Suspension of Australian National Electricity Market in 2022 Necessitates Mechanism Evolution Ensuring Power Supply Security

Zhenfei Tan, Hua Geng, Xiaoyuan Xu, Sijie Chen, and Zheng Yan

***Abstract*—The National Electricity Market (NEM) in Australia was suspended during June 15-23, 2022, with a primary attribution to the lack of available generation capacity. This incident is noteworthy because it was the first market suspension in NEM's history and took place in a major energy exporting country. In this letter, we review the outline and impacts of the incident. From the perspectives of market regulation, electricity supply, and electricity demand, we identify three underlying causes of the market suspension and offer four recommendations for the market mechanism evolution to ensure power supply security.**

***Index Terms*—Electricity market, administered pricing, power system security, energy crisis, demand response.**

I. Introduction

FOR the first time since the market's launch in 1998, the National Electricity Market (NEM) was suspended by Australia Energy Market Operator (AEMO) on June 15, 2022. During the 9 days of market suspension up to June 23, the generation output was scheduled by both the market-based dispatch and directions from AEMO, and the electricity price was set in accordance with the previously established suspension price schedule. The incident was primarily caused by the tight fuel supply that swept the globe in 2021, and was directly triggered by the withdrawal of generation capacity driven by the inversion between the soaring fuel costs and the depressed administered price.

The incident of electricity shortfall and market suspension is unusual in that it occurred in a major energy exporting nation, which necessitates an investigation into the underlying causes. In this letter, we revisit the process of the incident and analyze its causes and effects. Three factors, namely the incompatibility between the market and the administration, inadequate energy supply due to fuel shortage, and lack of demand elasticity, are identified as major causes of the incident. Four recommendations are then concluded concerning the causes of the incident for improving the power supply security. This letter may help the industry and academia to identify key factors that lead to the market suspension, and inspire the research to update the market design toward secure power supply under extreme conditions.

II. Outline of Market Suspension

A. Overview of NEM

The NEM serves the spot electricity trading in five states of Australia, including New South Wales (NSW), Queensland (QLD), South Australia (SA), Tasmania (TAS), and Victoria (VIC). In 2021, the NEM is responsible for 91% of electricity consumption in Australia, with a generation mix dominated by coal (64.7%), followed by wind (10.5%), solar (10.8%), and gas (6.6%). In the NEM, the electricity is traded on a 5 min interval based on biddings from participants and is cleared with the regional marginal price.

Besides the normal operation of the market, there are mechanisms for emergency conditions, which play a significant role in the suspension of the NEM, including:

1) Administered price cap (APC), which is used to restrict longstanding high electricity prices. When the cumulative price over the previous 2016 dispatch intervals (equivalent to 7 days) exceeds a threshold, the APC will be triggered. The threshold is assessed every fiscal year and equals 1359100 AUD/MWh from October 1, 2021 to June 30, 2022 (equivalent to an average price of 674.16 AUD/MWh) [1].

2) Lack of reserve (LOR) condition, which is declared by AEMO when there is possible load shedding due to the shortfall of capacity reserves. The LOR condition has three levels in the NEM, namely LOR1, LOR2, and LOR3, with increasing severity.

3) Reliability and Emergency Reserve Trader (RERT), which is a long-term reserve contract between AEMO and unscheduled resources for maintaining system reliability. The RERT will be triggered under conditions of projected shortfall of electricity and capacity supply.

Manuscript received: August 8, 2022; revised: September 20, 2022; accepted: October 19, 2022. Date of CrossCheck: October 19, 2022. Date of online publication: October 27, 2022.

This work was supported by the National Natural Science Foundation of China (No. U2166201) and China Postdoctoral Science Foundation (No. 2022TQ0206).

Z. Tan, H. Geng, X. Xu, S. Chen, and Z. Yan (corresponding author) are with the Key Laboratory of Control of Power Transmission and Conversion, Ministry of Education, and Shanghai Non-Carbon Energy Conversion and Utilization Institute, Shanghai Jiao Tong University, Shanghai 200240, China (e-mails: zftan@outlook.com; genghua@sjtu.edu.cn; xuxiaoyuan@sjtu.edu.cn; sijie.chen@sjtu.edu.cn; yanz@sjtu.edu.cn).

