5.3.2. APX and BELPEX

Netherland establishes the Stimulering Duurzame Energie for solar power, biomass power, hydropower, wind power on-shore/off-shore, and CHP. This scheme offers non-compulsory subsidies

Table 3
Major European TRMs, Imbalance Settlement and RES/DR Support Mechanisms.

Electricity market	Tertiary reserve	Procurement	Capacity pricing	Energy pricing	Imbalance settlement	RES policies	Demand participation
EPEX	German: Tertiary reserve	Auction	Pay-as-Bid	Pay-as-Bid	Single pricing	Ex-ante Fixed Price, Renewable energy law	Pumping units, other storages
	Switzerland: Tertiary reserve	Auction	Pay-as-Bid	Pay-as-Bid	Dual pricing	Feed-in Tariff	Not yet
	France: Contracted fast reserve, Non-contracted delayed or termly reserve	Tender	Fixed price	Pay-as-Bid	Dual pricing	Feed-in Tariff	Not yet
APX & BELPEX	Netherland: Reserve capacity, Emergency power (contracted tertiary reserve)	Tender	Regulated price	Marginal price	Single pricing with incentive	Subsidies scheme, Stimulering Duurzame Energie	Not yet
	Belgium: Tertiary reserve (contracted, non-contracted, interruptible reserve)	Tender	Contract price	Pay-as-Bid	Dual pricing	Offshore Wind Compensation Scheme, Green Certificates	R3-load
MIBE	Spain, Portugal: Tertiary regulation, Deviation Management Mechanism	Continuous Auction	Not remunerated	Marginal price	Dual pricing	Feed-in Tariff, Price-premium	Interruptible load contract
GME	Italy: Tertiary reserve (fast and slow)	Contractual obligation	Pay-as-Bid	Pay-as-Bid	Dual pricing	Green Certificate, Feed-in Tariff, Price-premium, Investment Subsidies, Gestore dei Servizi Energetici	Not yet

to compensate the difference between the cost and necessary revenues for a long period of 12–15 years [79–82]. In Belgium, there are two support schemes for RES: the Offshore Wind Compensation Scheme, and the Green Certificates Systems. DR can participate in tertiary reserve – load [83].

5.3.3. MIBEL

The Royal Decree 661/2007 stipulates that RES generators can chose a regulated tariff or the price plus a premium. DRs are allowed to participate in the TRM and the deviation management market. The Spanish TSO offers interruptible load contracts with big consumers for interrupting load shedding under contingency circumstances [84–87].

5.3.4. GME

In Italy, RES are eligible to access four different support schemes: green certificate market, feed-in tariff, price-premium mechanism and investment subsidies. The State-controlled company ‘Gestore dei Servizi Energetici’ simplifies the procedures of RES purchase and resale [88–90].

5.4. EcoGrid EU – a prototype for European RTM

European countries have taken great attention on the innovation of RTM. The large-scale demonstration project EcoGrid EU is the beacon example of RTM, which receives the highest research investment in Europe by now, total budget 21 million €. As one of the FP7-Energy projects, EcoGrid EU illustrates a prototype of the large-scale demonstration for a 5-min real-time marketplace integrating DER and DR. According to EcoGrid’s RTM concept, the new RTM has no restriction on the units’ size. ICT systems enable small DER and DR to offer rapid and efficient balancing services by complying with the RTM Operator’s instructions [91].

According to the EcoGrid EU research, the new RTM has the following features [92–95]

- Remain the conventional BM (in EcoGrid EU, called regulating power market), add a RTM (clears 5-min) which overlaps or complements or cooperates with the BM (clears 15-min).
- Allow DER and DR to receive and respond to variable electricity prices. Therefore, implies the potential for improving system operation by utilizing resources that would otherwise have been left unused.
- Bidless market: DR has no competence on creating bids and schedules, but only respond to the current market prices.
- RTMO: the real-time price is set by an independent RTM Operator, usually the TSO, and published in advance of each time period.
- 5-min intervals: the time resolution of pricing is 5 min with high computing performance for real time response signals’ exchange.
- Locational pricing: reflect the dynamic utilization of the grid capacity in order to manage possible congestions on both transmission and distribution levels.
- The RTM is an additional source of regulation capacity in parallel with the regulating power market. Consequently, the real-time prices must be set in close coordination with the price development on the regulating power market.

