Rethinking Restructured Electricity Market Design: Lessons Learned and Future Needs

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the duck curve effect [16, 17]. However, these revisions to market rules have been largely piecemeal attempts

2.1. Unit Commitment and Dispatch

Unit commitment and dispatch is one of the most important aspects of restructured electricity markets.

Separating the markets for these services requires agents to choose which services to offer. Most centralized market designs co-optimize the provision of energy, reserves, and ancillary services, which mitigates this source of inefficiency.

Another issue that is raised by the two market designs relates to pricing. Pricing in centralized market designs is complicated by the fact that the market model explicitly represents non-convex generation costs and binary unit commitment decisions. As such, marginal prices can be economically confiscatory in the sense that the market solution requires some generating units to be online and producing energy at a net profit loss [32]. Economic confiscation is not sustainable in the long-run as it either incentivizes generators to exit the market, which can threaten system reliability, or to misstate their costs to manipulate the resulting marginal prices, which destroys short-term market efficiency. The economic confiscation problem can, alternatively, be addressed through supplementary uplift payments [33]. These payments are discriminatory and complex to calculate and economically interpret, however. Moreover, these pricing schemes can have undesirable properties, such as eliminating the economic rents of inframarginal units [34]. As such, most centralized markets address the economic confiscation problem by providing generators with supplemental make-whole payments. These payments provide for any shortfall between the revenues that a generator earns from marginal prices and its operating cost (as computed by the market operator on the basis of the supply offers that the generator makes to the market). The cost of these make-whole payments are typically uplifted to load.

Decentralized market designs overcome these pricing issues by forcing generating firms to internalize their non-convex costs when submitting offers to supply energy, reserves, and ancillary services. As such, the marginal prices that are derived from the market model, which represent very few (if any) non-convexities, should not lead to such economic confiscation (so long as generators properly internalize their costs). This approach to handling non-convex costs does imply, however, that at least some generators offer energy and other products above their true marginal cost. This gives rise to in

Table 2: Generation-Unit Dispatch and Profits for Market-Clearing Example with Centralized Market Design

Unit	Dispatch [MW]	Profit From Energy Payments Only [$]	Make-Whole Payment Required [$]
1	80	800	0
2	20	−100	100

recover this profit loss. The total load payment is $2100, which exactly corresponds to the sum of the total revenues earned by the two units, which are $1600 and $500, respectively. Total producer welfare is $900 and consumer welfare $1900, meaning that social welfare is $2800.

We next consider a decentralized market design, whereby generators internalize their non-convex startup costs and are allowed to submit offers that are above marginal cost. Suppose that Unit 1 continues to offer its supply at its true marginal cost of $10/MWh, while Unit 2 offers its supply at a cost of $25/MWh. Table 3 summarizes the resulting dispatch and profits of the units. Because Unit 2 remains marginal, the market-clearing price is now set equal to $25/MWh.

Table 3: Generation-Unit Supply-Offers, Dispatch, and Profits for Market-Clearing Example with Decentralized Market Design

Unit	Supply Offer [$/MW]	Dispatch [MW]	Profit From Energy Payments Only [$]
1	10	80	1200
2	25	20	0

The final column of Table 3

steam-turbine units). Some flexible loads (*e.g.*, an industrial facility that may opt to furlough its operations) may also benefit from a day-ahead schedule.

The real-time market clears much closer to the actual operating period. The primary purpose of the real-time market is to allow for changes in production and consumption schedules, to accommodate differences between day-ahead forecasts of system conditions and actual conditions that are observed in real time. Originally, most real-time markets cleared hour-ahead. This was largely due to computational limits, which made market-clearing closer to actual delivery intractable. As computational capabilities advanced over time, many markets evolved toward fifteen- or five-minute-ahead real-time markets. The real-time market represents the last trading opportunity between producers and consumers prior to actual energy delivery.

Some restructured markets have introduced additional market-clearing opportunities between the day-ahead and real-time markets. Many markets in the United States now include an additional reliability unit commitment model. The reliability unit commitment model is typically solved in the afternoon or evening following the clearing of the day-ahead market. The purpose of the reliability unit commitment is to provide the system operator with an additional opportunity to commit units. This may be prudent if, for instance, its afternoon or evening forecast of system conditionso4(f)3.8755o

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marginal cost or scarcity of supply at a given time) or generating firms behaving uncompetitively in offering their generation to the market. Regulators are often left to use blunt instruments, such as offer or price caps constraints are prone to consistent congestion. As such, the zonal model assumes that a reasonable ap-

Table 4: Generation-Unit Data for Transmission-Representation Example

Unit	Minimum Capacity [MW]	Maximum Capacity [MW]	Marginal Cost [$/MWh]

utility support and investment. Overall, participation rates in demand response programs are quite low, estimated at less than 5% in 2016.[2]

Market designs have taken a mixed approach to incentivizing demand response. Industrial and large commercial customers are able, in many restructured markets, to directly participate in wholesale energy, ancillary service, and capacity markets (where the latter exist). Smaller (especially residential) customers

4. Principles for Efficient Electricity Market Design

Building on the discussion in the preceding sections, we outline here six principles, on which we believe (re)designs of future electricity markets should be based. These principles are informed by lessons learned from current or past market designs, as well as market-design proposals that appear in the technical literature. We also, as appropriate, raise market-design questions that are not well understood. These questions

delivery (*e.g.*, the real-time market) may employ a more accurate ac representa

There are a number of competing visions for how the demand side can

References