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A multi-scale optimization framework for electricity market participation

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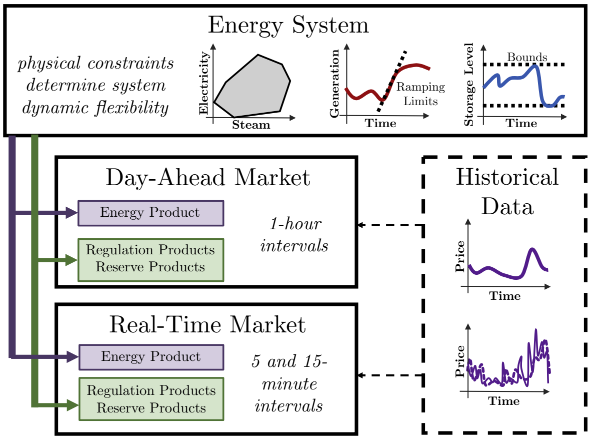
HIGHLIGHTS

- Present framework to assess economic incentives of markets at different timescales.
- Present studies for CHP and battery systems using real CAISO price signals.
- Found that 60–90% of revenue opportunities come from the real-time markets.
- Ancillary service provisions increase revenues by 40–100%.

GRAPHICAL ABSTRACT



Quantify revenue opportunities per market rules and energy system physics

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ABSTRACT

Power grids coordinate a diverse set of energy systems (generators, loads, storage devices) to ensure that supply and demands are matched at multiple timescales (from hours to milliseconds). Such coordination is achieved through hierarchical market transactions. This work presents an optimization framework to evaluate revenue opportunities provided by these multi-scale market hierarchies and to determine optimal participation strategies for individual participants. The proposed framework models day-ahead and real-time transactions of energy, ancillary services, and virtual bidding products provided by independent system operators (ISOs). We apply the framework to a combined heat and power system and a utility-scale battery to determine revenue potential from different market layers and products. Analysis using real price signals for 2015 from the California ISO reveals that 60–90% of the total revenue potential (obtained by participating in all markets) is provided by real-time markets alone (which operate at fast timescales). Our studies also indicate that providing ancillary services (in addition to day-ahead and real-time energy products) increases revenue potential by 40–100%, depending on the physical flexibility of the technology. The proposed framework can be used to identify which market layers and products offer the greatest economic potential for different energy technologies. Our results also highlight that existing techno-economic studies that focus exclusively on day-ahead energy markets (operating at slower timescales) can dramatically undervalue dynamic flexibility.

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1. Introduction

Power grids coordinate a diverse set of energy systems (generators, loads, storage devices) to ensure that supply and demands are matched at multiple timescales (from hours to milliseconds). Such coordination is achieved through hierarchical (multi-scale) market transactions. The proportion of transactions occurring at different timescales is changing as more intermittent and non-dispatchable power is injected into the system. For instance, wind power introduces power injection fluctuations at high frequencies, which require adjustments in fast real-time energy and ancillary services markets (regulation) [1]. Automation architectures for a broad spectrum of electricity generation and consumption systems (e.g., manufacturing building) are currently being re-designed to exploit incentives provided by faster and more volatile energy markets. For example, the Alcoa Point Comfort Power Plant, which is a utility plant that provides electricity and steam to the adjacent aluminum manufacturing facility, re-optimizes its operations every 15 min in response to electricity and natural gas price fluctuations [2]. These new flexibility-oriented automation architectures provide load flexibility to the power grid in exchange for monetary payments or deferred costs. Similarly, large-scale battery systems and building systems are becoming key providers of dynamic flexibility to the power grid [3,4].

1.1. Electricity markets and demand response

Understanding the economic incentives provided by generation and load flexibility requires careful consideration of wholesale electricity market structures and diverse products. Fig. 1 shows the multiscale control structure currently used to balance the power grid. Resources can participate by buying/selling electrical energy and/or providing ancillary services (regulation, reserves). Fig. 2 shows time-varying prices from the California Independent System Operator (CAISO) for three consecutive days. Energy is transacted at three timescales: in the integrated forward market (day-ahead market with 1-h intervals), in the fifteen minute market, and through the real-time dispatch process (5-min intervals). Table 1 lists the different products transacted at each timescale. Histograms for energy prices at different markets are presented in Fig. 3. As can be seen, prices are less volatile in the day-ahead market and the average price is higher. In the real-time market (FMM, RTD) prices are frequently negative and occasionally exceed $150/MW h. Energy systems with fast dynamics (e.g., flywheels, batteries) can exploit these fast price fluctuations.

