Title: Pricing Synthetic Inertia: Strategies for Grid Stability in a Renewable Energy Future

Authors: Omer Karaduman, Alison Ong, Guillaume Roger

Affiliations: Stanford GSB, Stanford E-IPER, Monash

1. Introduction

Integrating renewable energy sources into electricity systems introduces challenges such as intermittent power generation. These challenges are not only confined to energy procurement but also impact grid stability, particularly in terms of frequency regulation. When frequency disturbances occur, an immediate (sub-second) power exchange known as an inertial response helps mitigate the rate of change of frequency. Traditional power generators like coal and natural gas plants provide the necessary inertia to dampen frequency changes, but this feature is absent in renewable sources. As renewables increasingly displace fossil fuels, the lack of sufficient inertia becomes a concern for grid operators and policymakers.

This study examines the potential of battery energy storage systems in supplying synthetic inertia, offering a fast-responding power injection to mimic traditional generators' inertial response.

2. Motivation and Background

Electricity systems around the globe are experiencing significant changes due to the increased use of renewable energy resources. In 2022, "some 300 GW of renewables were added globally, accounting for 83% of new capacity compared to a 17% share combined for fossil fuel and nuclear additions." (IRENA 2023) As existing power system infrastructure ages and as variable renewable energy replaces baseline fossil generation, shocks to supply become more common, heightening the need for grid products that ensure reliability. Having sufficient system inertia is crucial to managing frequency disturbances.

In addition to providing frequency regulation and other ancillary services, a battery may be able to provide an analogous signal to traditional mechanical inertia. A battery can inject power very quickly where needed, with a degree of flexibility in ramping that even the most flexible gas-fired units cannot achieve. Therefore, storage may be a promising device to address multiple concerns around grid reliability. So far, existing storage devices tend to make a substantial amount of revenue from such ancillary services (AS) rather than from energy arbitrage. However, storage providers have also struggled to find it profitable to enter markets, even ones with large amounts of variable renewable energy (Karaduman 2023). Research showing additional value streams for storage or suggesting profitable strategies to operate across multiple markets could prove helpful for both storage providers and system operators.

3. Related Literature

Many of the issues surrounding renewables' impact on energy markets, including power intermittency, ramping constraints, and startup costs (Gowrisankaran et al. 2016, Reguant 2014, Jha and Leslie 2020), are well-studied in the energy economics literature. The impact of renewable generation on other grid services involving reliability, often referred to as ancillary services, is less well understood. Buchsbaum et al. 2022 study spillovers between energy and ancillary service markets, finding that exogenous policy changes concerning the ancillary services market had important impacts on generators in the energy market. Likewise, the economics literature involving energy storage focuses on storage opportunities for energy arbitrage rather than for ancillary services. While markets exist for energy and grid services such as frequency regulation, there are no market mechanisms for inertia.

4. Research Objectives and Questions

Our study has three related questions. First, when/how much inertia is needed, and how has this evolved? Second, what is the cost of procuring synthetic inertia? How might a market operator incentivize energy storage to provide inertia, and how does this compare to the cost of investing in other technologies that might provide inertia, such as synchronous generators? And third, what is the value of synthetic inertia that storage can provide compared to mechanical inertia?

More broadly, we must also characterize how storage responds to a combination of incentives from participating in multiple markets. Existing literature tends to focus on storage behavior in the energy market but not on how it considers tradeoffs between energy and AS markets. Existing work also often relies on simulated data, whereas we use real market price and generator bid data for our models.

5. Institutions, Data, and Methodology

Australia's National Electricity Market (NEM) provides a uniquely good case study for assessing the value of synthetic inertia. Australia has traditionally been mostly coal-powered, but given excellent natural renewable resources, the transition to clean energy sources is rapidly occurring (Lu et al. 2021). Renewable penetration is especially high in South Australia (McGreevy et al. 2021), which has experienced grid stability problems and made international news for using a Tesla battery project to improve grid reliability (McConnell 2018). But although batteries may be important in the Australian energy transition, a lack of market rules has so far seriously hindered adoption (Leslie et al. 2021).

We obtain four-second-level data for both energy and frequency control/ancillary services (FCAS) from the Australian Electricity Market Operator (AEMO). These data include various parameters (generation, frequency, power, etc.) for all major "elements" in the NEM (e.g., generators, interconnections, large loads). The dataset spans 2011–2021 and ~350 generators.

