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Does battery storage lead to lower GHG emissions?

Kaveh Rajab Khalilpour[a], Anthony Michael Vassallo[a,*], Archie C. Chapman[b]

[a] *School of Chemical & Biomolecular Engineering, University of Sydney, Sydney, Australia*
[b] *Centre for Future Energy Networks, School of Electrical and Information Engineering, University of Sydney, Sydney, Australia*

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ABSTRACT

A study of the Australian National Electricity Market shows that using battery storage in the Australian national electricity grid reduces CO_2 emissions by providing further flexibility for the operation of conventional generators and also by decreasing the amount of unused renewable energy. Interestingly, energy storage is more efficient at reducing carbon emissions in the context of higher carbon and/or fuel prices. In addition to reducing emissions, battery storage can decrease the cost of delivered energy.

1. Introduction

1.1. *Conventional grid and the reliability challenges*

Modern power grids have evolved to provide a high level of reliability, matching instantaneous consumer demand (load) with generator output, keeping within tightly controlled AC frequency limits (Kirby, 2004). Conventionally, power networks matched customer load through controlling generator output up or down according to need. These mostly large, remote thermal (coal, gas, and nuclear) and hydropower generators responded to system operator signals ensuring the network remained within stable operating limits for frequency and voltage. A necessary reserve of generation capacity needs to be maintained to meet unscheduled outages, to meet rapidly increasing loads and to provide flexibility in other network services, often called "ancillary" services (Ferc., 2015). Similarly, the transmission and distribution networks also need to be designed to meet the maximum, or peak, load conditions. Therefore, today we have (at least across industrialized countries), electricity grids with a significant portion of the capacity being utilized for limited hours each year to ensure continuous and reliable access to electricity. This high level of reliability, of course, comes at a cost to consumers. For instance, in New South Wales, Australia, about 25% of retail electricity bills is required to meet a few (around 40) hours of very high ("critical peak") demand each year (Productivity-Commission, 2013).

Thermal power generation provides a high degree of inertia to electricity grids, as rotating machines provide a degree of "stiffness" to the network that acts to stabilize or hinder rapid changes. However, the increasing amount of generation that comes from some renewable sources such as photovoltaic (PV) sources and wind is "inertia-less." Add to this problem the unavailability of the renewable energy source (solar radiation, wind, biomass, etc.) at certain times (minutes, days, weeks, season, etc.), which not only increases grid operation complexity but also requires higher reserve capacity and/or energy storage. Without consideration of these issues, energy security and autonomy with a very high fraction of renewable power sources, on their own, is impossible.

1.2. *The role of energy storage*

Electrical energy storage (EES) is not a new technology/concept; it has been practiced for over a century. It was 20 years after the invention of rechargeable lead acid batteries in 1859, (Chen et al., 2009) that Thomas Edison invented the light bulb in 1879 and developed the first centralized power plant in 1882 in New York City's financial district for lighting the shops and attracting customers (Sulzberger, 2013). Soon, demand increased and lead acid batteries were found as a solution for storing electricity at low-demand times and selling it to shops at peak evening times. In 1896, a 300-tonne, 400 kWh lead acid battery was used at a hydro-power station to avoid outage at equipment breakdown (Vassallo, 2015). Since then, battery and other types of energy storage have been developed, each with a certain learning rate. The objective of electricity storage has also become far broader than the initial intention of peak-shaving or short-term outage prevention (Baker and Collinson, 1999). Today, EES is used for many other reasons, including delay of capacity/network expansion, frequency regulation, and voltage

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* Corresponding author.
E-mail address: anthony.vassallo@sydney.edu.au (A.M. Vassallo).

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balancing (prevent brownouts) (Decourt and Debarre, 2013). As such, each of the energy storage technologies is suitable for a given objective. They are usually categorized based on the time scale of applications, such as instantaneous (less than a few seconds), short-term (less than a few minutes), mid-term (less than a few hours), and long-term (days) (Koohi-Kamali et al., 2013). A detailed background of the historical development of various energy storage options can be found in the Electricity Storage Handbook published by Sandia National Laboratories (Akhil et al., 2013).

Historically, pumped hydro has been the dominant option of electricity storage at large centralized power stations due to the notably lower cost compared with others (Vassallo, 2015). However, this popular storage option is geographically limited and, for obvious reasons, is not available/feasible for all levels of grid use, including at the distribution and community levels (e.g. residential, commercial, etc.). On the other hand, batteries may be feasible EES options for short- to medium-term storage, in the range of one to six hours.

The large-scale deployment of energy storage into future electricity grids is now widely accepted (Koohi-Kamali et al., 2013; Hadjipaschalis et al., 2009; Lemaire et al., 2017; Battke et al., 2013; Denholm et al., 2013; Vinois, 2017). However, the size, location, ownership/operation, and battery storage device cost trajectory is still evolving (Hoffman et al., 2017). Recent events also point to a rather rapid uptake of small units mostly at the residential scale (Kind, 2013) especially in conjunction with solar PV panels (M.I. and W.M., 2015; Khalilpour and Vassallo, 2016). Some business models are based on providing residential storage and PV as a means of reducing peak demand and time-of-use tariffs (G.A.H.S.C.I. et al., 2013; Khalilpour and Vassallo, 2015; Lu and Shahidehpour, 2005).