6. Discussions

As introduced in the previous sections, three groups of RTMs have distinct market mechanisms for integrating DER and DR, while coordinating with the relevant ancillary service markets for supporting the power system regulation. Table 4 summarizes the major philosophy of RTM integrating DER and DR.

6.1. Market policy

The market policies vary geographically, but mostly in common. All the electricity markets mandatorily require the large centralized producers to sign a bilateral contract with the Local Transmission Operating Organizations, e.g., TSOs. TSOs check large producers’ certifications and competences corresponding to market safety and reliability rules. TSOs also sign particular contracts with aggregators and retailers who offer DER and DR services. Under current market structures, most balancing services are provided by large centralized power plants, which have the market power to raise the market prices significantly to increase their profits. In contrast, the DER/DR services in RTM help to reduce system operating costs thereby decrease the market prices. Since large centralized producers dominate the market, when competing in the same market (e.g., DRs bid in the Day-ahead scheduling reserve market in PJM, and DER/DR bid in the eight Ancillary Service Markets in AEMO), DER/DR aggregators or retailers could not receive

Table 4
Major Philosophy of RTM Integrating DER & DR.

RTM group	I	II	III	Research project
Represent	PJM	AEMO	Nord Pool	EcoGrid EU
Pricing scheme	Nodal	Zonal	Zonal	Nodal
OPF	Yes	No	No	Yes
Pricing interval	5-min	5-min	45-min	5-min
Settlement interval	Hourly	Hourly	Hourly	Hourly
Markets coordinate	RTM, Operating Reserve Market	RTM, Ancillary Service Markets	BM, TRM	RTM, BM, TRM
DER & DR participate	Curtailment Service Providers, 5 DR Markets	Semi Gen, DRM, ASU	Aggregator over 10 MW	No unit size restriction
DER & DR major playground	RTM	RTM	TRM	RTM

equivalent transaction treatment as the large centralized producers.

6.2. Prosumers' behaviors

In RTM, there exist a large number of prosumers, aggregators, clusters, retailers. Each player aims at maximizing its profit. When joining in RTM, the Market Operator needs to develop incentives to encourage prosumers to behave in the way that want them to. Therefore, it is necessary to eliminate their financial risk and consider their market behaviors. Prosumers have different physical and financial conditions. Some prosumers are inelastic demand or without installing smart meters, who should only play a fix tariff scheme. Some prosumers are risk-averse with elastic demand, who would enjoy flexible electricity usage. Other prosumers are risk-neutral or risk-prone, who could enjoy flexible electricity usage and price volatility. The market equilibrium analysis based on the Nash Equilibrium is the popular method to investigate players' behaviors.

6.3. Pricing and settlement scheme

For pricing scheme, the nodal price is applied by RTM Group I and the research project – EcoGrid EU, while the zonal price is applied by RTM Group II and III. Normally, zonal price implementation is because of crossborder requirements between different regions' governments. Moreover, applied zonal prices need high enough margin capacities of the transmission lines, since the power flows on each line are unknown. For nodal prices, the accurate power flows on each transmission line are known, therefore, the marginal capacity of the lines could not be too ample. The economical meaning of nodal price is affirmative. For the long-term planning, the electricity loads continue to increase, consequently, the marginal capacity of transmission lines will become less and less. Thus, nodal prices have the advantage on maintaining system security and reliability.

For settlement, more markets choose dual pricing than single pricing. In single pricing, it is usual that the price is higher in undersupply and lower in oversupply.

6.4. Real time resolution

RTM Group I and II has the pricing interval as 5 min (e.g., PJM and AEMO), while RTM Group III (e.g., European Markets) has the pricing interval within an hour. The settlement interval for all the Groups is hourly. The future market design with short-term pricing entails rapidly adjustment to the fluctuations and uncertainties in the power system. The current hourly time resolution seems too rough since RES may vary greatly within one hour. The current gate closure time, in any markets of energy, regulating power and ancillary services, seems too rigid since RES may activate slowly. Recent time resolution implies that the equilibrium price is a constant within a time intervals, e.g., an hour; the settlement is based on average values over intervals, e.g., MWh/h. However, the activation of reserves is continuously. There exists the contradiction that pricing, settlement, and reserve payments may be not reasonable for RES/DER.