Resources (i.e., generators and loads) provide addition flexibility to the hierarchical grid control structure (Fig. 1) via *regulation* and *reserve* ancillary service market products. Generators and loads providing regulation capacity permit the Automatic Generator Control (AGC) layer (run by the ISO or similar grid entity) to adjust their power set-point with a specified range [5]. Depending on the market region, the AGC layer updates load set-points every 2–15 s. The regulation service provider is compensated both for the amount of regulation capacity provided (a load flexible *band* is offered) and the amount of *mileage*, which is the sum of the absolute distance between consecutive load set points. Mileage calculations are illustrated in Fig. 5. Order 755 of the Federal Energy Regulatory Commission (FERC) provides incentives to participants capable of tracking fast changing load set-points. In California, regulation services are procured as two separate products, regulation up and regulation down, depending on the direction of the flexibility band relative to the nominal set-point (from the corresponding energy market). Spinning reserves support regulation service and safeguard against unplanned outages and increased loads. Spinning reserves are rarely dispatched and resources providing reserves are compensated for providing flexibility/contingency. As additional intermittent and non-dispatchable wind and solar power is absorbed, balancing the power grid becomes more challenging due to high-frequency (minute) variations from these sources. As such, requirements for ancillary services are expected to grow. For example, regulation capacity requirements for Texas are anticipated to increase by 10–15% if wind penetration increases from 5000 MW to 15,000 MW [6]. In February 2016, CAISO approximately doubled regulation capacity requirements to account for non-dispatchable renewable sources. As consequence the market price for regulation doubled, resulting in a combined quadrupling of payments to some regulation providers [7]. Finally, reductions in the supply of ancillary services are expected with the retirement of coal-fired generators [8], creating additional opportunities for flexible load providers.

Manufacturing facilities and other large electricity consumers may also participate in electricity markets through Demand Response (DR) programs by manipulating their loads and/or by using on-site generators. DR is typically classified as dispatchable and non-dispatchable, as shown in Fig. 4. For dispatchable DR, the ISO directly controls the load (e.g., balancing authority sends new set points through AGC system to regulation resources), whereas non-dispatchable loads are coordinated through a variety of pricing signals including real-time electricity markets, which are updated every 5–15 min. In Texas, load resources provide 2400 MW of energy and ancillary services, including half of the spinning reserve capacity. To give an idea of the impact of manufacturing, around 1000 MW of this capacity is obtained from a single electrochemical processing facility that provides regulation and other services. Medium (10–50 MW each) and small (less than 10 MW) size industrial/commercial facilities provide the remaining 820 MW and 550 MW of capacity, respectively [8]. The Alcoa facility in Warrick, IN offers several ancillary services in markets run by the Midcontinent ISO. The aluminum smelter provides 70 MW of regulation capacity, which is 15% of its average load (470 MW). This type of operation represents a paradigm shift on the use of manufacturing loads for ancillary services. The same plant also provides 75 MW of interruptible load, which has been dispatched around 55 times per year for an average length of 42 min [10,11]. Alcoa generates up to *120,000* $/*day of additional revenue by participating in electricity markets*, and has identified potential for 10% energy cost reductions through more targeted operations [10]. Based on data from CAISO, a system providing 10 MW of regulation capacity for every hour in 2015 would have received 500,000 $/year plus mileage payments. Regulation capacity prices currently reach up to 59 $/MW and this number might increase as more renewable power is adopted. Moreover, shifting 10 MW of load during the 1% most extreme prices (in the 97 to 1621 $/MW h range) in the CAISO real-time energy market to the average price (30 $/MW h) would yield savings of 400,000 $/yr. The savings for large manufacturing facilities can reach millions of dollars per year. For instance, the pumping system of an oil pipeline comprised of 50 pump units with 6500 horsepower electric motors has a load of 200 MW. Large refineries in Texas have generation facilities of up to 500 MW and usually have excess power capacity installed.[1]

1.2. Literature review

Diverse studies have analyzed market participation of a variety of technologies such as combined heat and power (CHP) plants [12–17], steel furnaces [18,19], cement plants [20–22,14], air separation units [23,24,22,25–27], electrochemical manufacturing facilities [28], HVAC systems for large buildings [29,4,30–32], and

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[1] http://www.iaee.org/documents/denver/varela-salazar.pdf.