A Data-driven Analysis of Supply Bids in CAISO Market: Price Elasticity and Impact of Renewables

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***Abstract*—One month of supply bids in the California ISO day-ahead energy market are analyzed in this paper. A total of 1.5 million records of bid data are studied. The bids are studied based on their types and their distribution at different hours. The relationship between the market price and the offered supply capacity are investigated. A data-driven estimate is provided for the aggregated supply curve and accordingly the price elasticity of supply is identified for hours that price is highly inelastic. Importantly, this analysis shows the impact of the recent high capacity installations of renewable generation in the state of California on electricity price and price inelasticity. Finally, the undesirable consequences of price inelasticity, such as on creating price spikes and exercising market power, are discussed.**

***Keywords*: California ISO, energy market, real-world data, supply bids, supply curve, renewable generation, price elasticity.**

I. Introduction

The analysis of bids in electricity markets is necessary to reveal the fundamental economic characteristics of the market which play a key role in selecting the price of electricity. Such analysis also helps the market operator to adjust its policies in order to run a more efficient market. For example, a critical concept in electricity markets, or any market for that matter, is *price elasticity* which indicates how much the market is vulnerable to *exercising market power*. Note that, exercise of market power was identified as the main cause that led to creating the California Energy crisis in 2001 [1].

A limited number of studies have previously looked into *real-world data* for supply bids in electricity markets. Wolfram in [2] studied the bidding behavior of electricity supplies in the daily auction of England and Wales. In [1], the supply and demand bidding during the California market crisis in 2001 have been studied. Also, the authors in [3] has analyzed the PJM market prices and the behavior of supply bids.

In this paper, we work with real bidding data from the California ISO (CAISO) Day-Ahead Market (DAM) for energy. Our goal is to make fundamental observations about how supply sides behave in this market. The main contributions and novelties in this paper can be summarized as follows:

- To the best of our knowledge, this paper is the first study that addresses the supply bids in CAISO after the market is upgraded to Market Redesign and Technology Upgrade (MRTU) in 2009. In addition to the important changes in market rules, CAISO has also experienced a massive amount of solar power installations since 2009.
- Different types of supply bids are studied in this paper, including multi-stage generator bids as well as convergence bids, both of which are often less known to the academic research community.
- It is identified that the price does not follow the demand during the middle of the day, i.e., from 10:00 AM to 4:00 PM, because of not only high volume of renewable generation but also excessive supply convergence bids.
- There are several supply bids in the CAISO DAM energy market with *zero* or *negative* price components. The reason is the low operation cost of renewable generation units which is reflected in their bids. Also, the negative price offers provide a flexibility for generators to set a loss limit for staying "on" in the market.
- The aggregate supply curve is obtained for the CAISO DAM energy market, which is needed in order to identify whether or not the market price is within the designated elastic price range at different hours.
- Price elasticity is investigated and its potential impact, such as its adverse impact on the number and severity of price spikes, is discussed and evaluated. Accordingly, the peak hours in which the market prices are placed outside the range of the high-elastic prices are captured.

The rest of the paper is organized as follows. We first present the main peculiarities of supply bids in the CAISO market in Section II. Some fundamental data-driven observations are made in Section III. The relation between supply bids and DAM prices is analyzed in Section IV. Aggregated supply curve and price elasticity are estimated in Section V. Conclusions and future work are presented in Section VI.

II. Overview of Supply Bids in the CAISO Energy Market

A. Economic and Self-Schedule Bids

Generators participate in the CAISO energy market by submitting supply energy bids for each hour of the trading day. Each bid can be submitted as either Economic Bid (EB) or Self-schedule Bid (SB) [4]. Generators who are self-schedule, i.e., price taker, do not have any price components associated with the amount of energy in MWh that they are willing to sell. Some SBs also represent the existing bilateral contracts between market participants, see the CAISO document on Inter-SC Trades for details [4]. In contrast, generators who submit EBs are deemed to be *price maker* due to the fact that their bids are associated with the price component.