DOI: 10.35833/MPCE.2022.000500

B. Power Balance Condition

Due to the limited supply of thermal coal and natural gas and the early arrival of winter in Australia, the electricity balance of the NEM had been getting tight since the beginning of 2022. The power balance situation and spot electricity price in NEM are shown in Fig. 1. It can be observed from Fig. 1(b) that the electricity price increased and became more volatile in the second week of June as a result of tightening the power supply. Before June 12, the regional price in QLD broke through 1000 AUD/MWh almost every day. In June, the average price of NEM increased to 337 AUD/MWh, about 3.9 times what it was during the same period in 2021.

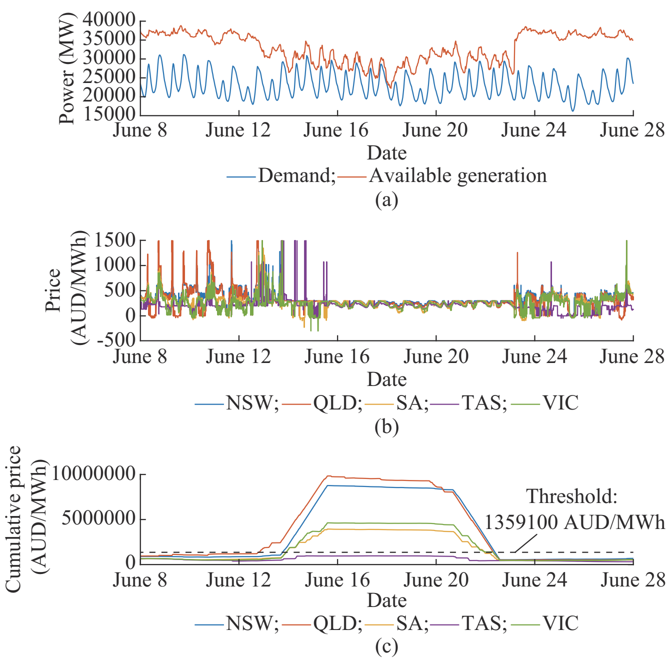

Fig. 1. Power balance situation and spot electricity price in NEM. (a) NEM-level aggregated demand and available generation. (b) Regional reference prices of NSW, QLD, SA, TAS, and VIC. (c) Cumulative prices.

The longstanding high price triggered the administered pricing, which capped the market price at the APC of 300 AUD/MWh. As shown in Fig. 1(c), the threshold was first exceeded in QLD on June 12, then in NSW, SA, and VIC on June 13. The spot prices of these four regions were capped once the cumulative prices reached the threshold, as can be observed in Fig. 1(b).

The APC suppressed generators' willingness of participating in the market. As shown in Fig. 1(a), there was an immediate drop in available generation capacity on June 13 when the administrated pricing was activated. Over 3 GW of generation capacity was withdrawn in NSW and 2 GW in VIC once the APC was implemented. The shrinking of the power supply was also reflected in the price. Though the market price was capped at the APC, the cumulative price was calculated as if the administrated pricing was not exercised. As shown in Fig. 1(c), the cumulative price climbed sharply in the four regions with the APC following the commencement of the administrated pricing. Facing the tight power supply, AEMO declared 406 actual and forecast LOR conditions in the second quarter of 2022, which is roughly 6 times more than the corresponding period in 2021. In response to the forecasted shortfalls of supply and LOR, AEMO began to intervene in the market on June 10. On June 14 and 15, directed generation capacity reached close to 5 GW, which became the prelude of the market suspension.

C. Market Suspension

The NEM spot market was suspended in all 5 regions starting at 14:05 Australian Eastern Standard Time (AEST) on June 15, 2022. The market suspension was declared under Clause 3.14.3 of the National Electricity Rules (NER) [2], which allows AEMO to suspend the spot market in a region when any of the three conditions occur, i.e., ① power system blackout, ② jurisdictional direction to suspend the market, and ③ inability to operate the spot market in accordance with the NER. The third condition may be encountered in two circumstances including information technology (IT) failures and a major power system emergency other than blackout [3]. The current market suspension was triggered by the third condition owing to critical inadequacy of generation and reserve capacity, as AEMO had announced that "it has become impossible to continue operating the spot market while ensuring a secure and reliable supply of electricity for consumers in accordance with the NER" [4].

D. Dispatch and Pricing During Suspension

The bidding-based optimal dispatch was still performed during the market suspension. To maintain the system reliability, AEMO intervened in the operation of generators and non-regulated interconnectors by issuing directions. AEMO issued a total of 439 directions with a combined capacity of 30389 MW during the suspension period. In addition, the RERT was activated in NSW and QLD to offset the LOR, with a total volume of 4042 MW [5].