Using the four-second-level dataset, we flag an event of interest if there is an abrupt and significant change in generation, which indicates a supply shock that may trigger an inertial response. We define such an event as satisfying abs(change in generation) >20% capacity AND >20MW across consecutive four-second time intervals. This allows for detecting spikes (a sudden increase/decrease in output, which only occurs for a few seconds), a sustained jump upwards in output, or a sudden drop, which may indicate an unplanned outage or failure. We are most interested in large drops, as they tend to cause a reduction in frequency and induce a significant inertial response.

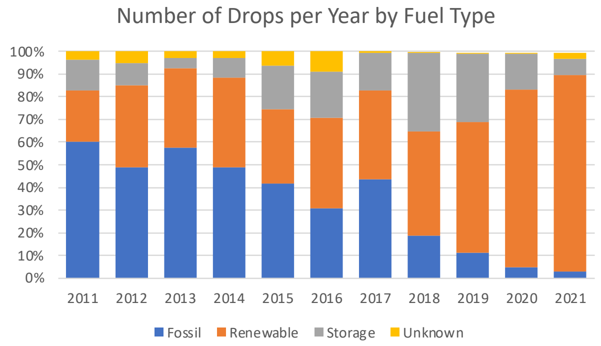
We also obtain historical bidding data for the NEM. We record each power plant's price and quantity bid schedules for each half-hour (which reflects the 30-minute settlement system of the NEM until October 2021) to reconstruct the supply function for each time interval and for each market within the NEM.

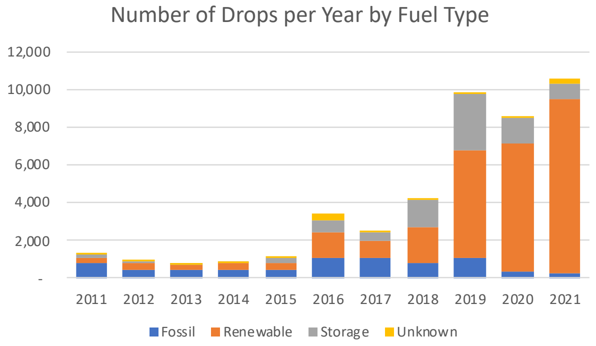
The existing structure of the NEM has several markets that run jointly to ensure a reliable electricity supply. During most of the period analyzed, there was one energy market and eight FCAS markets, which span from a few seconds to five minutes of contingency response. The NEM separately prices raise AS (i.e., raising the frequency if it is too low when demand outstrips supply) and lower (vice versa). In line with intuition about shortfalls in supply due to aging fossil generation and new, intermittent renewable generation, raise AS markets tend to be more valuable than lower AS markets. Two additional markets were recently introduced for fast frequency response, which operates on a one-second level.

Inertia could be procured through the introduction of a new market. In our analysis, we preliminarily explore one possible form of such a market via daily procurement of inertia from batteries. By obtaining an estimate of the cost to incentivize inertia commitments from storage, we then use this as a benchmark against the cost of alternative energy storage sources, such as synchronous condensers.

5. Preliminary Results and Analysis

We find that the increase in renewable penetration has been associated with a sharp increase in the number of frequency deviations outside the acceptable operating range in the NEM. Thus, the renewable transition has decreased the supply of inertia and appears to increase the demand for inertia in this market.


Number of Drops per Year by Fuel Type


Number of Drops per Year by Fuel Type

In recent years, there have been notable demonstrations of the potential of batteries to relieve grid instability. The Hornsdale Power Reserve in South Australia has reduced FCAS Regulation costs by 90% and provided frequency stabilization when the state was islanded in 2019 (Neoen 2023).

We explore how batteries might allocate their capacity between energy and ancillary service markets, finding that batteries generally participate more often in AS rather than energy markets. In multi-year sample simulations of battery storage bidding in the states of New South Wales, South Australia, and Victoria, the percentage of total battery revenue attributable to energy market participation is just 5%, 10%, and 8% respectively. When we layer on a hypothetical daily market for inertia procurement, we find that storage would have to be incentivized by ~$500/MW each day to set aside even a quarter of its capacity on average for inertia.

6. Discussion

Buchsbaum et al. found that focusing only on the energy market and neglecting to consider spillovers with AS markets may lead to misleading conclusions and recommendations. We confirm that this holds when considering energy storage behavior in electricity markets. Storage does not charge/discharge in the energy market during every single interval, but it often does participate in ancillary services even when its energy market participation is zero.
Our work underscores a larger point about the energy transition—the concern is not simply about meeting demand at all times in the energy market; it also encompasses reliability and grid services more broadly.