EBs consist of two components: first, the economically-dispatchable part of the bid, denoted by q^{ED}, which itself consists of up to 10 segments of energy offer prices in \$/MWh

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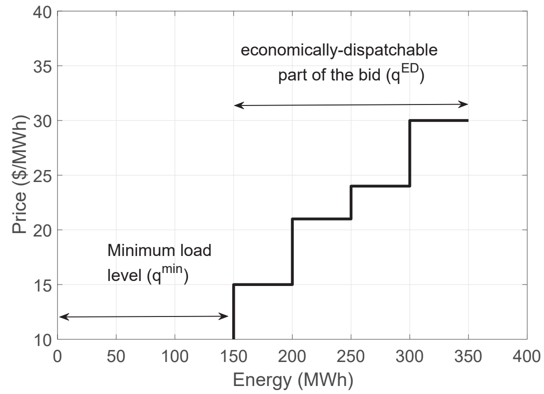

Fig. 1. A sample of economic bid

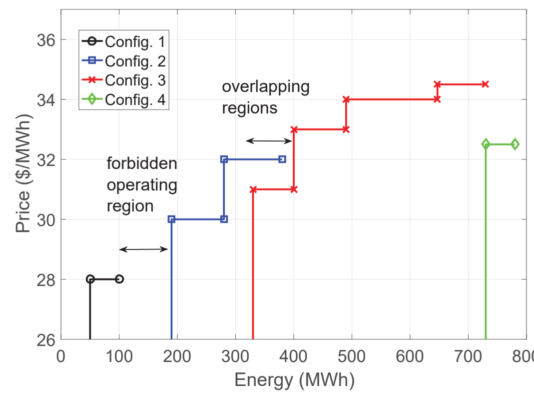

Fig. 2. A sample of multi-stage generator bid

versus the generation output level in MWh for each segment. Second, the minimum Load level, denoted by q^{min}, of the generation unit which shows the minimum generating power of the unit if its bid is cleared in the market. The total offered economic bid is a summation of q^{min} and q^{ED}. For instance, q^{min}=150 MWh and q^{ED}=200 MWh for the 350 MWh economic bid is exemplified in Fig. 1. As shown in Fig.1, a supply energy bid must always be *monotonically increasing* with respect to the price. Note that, in CAISO demand response providers are considered as generation resources and submit supply energy bids to participate in the energy market.

B. Multi-Stage Generators

CAISO has provided the flexibility for multi-stage generators (MSGs) to submit multiple economic bids to the market. An example of MSG is combined cycle gas turbine resources. These types of resources consist of multiple operating configurations that can be characterized as having distinct operating parameters with distinct operating constraints [5]. These resources may have a crossing range during transition that is considered a forbidden operating region. Also, they may have overlapping regions within different configurations. CAISO allows MSGs to submit separate bids for each configuration, however, only one of them can be cleared in the market at each operating hour. For instance, Fig. 2 shows a sample supply bid submitted by an MSG resource. It has four configurations, marked by four different colors; therefore, four different economic bids are essentially submitted together. There is a forbidden region between configuration 1 and 2. Also, there is an overlap between configurations 2 and 3. For this study, the maximum output power of the last stage is considered as the total offered economic bid. Also, the maximum offered economically-dispatchable part among different MSG's economic bids are considered as q^{ED} of the MSG's bid. For example, for the bid in Fig. 2, the total offered economic bid is 780 MWh, and q^{ED} is equal to 400 MWh.

C. Convergence Bids

CAISO allows participants, including financial firms, to submit Convergence Bids (CBs) in addition to physical bids in order to increase the liquidity and efficiency of the market [6]. Supply and demand CBs allow market participants to arbitrage between the DAM and Real-time Market (RTM), exempting them from physically producing or consuming energy [6]. For instance, if the supply CB is cleared in the DAM, then the bidder is credited at the DAM price and charged at the RTM price. Therefore, the difference between the revenue in the DAM and the cost in the RTM will be the payment to the bidder. CBs in DAM are treated similar to physical bids. Therefore, they affect DAM prices as well as unit commitments. The CBs must be of type EB and their minimum load level of the bid, i.e., q^{min} must be set to 0 MW.

D. Out of State Import Bids

Finally, in addition to generators and financial firms, CAISO receives import and export bids at its inter-ties with other states. An import (export) bid is a supply (demand) bid submitted by a generator (load entity) out of CAISO territory. Import and export bids can be both SB or EB types and they participate directly into DAM CAISO energy market [4].

III. Data-driven Analysis of Real-World Data

The data in this paper is obtained from the CAISO Open Access Same-time Information System (OASIS) [7]. In this section, several analyses are conducted on supply energy bids in the DAM CAISO energy market during the month of March 2016. A total of 1.5 million records of bid data are studied.