What differs most during the suspension is the pricing scheme. At the beginning of the suspension, AEMO identified that it was impracticable to determine prices with the bid-based market clearing. Therefore, the Market Suspension Pricing Schedules (MSPSs) were employed to determine settlement prices for each product (energy and ancillary services) and each region. The MSPS contains two sets of 30 min prices, one for business days and the other for non-business days. Each set of prices in the MSPS is calculated as the average of historical prices for the previous 28 same-type days and is then capped at the APC. Since the systems in different regions are interconnected, regions that have net power flow towards a suspended region will also be capped at the price of the suspended region. The MSPS for the net-export regions is also adjusted by power loss factors to avoid negative inter-regional settlement residues. The MSPS is updated and released once per week [6].

The direct dispatch instruction and the price cap may cause economic loss for participants. Hence, AEMO and Australian Energy Market Commission (AEMC) had to pay additional compensations to scheduled generators and demand response providers who failed to recoup the benchmarked costs during the MSPS periods [7]. All the compensation payments will be recovered from customers and retailers in the NEM [8].

E. Market Resumption

The power balance conditions kept improving across the NEM regions since the market suspension, thanks to the direct instruction to generation capacity and the milder power demand driven by warmer weather. Up until June 22, 4 GW of generation capacity, or 13.6% of the daily peak load, had been restored. The administrated pricing ended in South Australia on June 22 and ended in QLD, NSW, and VIC on the following day as the cumulative price fell below the threshold. AEMO moved to lift the market suspension after this improvement. The market was resumed following two steps. The first step was market-based pricing, starting from 04:00 AEST on June 23; and the second step was a complete return to normal market operation without manual interventions, starting from 14:00 AEST on June 24. By this time, the market suspension lasting for 9 days in the NEM finally ended.

After the first-step movement, the APC was also removed, which immediately caused market prices to become more volatile, as shown in Fig. 1(b). The figure also shows that negative prices began to appear, indicating that there was an excess of renewable generation during the period.

III. Impacts on Participants

A. Supply Side

The supply side is most likely to profit from the market suspension. Because of the tight electricity supply, generators had opportunities to set the price and earn more payments. Before the administrated pricing, the increasing market price increased the income of online generators. During the market suspension, though the market price was set by the MSPS and was capped at the APC, generators can obtain extra compensation for providing energy and ancillary services.

There are five types of compensation for generators. ① Direction compensation, paid to directed participants at 90% spot price. ② Market suspension compensation, paid at benchmark value to scheduled generators. Based on the corresponding generation cost with a 15% uplift, the benchmark value is determined for different generating fuel sources or technology types [9]. ③ The RERT payment, which is applicable for generators with an exercised RERT contract to provide reserve capacity. ④ Intervention pricing compensation, which is paid to generators impacted by the intervention of AEMO following a what-if pricing manner. ⑤ Administered price compensation, which compensates the direct cost and opportunity cost of generators when the administrated pricing is effective. The first four types of compensation are paid by AEMO, while the last type is paid by AEMC in response to requests from generators.

B. Demand Side

For electricity users, the immediate market suspension prevented the widespread of electricity shortage and system-level blackout. According to the contracts with AEMO under RERT, some industrial loads were curtailed, and residents in QLD were also suggested to use less electricity during peak hours. However, the power consumption of users was not significantly interrupted during this incident.

For retailers, the impacts were more diversified. Retailers were under financial strain as a result of the high electricity prices that persisted for months before the market suspension. Large retailers would be exposed to less financial risk if they had sufficient generation assets or future contracts. Small retailers, on the other hand, would be more financially vulnerable due to the exorbitant wholesale price that might reduce their margins. The administrated pricing before and during the market suspension protected retailers from exposure to the extremely high wholesale electricity price. This was an improvement in comparison with the electricity crisis that happened in California, USA in 2001. In California, the deregulated wholesale price soared owing to the tight power supply and market manipulations, while the retail price was capped, which resulted in significant financial loss and even bankruptcy of retail companies.

In addition, retailers are under pressure to incur compensations paid to generators during the market suspension. First, these costs are outside long-term hedging contracts of retailers and have to be recovered from customers. Second, the fees that customers pay cannot be frequently changed. Retailers will bear the additional cost until the retail price can be adjusted, which will put a strain on their cash flow.

