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Suitability of representative electrochemical energy storage technologies for ramp-rate control of photovoltaic power

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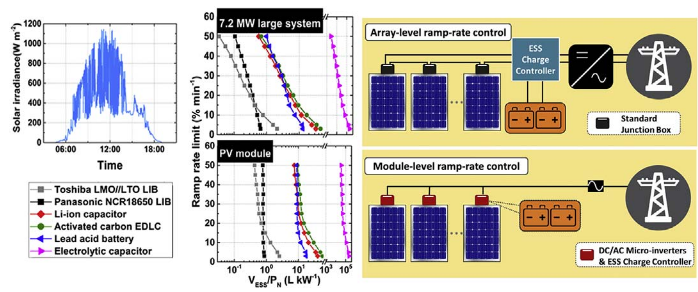
HIGHLIGHTS

- Suitability of LIBs, lead-acid batteries and ECs for ramp-rate control was studied.
- Power-normalised volume requirements show LIBs are the most suitable technology.
- LIBs with a high energy density are optimal for low ramp rates or high compliance.
- With larger PV systems, LIBs with a high power are increasingly more favourable.
- ESS with 400 Wh L^{-1} and 2300 W L^{-1} is required for 10% min^{-1} ramp rates in modules.

GRAPHICAL ABSTRACT



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ABSTRACT

Photovoltaic (PV) systems can exhibit rapid variances in their power output due to irradiance changes which can destabilise an electricity grid. This paper presents a quantitative comparison of the suitability of different electrochemical energy storage system (ESS) technologies to provide ramp-rate control of power in PV systems. Our investigations show that, for PV systems ranging from residential rooftop systems to megawatt power systems, lithium-ion batteries with high energy densities (up to 600 Wh L^{-1}) require the smallest power-normalised volumes to achieve the ramp rate limit of 10% min^{-1} with 100% compliance. As the system size increases, the ESS power-normalised volume requirements are significantly reduced due to aggregated power smoothing, with high power lithium-ion batteries becoming increasingly more favourable with increased PV system size. The possibility of module-level ramp-rate control is also introduced, and results show that achievement of a ramp rate of 10% min^{-1} with 100% compliance with typical junction box sizes will require ESS energy and power densities of 400 Wh L^{-1} and 2300 W L^{-1}, respectively. While module-level ramp-rate control can reduce the impact of solar intermittence, the requirement is challenging, especially given the need for low cost and long cycle life.

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1. Introduction

The world is transitioning to use more renewable energy sources, among which photovoltaics (PV) is the fastest growing accounting for almost 30% of net additions to global power capacity in 2016 [1]. However, PV systems can exhibit significant variances in their power output due to the intermittence of sunlight. As the penetration level of PV power into the utility grid continues to increase, these variances can impact voltage and frequency stability of the electricity grid, if not appropriately managed [2–5]. This is particularly problematic for small utility grids or islanded microgrids with high levels of PV penetration and limited opportunity for aggregation smoothing of the generated power [6,7].

In order to ensure the power quality and reliability of the distribution network, some utility grid operators have started to impose restrictions on the ramp rate of the generated power from grid-connected PV systems. For example, the Puerto Rico Electric Power Authority has imposed a limit of 10% of system rated capacity per minute (denoted as 10% min^{-1}) to both power ramp-up and ramp-down rates [3], and Germany requires a 10% min^{-1} limit for positive power ramps [3]. In many countries, new standards for grid connection of PV (e.g., in Australia [8]) require that inverters must implement, at least the lower level modes, demand response management modes to allow greater control over inverter response to the grid. Lower level modes require that inverters can rapidly disconnect themselves from the grid on demand, whilst higher level modes can require inverters to reduce their output to a fraction of their rated power during excursions of normal voltage and frequency operating ranges. Additional demand response management functions of ramp-rate control to allow the generated power to change smoothly from one level to another are also suggested [8,9]. Increased implementation of new grid connection standards worldwide may increase the importance of localised power-management strategies that can make possible higher penetration levels of PV in electricity grids.

PV power variability due to cloud shading can be mitigated in part by the use of module-level power-management electronics, such as DC/DC power optimisers [10,11] and DC/AC micro-inverters [2]. However, the extent of power buffering (i.e., ramp-rate control) by these electronics is inherently limited by insolation conditions. An alternative approach is to use an energy storage system (ESS) to buffer the variances by discharging to or charging from the PV generated power to compensate for PV power changes [12]. This approach enables the inverter output power to be partly decoupled from PV generated power and therefore allows more control over the power injected into the grid. Although non-electrochemical ESS technologies such as the pumped hydroelectric storage, compressed air energy storage and flywheels [2] may also be candidates for this application, this study focuses on electrochemical ESS technologies.