Our observations in this section are focused on the maximum capacity offered by different supply entities, including renewable generators, to determine the share of each participating entity in the DAM. We also study the capacity of the submitted SBs and EBs at different hours. Taking the sources of supply bids into account, we present our observations in three categories: generator bids, convergence bids and imports.

A. Generator Bids

Fig. 3 shows the detailed information of the generators' bids submitted to the DAM. Note that, in this study, the generator bids also include MSGs as explained in Section II. In Fig. 3(a), the bids are categorized based on the electric companies namely, based on whether the bid is submitted by any of the two largest utilities in California, i.e. Southern California

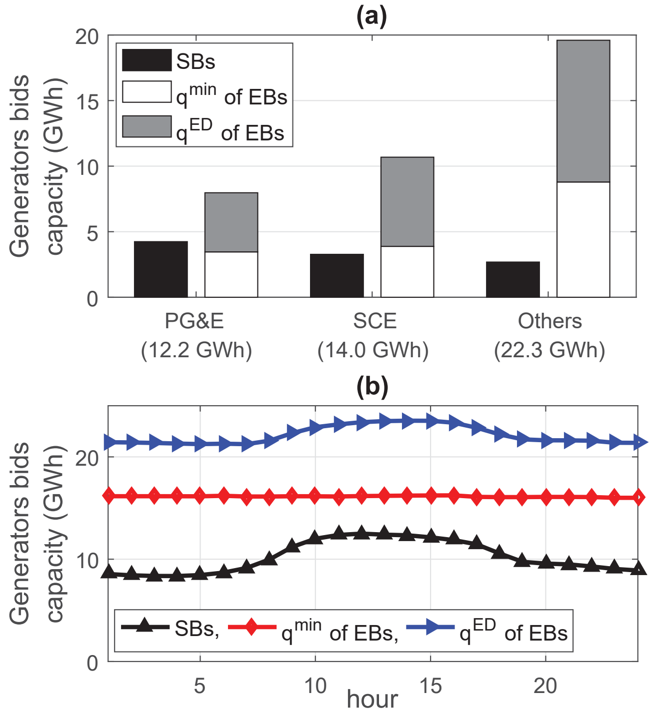

Fig. 3. The average capacity of submitted generators bids in March 2016: (a) categorized by the owners, (b) at each hour of the day.

Edison (SCE) and Pacific Gas and Electric (PG&E)[1], and also the owners of other generators that are collectively called “Others”. As can be seen from Fig. 3(a), PG&E and SCE posses 25% and 29% share of the total offered capacity in the CAISO market. That is, interestingly, the two utilities are not only the two largest energy buyers in California [8], but also, they have large shares of supply side bids in the CAISO energy market. The other 46% of the submitted generation capacity bids belong to 55 different generator participants. Moreover, Fig. 3(a) illustrates the submitted bids based on their types. An interesting observation is that although the capacity offered by “Others” is more than the ones offered by PG&E and SCE, the portion of self-schedule bids is less for “others”. That is, the non-utility owners of generators behave in the market in a more *price-responsive* fashion than the large utilities. One reason could be that those “Others” generators are more concerned in managing their risk, since the offered prices associated with EBs can be applied for risk management purposes [9]. Moreover, since utilities submit bid for their both generators and loads; they do not have incentive to participate very actively in the market. In other words, if they loss money from the supply side, it can be compensated from demand side.

Fig. 3(b) represents the average submitted supply bids at different hours during March 2016. It is seen that the offered capacity between 8:00 AM and 6:00 PM is more compared to other hours. This is because there are many *renewable generation units* that participate in the market only during these hours of the day. Also, they do not submit any bid

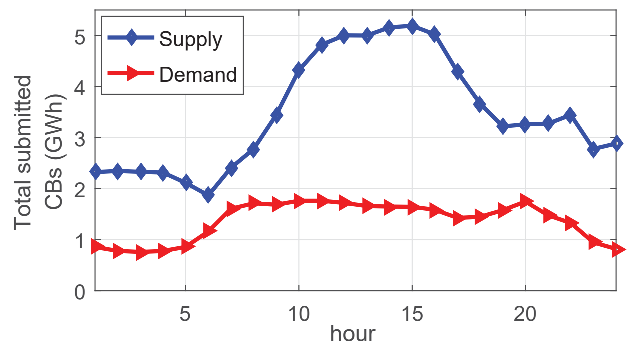

Fig. 4. The hourly total submitted Convergence bids in March 2016.

at night. For example, on average, the number of generators participating in the DAM during the day is 710, while it decreases to 515 at night. Moreover, Fig. 3(b) shows the type of submitted bids at different hours. As shown in this figure, renewable generation units submit their capacity using both SB and EB. Also, since those units do not have minimum load level, i.e., $q^{min} = 0$, their whole submitted economic bids are price-responsive. Therefore, it is expected that the capacity of q^{ED} and SBs increase around the middle of the day, while q^{min} remains constant; as shown in Fig. 3(b).