C. System Operator and Regulator

AEMO is in charge of both wholesale market operation and physical system dispatch for the NEM. Though the NEM market was suspended in accordance with the NER, the industry had reservations about the rationality of the APC setting and cost allocation for the compensation payment. It is thought that the direct cause of generators leaving the market is the relatively low APC in comparison with the high fuel cost. The rationality of the administrated pricing and the APC setting were queried for this incident. Another complaint is about the cost allocation for compensations to generators. The compensation payments are allocated to the demand side based on the gross energy consumption and the region benefit assigned by AEMO. However, it is difficult to judge who benefits more from the market suspension and administrated pricing, and thus raising concerns about fairness.

IV. Cause Analysis

The market suspension was triggered by the shortfall of available generation capacity, as analyzed in Section II-C. Several factors, including planned generator maintenance and transmission outage, low wind and solar generation, generation withdrawal, and the rising electricity demand driven by the early onset of winter, were listed by AEMO in its announcement of the market suspension. We categorize the contributing factors that lead to the incident into direct causes and underlying causes regarding the supply and demand sides, as shown in Fig. 2. Three causes, namely the inversion between low APC and high fuel costs, the limited fuel supply, and the insufficient demand-side elasticity, are most notable and are analyzed as follows.

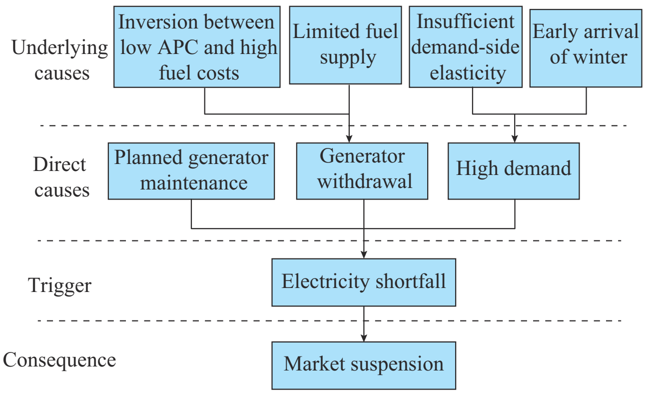

Fig. 2. Reason analysis of market suspension.

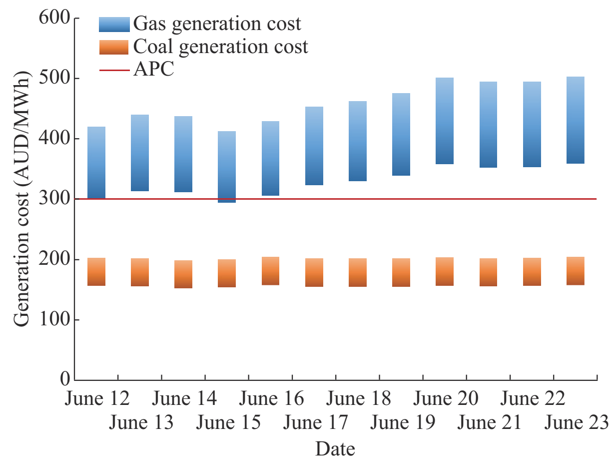

Fig. 3. Estimated fuel-related cost of coal-fired and gas-fired generators.

A. Inversion Between Low APC and High Fuel Costs

Prices of coal and natural gas started to soar globally in 2021 due to the loose monetary policy, rebound demand after the COVID-19 pandemic, and regional conflicts. In June 2022, Newcastle coal was recorded at over 600 AUD/ton, and the spot price of natural gas in Australia reached the cap of 40 AUD/GJ, which were 3-5 times higher than in previous years. The rising fuel costs pushed up the electricity price significantly, which ultimately triggered the threshold for applying the APC.

In Fig. 3, we estimate the fuel-related costs of thermal generation based on the prices of coal and natural gas in Australia. The gas price is collected from the Short Term Trading Market operated by AEMO [10], and the coal price comes from the ICE Newcastle coal futures. Fuel consumptions for coal-fired and gas-fired generation are set at 0.27-0.35 kg/kWh and 8.6-12 MJ/kWh, respectively. As shown in Fig. 3, the fuel-related costs of gas-fired generation were higher than the APC for the majority of the time between June 12 and June 23. Though fuel-related costs of coal-fired generation were lower than the APC, the high price of coal would significantly reduce generators' profit margins. Compared with staying in the market with the APC, generators would be paid more if the market would be suspended. Consequently, generators have a strong motivation to withdraw capacity from the market.