The objective of this paper is not merely to assess the economics of energy storage; the literature is rich in this aspect. There is a general consensus that energy storage is a desirable attribute for the operation of grids with high levels of variable energy sources (Yang et al., 2010). The argument is mainly around the economics of energy storage and whether it results in lower delivered cost of electricity for the public. However, it has not yet been discussed whether non-hydro energy storage technologies, such as batteries, have an impact on GHG emissions at all. If, in the future, significantly low-cost battery storage systems are introduced so that energy storage becomes economically viable at all grid levels, will this result in lower emissions? While batteries may provide storage capacity that can facilitate the uptake of renewable power sources and provide stability to networks, they also waste energy through inefficiencies in the electrochemical processes, and through the associated conversion and control power systems. They may also alter the merit order of dispatch, favoring higher-emission intensity sources, for example using coal-fired generation during nighttime for charging and displacing gas-fired power generation during peak times. In this paper we address the fundamental question of the effect of battery energy storage on GHG emissions of a modern, largely fossil-fueled power system.

2. Methods

In order to estimate the effects of large-scale battery energy storage on GHG emissions from power networks, we construct a mathematical model of the National Electricity Market of Australia (the NEM), using actual hourly generator, load, weather and economic data (fuel cost etc.) in conjunction with the transmission network capacity and characteristics. Mathematical optimization is then used to determine the mix of generation and storage that provides the lowest operating cost for each hour of the analysis period, with and without energy storage. The total GHG intensity of the generation mix is then determined for each hour (or period).

Several assumptions are made in this model regarding the operation of the battery storage. To begin, the storage is fully integrated into the dispatch process. This implies that ownership and/or control of the storage devices is by a wholesale market participant, and that the storage devices are used entirely to minimize operational cost. Furthermore, the storage is used solely for bulk energy trading (dispatch); other value streams (e.g. frequency regulation or voltage support) are not targeted by its use, which is not to say that these services are not provided incidentally or could be provided synergistically.

In summary, given:

1. A multi-period planning horizon;
2. Available G units of generators and S units of storage systems;
3. The transmission network topology and capacity constraints; and
4. The forecast electricity demand and weather condition in each location and period;

We wish to determine:

1. The periodical operation schedule of each generator and storage system;
2. The transmitted load profile over each transmission line;
3. Startup and shutdown times, and durations of generating plant operation;
4. The CO_2 emission profile (each system and in aggregation);
5. The periodical short-run marginal cost of each generator and storage; and
6. The power reliability of each zone over the planning horizon;

with the aim of finding the minimum operating cost for the grid over the dispatch interval. The full details of the model are provided in the Supplementary information, and it is effectively the same model solved as part of AEMOs pre-dispatch procedure (and most other market-based ISO operations worldwide).

Details of the Australian NEM are provided in the SI, but in summary, the Australian NEM supplies electricity to five states in the eastern and southern part of the continent, serving approximately 19 million residents with approximately 48 GW of generation provided by over 300 generators. The generation mix is largely steam (black and brown coal, 61%) and gas turbine (22%), with approximately 15% renewables in the form of hydro (7.5%), wind (4%) and PV solar (2%) (Australian energy update, 2017).

We assess the impact of using energy storage by introducing lithium-ion batteries into each of the five regions of the NEM, with a total installed capacity of 1500 MWh (made up as 500 MWh for NSW, 400 MWh QLD, 300 MWh Vic, 200 MWh SA and 100 MWh Tas). Details of the efficiency and dis/charge rate etc. are given in the SI. The optimization model is executed for a 168-h period in July (typically the highest demand arising from the winter peak in Australia) as a base case. Then, the sensitivity analysis cases are for 72-h periods in each of

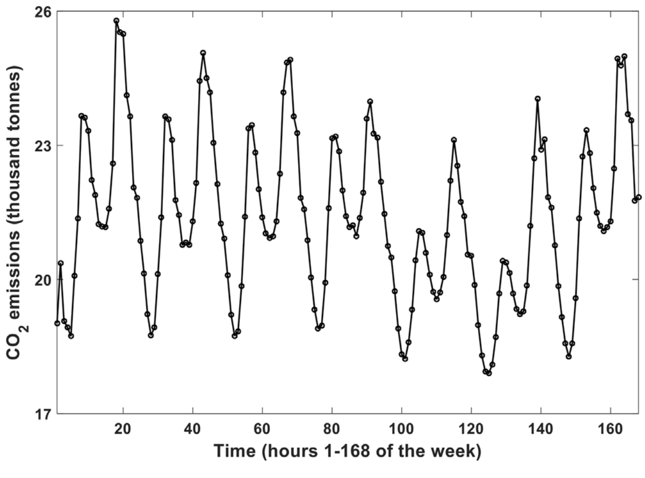

Fig. 1. Profile of CO2 emission over the July planning period for the NEM.