B. Convergence bids

On average, 25 supply convergence bidders and 15 demand convergence bidders participate in the CAISO market at each hour. Fig. 4 shows the total submitted supply and demand CBs at different hours of the day during March 2016. On average, the price at DAM is \$1.9 higher than that at RTM, which explains why the submitted supply CBs are larger than demand CBs. Furthermore, as shown in Fig. 4, the submitted supply capacity is higher during the time frame between 10:00 AM and 4:00 PM, which is counter-intuitive. In fact, one may think that the supply bids should be higher at the pick-hours because the price at peak hours are higher and the supply bidders could obtain more credit at DAM. However, this intuitive analysis is not valid as shown in Fig. 4, for two main reasons:

- First, in the case of CBs, the price difference in DAM and RTM is important. The more DAM price is higher than RTM price, the more profit is gained by submitting a supply CB. For example, on average, the DAM price between 10:00 AM and 8:00 PM is higher than that at RTM by \$4.2, compared to \$0.75 at other hours.
- Second, the reduction of submitted supply bids at peak hours, i.e., from 5:00 PM to 8:00 PM, may be resulted from the higher probability of price spike at the RTM at those hours[2]. Therefore, we expect higher supply CBs at hours that rarely experience price spike.

C. Import bids

On average, the submitted capacity of import bids in March 2016 was 10,028 MWh per hour, of which 30% is SB and the

[1]Even though CAISO uses anonymized market participant IDs, one can easily recognize the bids from PG&E and SCE bids with a high degree of confidence because of the large sizes of their bids and also because CAISO’s anonymized IDs are *fixed* on all days, also see [8].

[2]The RTM price spike occurs when the RTM price is unexpectedly much more than the DAM price. In 2015, the number of price spikes between 5:00 PM and 8:00 PM is 13, while for other hours the number of price spike events is 3. These numbers are based on price differences greater than \$100.

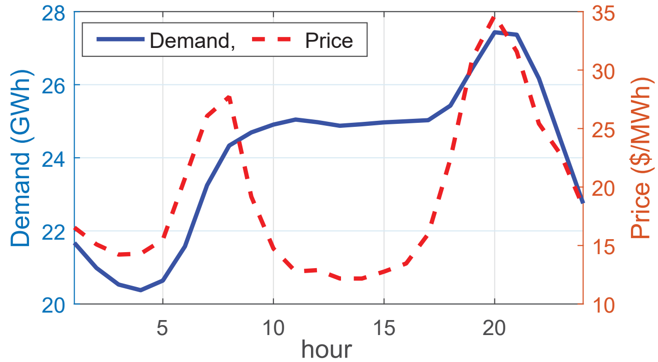

Fig. 5. The monthly average of demand and the cleared price at each hour.

rest are EBs. Interestingly, the submitted import bids do not change significantly at different hours. This could be because most out-of-state resources are non-renewable generators.

IV. Impact of Renewable Generations

In Fig. 5, the average of demand and price in March 2016 are presented. The demand curve has a high increase rate in the morning and in the evening. Also, the demand is almost constant during 10:00 AM to 4:00 PM. However, the price does *not* follow the demand curve. In fact, the price drops in the middle of the day, and it goes up rapidly in the evening. There are three reasons which may drive the above outcome;

- First, the capacity offered by renewable generation units is large and concentrated in the middle of the day.
- Second, the bids from renewable generators are almost entirely cleared in the market due to low offered prices.
- Third, another reason that is often overlooked in the literature, is the difference between supply and demand convergence bids. This difference also increases during the hours in the middle of the day, see Section. III-B.

In fact, the DAM price follows the net demand, i.e., load minus the renewable generators. The impact of renewable generations on the net demand is known as the duck curve discussed in the literature [10], [11]. The *Duck Curve* is intensified by the supply CBs. Therefore, the market experiences more excessive supply in the middle of the day resulting in even more decrease in the price during those hours as shown in Fig. 5.