B. Limited Fuel Supply

In addition to the economic drive, physical restrictions such as the limited fuel supply also contributed to the shortfall of the power supply. The local coal mining and transportation in eastern Australia were negatively impacted by floods and heavy rains in March 2022, which led to the surge in coal prices. Furthermore, because wind and solar generation output was relatively low in the previous months, the power supply in Australia relied more on thermal generation, hastening the depletion of coal and gas storage. The limited fuel supply and storage suppressed the generation capability of thermal generators, which was also an inducement to the market suspension.

C. Insufficient Demand-side Elasticity

Demand-side elasticity is an economical manner to maintain the power system security in emergencies; however, the demand-side elasticity was not fully activated in the market suspension event in Australia. AEMO started the wholesale demand response (WDR) program on October 24, 2021. As of June 2022, a total capacity of 59 MW of WDR resources was registered in NSW, VIC, and SA. During the market suspension, only 20 MW of WDR was activated. This amount of active WDR was tiny compared with the forecast capacity shortage of several thousand megawatts. The insufficient demand-side elasticity not only aggravated the difficulty of power balance, but also amplified the market power of the supply side and created conditions for generators to manipulate the market when the supply was tight.

V. Lessons and Concluding Remarks

After examining the process and causes of the market suspension, some issues regarding the market design, regulation, supply-side adequacy, and demand-side elasticity are note worthy. Lessons and recommendations regarding these aspects will be discussed in what follows.

A. Incorporating Emergencies in Market Design

The design of the electricity market considers the mild power supply and demand conditions. However, with the increasing penetration of volatile renewable generation, extreme weather conditions, and unstable energy supply worldwide, the electricity market design should get ready for more frequent emergencies caused by abnormal supply-demand conditions. First, to deal with power crises caused by fuel tightness, the fuel delivery and storage conditions should be incorporated in the assessment and declaration of the LOR. Second, the power scarcity should be reflected in the real-time price signal and should be conducted to terminal users. Possible ways may include: dynamic setting of the price cap considering the fuel supply cost, pricing for diversified reliability requirements, and cost-causation-aware allocation of RERT payment.

B. Concerting Market and Administration for System Security

The market failure may occur in the presence of supply shortfall and market power. In these situations, administrative interventions are necessary to rectify the market. In the NEM, however, the incompatibility between the market pricing and the administrative intervention is a primary cause of the market suspension, as analyzed in Section IV-A.

First, administrated pricing may distort the market. The administrated pricing is implemented to protect the demand side from the longstanding high electricity price, but it offers inadequate incentives for the participation of both generation and demand response. Consequently, the capped price aggravates the tight power balance condition. The function of the spot price is to reflect the short-term operating cost and the supply-demand condition. Though the volatility of the spot price may bring financial risks to participants, these risks should be hedged through financial instruments rather than administrative interventions.

Second, the fixed value of the APC is incompatible with the fluctuating fuel cost. The administered pricing scheme was designed to protect and sustain electricity trading in the scenarios with sustained high prices. The APC of 300 AUD/MWh was set when the NEM was launched in 1998, and has remained unchanged ever since. As analyzed in Section IV-A, gas-fired generators that are usually used to serve peak loads cannot recover the fuel-related cost at the APC. Consequently, generators would withdraw their capacity and wait for the market suspension to get additional compensations. Therefore, it is necessary to dynamically adjust the APC adapting to the present fuel costs and internalizing the compensation payments into the administered pricing.

C. Recognizing Importance of Energy Adequacy for Power Supply Security

The demand and supply of electricity need to be balanced simultaneously, which requires the adequacy of controllable generation capacity to follow the fluctuant load and renewable generation. However, the market suspension that happened in the NEM is a reminder of the necessity of energy adequacy to deal with the electricity shortage lasting for a period.

In the NEM incident, the limited supply of thermal coal and natural gas was a significant reason for the electricity shortage. In recent years, similar electricity shortfall caused by energy inadequacy also occurred in Texas, USA and China. In February 2021, Texas experienced a large-scale electricity shortage lasting for more than 5 days and had a maximum load shedding of 20 GW [11]. According to [12], the direct cause for this event is the insufficiency of sustainable natural gas supply for electricity generation caused by extreme cold weather. In China, the electricity shortage occurred in the last two quarters of 2021, impacting electricity consumption in more than 20 provinces. Load shedding and rolling blackouts were exercised in provinces with extremely tight electricity supply. Complex factors contributed to the electricity shortage in China, but the limited supply and rising price of thermal coal were key factors.