A range of electrochemical ESS technologies have been proposed for power buffering of PV systems [13–17]. However, most reports have assumed the use of rechargeable batteries at an array level [16,17], with some reports having also investigated the use of electrochemical double-layer capacitors (EDLCs) [14,15], or a combination of EDLCs and fuel cells [13]. Although the storage requirements (i.e., capacitance and capacity) for specific ESSs have been determined, simple justifications were made for the choices of ESS technology. Marcos et al. [18,19] and Schnabel et al. [20] derived empirical relations between the energy and power required for a generic ESS to limit the ramp rate of PV power to different levels. These studies, however, did not consider which ESS technologies would be optimal for PV power buffering applications. The energy and power density of any electrochemical ESS are correlated (with exception of the flow batteries) [21] and therefore typically need to be considered concurrently when selecting and sizing a suitable ESS.

In this paper, we incorporate into the analysis, for the first time, the volumetric energy and power densities of different electrochemical ESS technologies. Using these ESS characteristics, the suitability of a set of state-of-the-art electrochemical ESS technologies were quantitatively compared based on their required volumes for power ramp-rate control for PV systems of different sizes. Section 2 briefly reviews the ESS technologies that were considered in this study. The methods used in the study are described in Section 3 and then in Section 4 the results of the analysis are presented. First, in Section 4.1, the power generation profile for: (i) a residential rooftop PV system (5 kW); (ii) a small commercial PV power system (100 kW); and (iii) a large PV power system (7.2 MW) was simulated using 1 s solar irradiance data recorded in Sydney, Australia and a previously reported low-pass filtering method [22] to model the effects of smoothing arising from geographic aggregation and module-level electronics. A ramp-rate analysis of the solar irradiance and power generation data for a period of 46 days is presented. In Section 4.2, calculations of the power-normalised ESS volume required for different allowable ramp rate limits and compliance levels are reported, in order to determine the most suitable ESS technology for each of the different PV system sizes. Then, in Section 4.3, we introduce the new concept of PV module-level ramp-rate control, where compact ESSs are integrated into the module electronics of DC/AC micro-inverters. The requirements for an ESS for this concept and the limitations of the current ESS technologies for this application are discussed. We conclude with a discussion of the costs of the different ESS technologies and highlight the need to consider not only capital cost but also the levelised cost of storage, which takes into account the different cyclability capabilities of the different ESS technologies.

2. Electrochemical ESS technologies

The characteristics of an ESS that are of particular interest for our investigation are the energy density (storage capacity) and power density (rate capability). Although gravimetric values are commonly reported, the volume available to an ESS may be more restricted for PV ramp-rate control applications; therefore, volumetric energy and power densities are discussed in this study. Three types of ESS technologies were investigated: (i) rechargeable batteries; (ii) electrochemical capacitors; and (iii) electrolytic capacitors. Their representative energy and power densities are shown in the Ragone plot in Fig. 1.

Two examples of commonly-used rechargeable batteries that may be suitable for ramp-rate control are lithium-ion batteries (LIBs) and lead-acid batteries. Lead-acid batteries are one of the most mature and affordable ESSs and they have already been implemented in many stand-alone PV systems for load levelling [23–25]. Their energy densities are typically in the range of 50–90 Wh L^{-1} [26,27], but compared to other rechargeable batteries, their power capability is very limited. Besides, the main limitation of lead-acid batteries is their low cycle life (200–300 cycles at a 80% depth of discharge for valve-regulated lead-acid batteries [28]). Flooded lead-acid batteries have a higher cycle life but require more frequent maintenance.

Lithium-ion batteries are used commonly for portable electronic devices because of their high energy and power densities, flexibility in packaging and longer lifespan than other types of rechargeable batteries [29]. In comparison to lead-acid batteries, LIBs have substantially higher energy densities over a wide range of power densities suggesting their potential for high rate capability. State-of-the-art commercial LIBs have energy densities ranging from 200 to 700 Wh L^{-1} [30–34] and cycle lives in the order of 10^2 to 10^4 cycles [34,35]. Values vary depending on the active materials used for battery anodes and cathodes as well as device architectures. Most commercially-produced LIBs use insertion-type cathode materials, typically transition metal oxides, such as layered $LiCoO_2$ (LCO) [36], spinel $LiMn_2O_4$ (LMO) [37], layered $LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$ (NCA) [38] and $LiNi_xMn_yCo_zO_2$ (NMC) with various stoichiometries [39]. Coupled with graphite anodes, commercial cells incorporating LCO or NCA cathodes can have energy densities as large as 600–700 Wh L^{-1} but a cycle life of < 1000 cycles [31,40].