Moreover, the high increase rate of price between 5:00 PM and 8:00 PM is not only because of higher demand at those hours; but also the reduction in the renewable generation and the supply CBs. Therefore, more traditional generators with high ramp-rate are needed to follow and meet the demand which causes the significant increase in the price.

V. Analysis of Price Elasticity

The price elasticity is one of the important economic characteristics affecting the participants' decisions and their bidding strategies in the market. Therefore, many studies are done previously to estimate the price elasticity of supply (or demand) in different electricity markets [12], [13]. Generally speaking, elasticity represents the ability of the supply (demand) to respond to price changes. Some applications of price elasticity include measuring market power, price forecasting, and optimal bidding, c.f. [14]–[18]. In this section, we study the price elasticity of supply side in the CAISO DAM. To do so, we need to obtain the *aggregated supply curve* to derive the elasticity at different prices [19]. However, in electricity markets, it is difficult to calculate an accurate aggregated supply curve due to many real-world market complexities[3]. Thus, instead of studying the whole aggregated supply curve which contains both price maker and price taker bids, we only focus on the price maker ones. That is, we analyze *aggregated economically-dispatchable* (AED) part of economic bids.

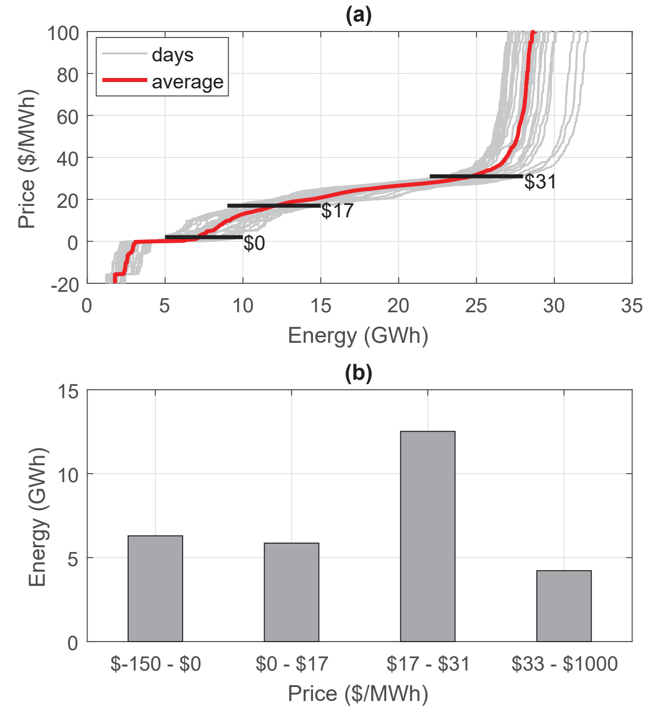

Fig. 6. Aggregated economically-dispatchable part of economic supply bids at 6:00 PM in March 2016 (a) at different prices, (b) based on the price range

A. Estimation of Aggregated Supply Curve

Fig. 6(a) shows the AED curve as well as its average during the market hour 6:00 PM of different days and for different days in March 2016. In this figure, the energy associated with price p shows the aggregated submitted capacity of which offered price is less than or equal to p. For example, the aggregated offered economically-dispatchable bids at $p =$\$31 or less is 25 GWh. The *slope* of AED curve reveals the concentration of EBs on that price. The lower slope of AED means that more EBs are submitted to the market.

Built upon the level of slope in AED curve, we define four price ranges and identify the submitted EBs within each range as shown in Fig. 6(b). Based on the Figs. 6(a) and (b), several observations and conclusions can be made, as follows:

- About 20% of the submitted supply bids have the price component of $0 or less. That is, some suppliers prefer to

[3]The many complexities of real-world electricity markets, such as the CAISO DAM energy market, include transmission line congestion, unit commitment, co-optimization, and multi-hours market clearing process.