The aforementioned electricity shortage events share common features, i.e., the installed capacity of the system is adequate, but the energy supply capability is insufficient due to fuel limitations. Compared with incidents driven by contingencies such as element faults, the load shedding caused by energy insufficiency may last longer from several days to months. With the growth of renewable generation and the increasing frequency of extreme weather conditions [13], energy insufficiency may become a critical threat to the reliable power supply. The generation capability from wind and solar energy is volatile, and the long-duration low output of renewable generation will hasten the consumption of fuel storage, and thus suppressing the power supply. More attention is needed to the energy adequacy for the power system security, including medium- and long-term renewable generation forecast, energy balance analysis, integrated analysis of fuel supply and power system operation [14], long-duration energy storage [15], and mechanisms for incentivizing the energy adequacy.

D. Updating Market Design to Activate Demand-side Elasticity

The market design needs upgradation to enable the direct involvement of users to stimulate the elasticity of electricity demand. In addition to the widely-studied demand response programs that focus on incremental adjustment, this letter suggests three schemes to enable the integral involvement of electricity consumption.

The first is the two-sided market, which allows the demand side to directly bid into the market and set the price. Compared with the single-sided market where users can only respond to the price after the market is cleared, the two-sided market considers demand-side bidding in the market clearing phase and can maximize the utilization of demand-side elasticity [16]. This scheme has already been discussed by the Council of Australian Governments Energy Council, with an ambition to transit NEM into a two-sided market in 2025.

The second is the popularization of distributed energy trading. Transaction costs and participation requirements are obstacles for small-scale users to participate in the wholesale market directly, which calls for energy trading at the distribution level. The local utilization of distributed resources will reduce the net load supplied by centralized generators, which will alleviate the supply pressure of the centralized system in emergencies [17].

The third is differentiated demand bidding and pricing for the reliability requirements of customers. Conventionally, the electricity is traded as a homogeneous commodity with identical prices for participants at the same location based on the hypothesis that users have the same preference for power supply reliability. However, this scheme neglects the fact that the importance of loads is diversified and some loads are willing to be interrupted if they are charged less. By allowing users to choose supply services with diversified reliability guarantees, the reliability constraint of power system planning and operation will be relaxed, which will reduce the technical difficulty and economic cost of maintaining the secure power supply. Differentiated reliability treatment can improve the demand-side elasticity for capacity, which will also restrain the supply-side market power during electricity shortage.

REFERENCES

[1] AEMC. (2021, Apr.). Schedule of reliability settings. [Online]. Available: https://www. aemc. gov. au/sites/default/files/2021-04/Schedule% 20of% 20reliability% 20settings% 20-% 20Calculation% 20FY21-22%20-%207%20April%202021.pdf

[2] AEMC. (2022, Jul.). National electricity rules clause 3.14.3. [Online]. Available: https://energy-rules.aemc.gov.au/ner/396/127266#3.14.3

[3] AEMO. (2021, Oct.). Market suspension and systems failure. [Online]. Available: https://aemo. com. au/-/media/files/electricity/nem/security_and_reliability/power_system_ops/procedures/so_op_3706-failure-of-market-or-market-systems.pdf?la=en

[4] AEMO. (2022, Jun.). AEMO suspends NEM wholesale market. [Online]. Available: https://www. aemo. com. au/newsroom/media-release/aemo-suspends-nem-wholesale-market

[5] AEMO. (2022, Aug.). RERT reporting. [Online]. Available: https://aemo.com.au/en/energy-systems/electricity/emergency-management/reliability-and-emergency-reserve-trader-rert/rert-reporting

[6] AEMO. (2022, Jun.). Market suspension pricing methodology. [Online]. Available: https://aemo. com. au/-/media/files/electricity/nem/data/mms/estimated-price-methodology-suspension-ner-3-14-5.pdf

[7] AEMO. (2022, Jun.). AEMO/AEMC compensation mechanism briefing. [Online]. Available: https://www. aemo. com. au/-/media/files/electricity/nem/data/mms/2022/compensation-mechanism-briefing-23-june-2022.pdf?la=en