6.5. Market coordination

Recently, RTMs (5-min in Group I, II and EcoGrid EU) usually work coordinating with the relevant ancillary service markets, which support the power system regulation. The reason for this kind of cooperation is that most of the balancing services are provided by centralized large generating units. The aggregators of DER/DR provide balancing service in RTM in a small quantity but faster (5-min) than large centralized generators (15-min). Hence, the DER/DR complement the balancing services in RTM and other markets which support the power system regulation (e.g., Operating Reserve Market in PJM, and Ancillary Service Markets in AEMO). For Group III, the time resolution is within an hour, rougher than the 5-min Groups. The RTM (i.e., BM) coordinates with TRM intro-hourly.

6.6. RES support

All the markets welcome RES by providing some preferential incentives, such as Feed-in Tariff, Green Certificates, Price-premium, etc. Besides, special organizations are operating for supporting RES, e.g., the Australia Wind Energy Forecasting System, Stimulering Duurzame Energie in Netherland, Gestore dei Servizi Energetici in Italy, and so on. However, restrictions still limit the total generation of RES. AEMO limits the trading volume of RES by semi generator registration. Most electricity markets set the upper bound of total RES production not to exceed a certain proportion of the total trading volume. When the RES suddenly generates too much due to meteorological reasons, there will be excessive energy production leading to power system imbalance. One common solution is storage. Right now, storages can bid in certain reserve and ancillary service markets. Especially in Germany, storages bidding in markets can still enjoy their feed-in tariffs.

6.7. DER and DR participation

A large gap exists on DER and DR participating in electricity markets among different Groups. In Group I and II, DER/DR have become the integrated part of the market. DER/DR aggregators are permitted to participate in RTM and other Ancillary Service Markets. In PJM, there are five special market places for DR services' transactions. Professional organizations have been established for aggregating DER and DR, e.g., Curtailment Service Providers in PJM, and DRM/ASU in AEMO. However, in Group III, only certain types of DER/DR aggregators are allowed to participate in TRM, e.g., some storages, interruptible loads.

Another main difference is the major playground of DER and DR. For Group I, II and project EcoGrid EU, DER/DR participate mainly in RTM. While for Group III, DER/DR mainly play in TRM.

6.8. OPF and reactive power

Since DER and DR integrated in power systems, sharing large fluctuations and flexibilities, the Power Quality problems are obvious. Most small DER and DR connect to the local distribution network, enable the distribution grid actively to produce energy and reduce consumption. The active distribution grid (opposite to the conventional passive distribution grid without monitoring and control, with the 'fit and forget' philosophy for DER and DR) are able to handle bi-directional power flows and information exchanges based on the advanced ICT systems. The voltage decline can be a threat to Power Quality. Due to integration of many electronic equipment, storages, and batteries, DER/DR usually consume reactive power greatly. Only reactive power can contribute to voltage compensation. Therefore, DC OPF seems not appropriate so that it is better to select AC OPF to dispatch the system. When it comes to market implementation, fixed contracts are used to confirm the volumes of reactive power compensations in advance, and pay them no matter how much reactive power really used.

7. Conclusions

This paper reviews the advanced typical representatives of RTMs respectively in the North America, Australia and Europe, focusing on the market architectures and incentive policies for integrating DER and DR in electricity markets. The conclusions are summarized as follows:

(1) The nodal price and zonal price are both implemented in different kinds of RTMs. The nodal pricing scheme is relatively more economical due to the more detailed modeling of the system.
(2) The pricing interval for RTM is 5 min in North America and Australia, intro-hourly in Europe. The settlement interval for RTM is usually hourly.
(3) The RTM coordinates with the relevant ancillary service markets, which support the power system regulation, e.g., ASMs, TRM.
(4) DER and DR participate in electricity markets through Aggregators.
(5) The major playgrounds for DER/DR in an electricity market are RTM and TRM.

In the future, DER and DR will play their roles in RTM to provide balancing power for handling unpredicted imbalances and relieving the expensive frequency control based reserves like primary and secondary reserves. The RTM integrating DER and DR will facilitate asset utilization, stimulate prosumers' active responses, and consequently, maintain the security and reliability of power systems.

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