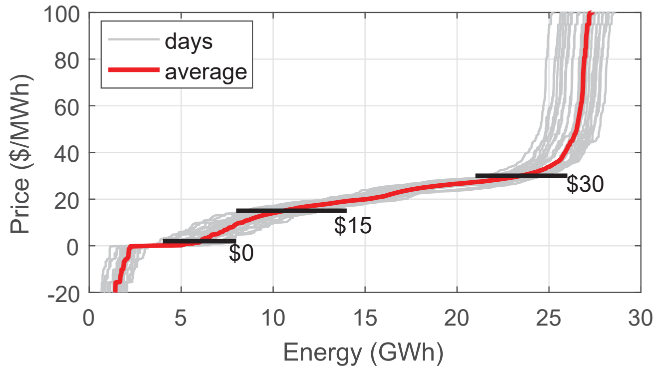

Fig. 7. Aggregated economically-dispatchable part of economic supply bids versus price at 4:00 AM in March 2016

bid at very low or negative prices. One reason can be the offered price of renewable generation units. Since those units do not have large operational cost, their offered price is very small. This explanation is also supported by the lower offered capacity at $p=$\$0 during night when the renewable generation is minimum. For instance, the offered capacity at $p=$\$0 is 3.8 GWh at 1:00 PM, but it drops to 2.8 GWh at 4:00 AM.

- The negative offered prices may also belong to generators which prefer to be "on" even if it costs for them. For example, several SCE generators submit EBs at $p=$\$-150. This low price shows how much they are willing to pay to stay "on". Note that, if they bid SB, then even if the price goes to \$-1000, they must produce energy.
- As can be seen, the most offered capacity is at price range \$17 to \$31. Interestingly, around 70% of SCE bids are spanned in this range. Because of the large share of SCE in the market, the concentration of the EBs in this price range is high. Also, it shows the higher probability of SCE's resources to set the price in this range.
- Finally, from Fig. 6(a), we can see that the non-elastic part of the price curve begins at $p=$\$31. After this price level, any small supply (demand) variation may cause the drastic changes in the price level, or vice versa.

The above observations and conclusions are based on the AED curve at 6:00 PM. Similar patterns can be seen for AED curve at other hours. For example, Fig. 7 shows AED curve at 4:00 AM. The overall pattern is similar to the one at 6:00 PM, however, the price levels are different.

B. Estimation of Price Elasticity

The AED curve indicates that as price increases, the supply increases too, but it does not show to what degree. In fact, one cannot know from the AED curve how much supply will rise in response to an increase in price. To address this issue, the elasticity of supply is defined as the measure for the degree of responsiveness of supply to a change in market price. Mathematically, we denote elasticity by E_s and define it as the change in supply divided by the change in price:

$$E_s = \left(\frac{\Delta q}{q}\right) / \left(\frac{\Delta p}{p}\right), \tag{1}$$

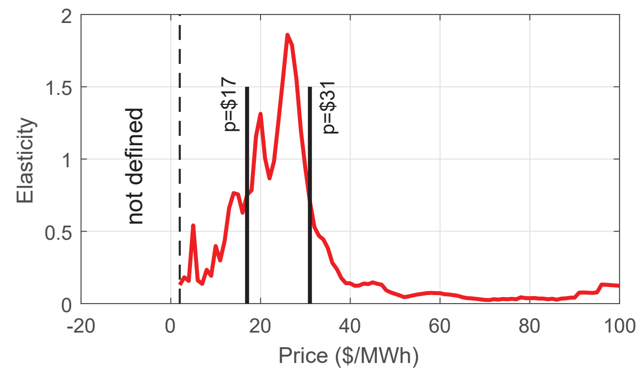

Fig. 8. Average of price elasticity of supply curve at 6:00 PM in March 2016

where q is the supply quantity. By using the AED curve, the average price elasticity of supply at 6:00 PM in March 2016 is as shown in Fig. 8. The elasticity greater than 1, i.e., $E_s > 1$, indicates elastic prices [19]. We can see that, on one hand, the price range between \$17 to \$31, where the concentration of economic bids is high, is the most elastic price range. On the other hand, the prices greater than \$31 are highly inelastic. The elasticity for the prices no greater than \$0 cannot be defined. The reason is that when the price is close to \$0, regardless of the change in supply, the elasticity in (1) tends to be 0.

C. Example Use Cases

The elasticity curve shown in Fig. 8 gives us a bright insight into the elasticity level at different prices. However, the more important concern is that where the market clearing price is placed in this curve. In particular, it is important for the market participants to know when the price of market is *high* and it is within the *inelastic* price range. In these circumstances, the large generators (or the demand entities) can strategically bid to the market to set the price and maximize their profit (or minimize the cost). Therefore, our next analysis is to study where the market price is located from the elasticity perspective. In fact, we study whether the market clearing price is within the high elastic price range or not.