[8] AEMO. (2022, Jun.). Market suspension FAQs-June 2022. [Online]. Available: https://www. aemo. com. au/-/media/files/electricity/nem/data/mms/2022/market-suspension-faqs-june-2022.pdf?la=en

[9] AEMO. (2022, May). Market suspension compensation methodology. [Online]. Available: https://aemo. com. au/-/media/files/stakeholder_consultation/consultations/nem-consultations/2020/wholesale-demand-response/final-stage/market-suspension-compensation-methodology. pdf? la=en&hash=4D9C7546C80F984B0808862E48871CD0

[10] AEMO. (2022, Jul.). Ex post market data of the short term trading market (STTM). [Online]. Available: https://aemo. com. au/energy-systems/gas/short-term-trading-market-sttm/data-sttm/daily-sttm-reports

[11] K. Gruber, T. Gauster, G. Laaha *et al*., "Profitability and investment risk of Texan power system winterization," *Nature Energy*, vol. 7, no. 5, pp. 409-416, Apr. 2022.

[12] G. Zhang, H. Zhong, Z. Tan *et al*., "Texas electric power crisis of 2021 warns of a new blackout mechanism," *CSEE Journal of Power and Energy Systems*, vol. 8, no. 1, pp. 1-9, Jan. 2022.

[13] A. T. D. Perera, V. M. Nik, D. Chen *et al*., "Quantifying the impacts of climate change and extreme climate incidents on energy systems," *Nature Energy*, vol. 5, no. 2, pp. 150-159, Feb. 2020.

[14] C. M. Correa-Posada and P. Sanchez-Martin, "Integrated power and natural gas model for energy adequacy in short-term operation," *IEEE Transactions on Power Systems*, vol. 30, no. 6, pp. 3347-3355, Dec. 2014.

[15] T. Yang, W. Liu, G. J. Kramer *et al*., "Seasonal thermal energy storage: a techno-economic literature review," *Renewable and Sustainable Energy Reviews*, vol. 139, pp. 110732, Apr. 2021.

[16] M. Khorasany, R. Razzaghi, A. Dorri *et al*., "Paving the path for two-sided energy markets: an overview of different approaches," *IEEE Access*, vol. 8, pp. 223708-223722, Nov. 2020.

[17] L. Strezoski, H. Padullaparti, F. Ding *et al*., "Integration of utility distributed energy resource management system and aggregators for evolving distribution system operators," *Journal of Modern Power Systems and Clean Energy*, vol. 10, no. 2, pp. 277-285, Mar. 2022.

Zhenfei Tan received the B.E. and Ph.D. degrees in electrical engineering from Tsinghua University, Beijing, China, in 2017 and 2022, respectively. He is currently a Postdoctor Researcher with Shanghai Jiao Tong University, Shanghai, China. His research interests include electricity market, distributed resource aggregation, and non-iterative coordinated optimization.

Hua Geng received the B.S. degree in electrical engineering from Shanghai Jiao Tong University, Shanghai, China, in 2022. She is currently pursuing the Master's degree in the Department of Electrical Engineering, Shanghai Jiao Tong University. Her research interests include uncertainty analysis of power system, coupled operation analysis of transportation and distribution network.

Xiaoyuan Xu received the B.S. and Ph.D. degrees in electrical engineering from Shanghai Jiao Tong University, Shanghai, China, in 2010 and 2016, respectively. He was a Visiting Scholar with the Robert W. Galvin Center for Electricity Innovation, Illinois Institute of Technology, Chicago, USA, from 2017 to 2018. He is currently an Associate Professor with Shanghai Jiao Tong University. His research interests include power system uncertainty quantification and power system optimization.

Sijie Chen received the B.E. and Ph.D. degrees from Tsinghua University, Beijing, China, in 2009 and 2014, respectively. He was an Assistant Research Professor with the Department of Electrical Engineering and Computer Science, Washington State University, Pullman, USA, from 2014 to 2016. He is currently a Tenure Track Associate Professor of Electrical Engineering, Shanghai Jiao Tong University, Shanghai, China. His research interests include energy blockchain, demand response, transactive energy system, and electricity market.

Zheng Yan received the B.S. degree in electrical engineering from Shanghai Jiao Tong University, Shanghai, China, in 1984, and the M.S. and Ph.D. degrees in electrical engineering from Tsinghua University, Beijing, China, in 1987 and 1991, respectively. He is currently a Professor with Shanghai Jiao Tong University. His research interests include application of optimization theory to power systems, electricity market, and dynamic security assessment.