Inducing a battery to devote more of its capacity towards inertia means less participation in energy or other AS markets is available. With its ability to participate in other markets diminished, its revenue opportunities—especially its ability to respond to high-value events—are curtailed. As a result, the incentives must be significant for storage to reserve its capacity for inertia. Because inertia needs are hard to predict, this might lead to even more lost opportunities for energy storage in real-world settings.

7. Future Work

Our analysis is ongoing, and we are planning multiple extensions to our work in the coming months. The model applies a simple linearization to each bid curve to determine storage's impact on market price. In the next phase of the analysis, we will instead use a piecewise linear form to reflect the shape of the supply curve better. The existing optimization also assumes perfect foresight as a starting point; therefore, our results so far represent an upper bound. We plan to make our model non-deterministic to better quantify storage's realistic revenue potential across energy and AS markets.

Although four-second-level data yields many insights, estimating the demand for inertia requires sub-second data. Pending the release of this data from market operators, data at the 20-ms level will allow us to improve our modeling of a prospective inertia market, as we can then tie prices for inertia to demand for inertia.

The scope of this project currently looks at shocks to system supply. Consideration of demand shocks would be an essential potential direction for future study.

8. Conclusion

We find that the need for inertia has increased over time alongside a rise in intermittent generation resources. We can better estimate storage bidding behavior and the costs to incentivize storage to provide useful grid products by employing empirical datasets.

Many electricity markets face novel challenges with the rapid transition to a renewable energy future. Inertia is one such challenge, which has generally not been a first-order concern for market operators in the US. We identify a market where reliability problems are inherently more acute due to the physical shape of its grid, which has gone far ahead in the renewable transition. This serves as a demonstration of what is going to happen to grids across the globe as the transition ramps up.

References

Buchsbaum, Jesse F., Catherine Hausman, Johanna L. Mathieu, and Jing Peng. "SPILLOVERS FROM ANCILLARY SERVICES TO WHOLESALE ENERGY MARKETS." *NBER Working Paper*, September 2022. https://www.nber.org/system/files/working_papers/w28027/w28027.pdf.

Gowrisankaran, Gautam, Stanley S. Reynolds, and Mario Samano. "Intermittency and the Value of Renewable Energy." *Journal of Political Economy* 124, no. 4 (August 2016): 1187–1234. https://doi.org/10.1086/686733.

IRENA. "World Energy Transitions Outlook 2023," n.d. https://www.irena.org/Digital-Report/World-Energy-Transitions-Outlook-2023.

Jha, Akshaya, and Gordon Leslie. "Dynamic Costs and Market Power: Rooftop Solar Penetration in Western Australia." *SSRN Electronic Journal*, 2020. https://doi.org/10.2139/ssrn.3603627.

Karaduman, Ömer. "Economics of Grid-Scale Energy Storage in Wholesale Electricity Markets," March 26, 2023. https://gsb-faculty.stanford.edu/omer-karaduman/files/2022/09/Economics-of-Grid-Scale-Energy-Storage.pdf.

Leslie, Gordon, Orrie Johan, Tom Meares, and Russell Pendlebury. "Prospects for Battery Investment Under More Spatially Granular Electricity Spot Pricing." *SSRN Electronic Journal*, 2021. https://doi.org/10.2139/ssrn.3877758.

Lu, Bin, Andrew Blakers, Matthew Stocks, Cheng Cheng, and Anna Nadolny. "A Zero-Carbon, Reliable and Affordable Energy Future in Australia." *Energy* 220 (April 2021): 119678. https://doi.org/10.1016/j.energy.2020.119678.

McConnell, Dylan. "A Month in, Tesla's SA Battery Is Surpassing Expectations." *The Conversation*, January 10, 2018. https://theconversation.com/a-month-in-teslas-sa-battery-is-surpassing-expectations-89770.

McGreevy, Dr Michael, Colin MacDougall, Dr Matt Fisher, Mark Henley, and Fran Baum. "Expediting a Renewable Energy Transition in a Privatised Market via Public Policy: The Case of South Australia 2004-18." *Energy Policy* 148 (January 2021): 111940. https://doi.org/10.1016/j.enpol.2020.111940.

Neoen. "Hornsdale Power Reserve Consumer Benefits." 2023. https://hornsdalepowerreserve.com.au/consumer-benefits/.

Reguant, Mar. "Complementary Bidding Mechanisms and Startup Costs in Electricity Markets." *The Review of Economic Studies* 81, no. 4 (October 2014): 1708–42. https://doi.org/10.1093/restud/rdu022.