Fig. 9(a) shows the average of market prices as well as the elastic price range at different hours. The high elastic prices are the ones that have $E_s > 1$. As can be seen, the highest average price in March is occurred at 8:00 PM, which is inelastic.

To compare the elastic prices at other months of the year, we present the market outcome in August 2015 in Fig. 9(b). Note that, the market experiences the highest demand in this month during the year. Thus, it is expected to see more vulnerable hours with high and inelastic prices in August compared to March. As shown in Fig. 9(b), even though the range of elastic prices is more, the market price is high and placed in the inelastic price range between 5:00 PM to 7:00 PM. This very low elasticity of the supply curve at the high price level has several undesirable consequences for the electricity markets:

1) Exercising Market Power: Large demand entities and large generators can both exploit low price elasticity [20]. For example, a demand entity can bid less than its actual load in DAM, and buy the remaining load from RTM. Since, the supply curve is inelastic, by small reduction in demand

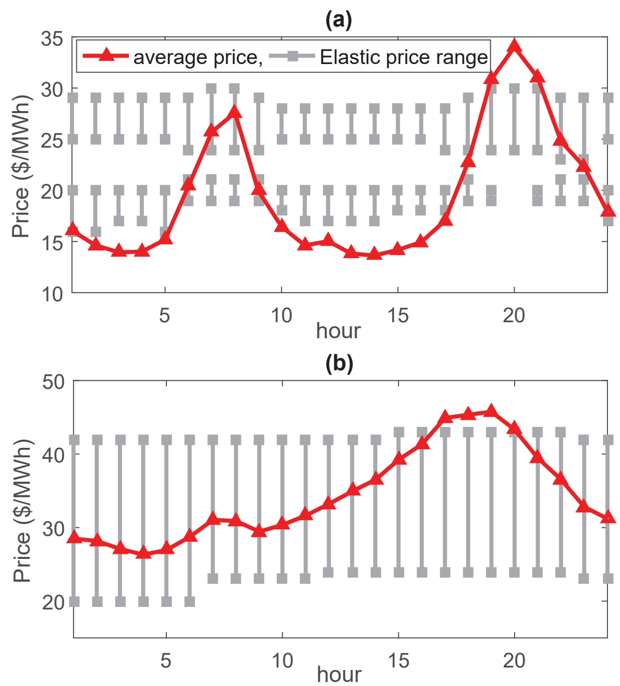

Fig. 9. Average market and elastic prices range of supply curve in (a) March 2016, (b) August 2015.

bid, the market price decreases significantly. Accordingly, the collective cost of purchasing energy from DAM and RTM will decrease. Note that, this type of strategy applied by demand entities has been identified as one of the factors that caused the California energy crisis in 2001 [1]. Moreover, the elasticity value is one of the main criteria to measure market power in the system [14]. The less the elasticity is, the more potential of exercising market power is expected.

2) Price Spike: When the equilibrium of the market is at very low elastic prices, the probability of the price spikes increases [20]. In this condition, the price spike may happen by a line or generator outage or even a small increase in the demand bid. In this case, the demand entities lose so much money, while the suppliers could earn high profit. However, some scholars believe that these price spikes show the healthy market since they induce more investment in generation and solve the inadequacy of the supply [21], but it puts a huge burden on the demand side in the market.

VI. Conclusions and Future Work

This study has dug into the details of supply bids in CAISO energy market. Accordingly, the comprehensive observations on different supply bids aspects which were submitted in March 2016 have been reported. First, the distribution of supply bids at different hours have been analyzed based on not only the bid types, but also the share of supply bidders in the market. Then, the impact of supply bid on the DAM price is analyzed. It is observed that the market price does not follow the demand during the mid-day, due to the very low offer price of renewable resources and the excessive supply convergence bids. Moreover, the price elasticity of supply has been addressed. We found that in the peak hours, in which the price is high, the supply side is highly inelastic which causes several undesirable consequences such as exercising the market power as well as price spikes.

The results in this paper can be extended in several directions. First, they can be used by market participants for determining their strategy to optimally bid into the CAISO market. Second, a market operator may use the results in this paper to calculate market power indexes associated with the supply bids in the CAISO energy market. Of course, the analysis in this paper can be applied to other deregulated electricity markets in the U.S. and elsewhere.

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