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# Modelling electrochemical energy storage devices in insular power network applications supported on real data

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## HIGHLIGHTS

- A comprehensive performance study between a set of competing electrochemical energy storage technologies is provided.
- Several key engineering parameters with regards to the PbA battery-based storage solution are examined.
- An ES system operating criterion is discussed and proposed to manage the inherent rapid aging of the batteries.
- The simulation results are supported on real data from two non-intercontinental power grids.

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## ABSTRACT

This paper addresses different techniques for modelling electrochemical energy storage (ES) devices in insular power network applications supported on real data. The first contribution is a comprehensive performance study between a set of competing electrochemical energy storage technologies: Lithium-ion (Li-ion), Nickel–Cadmium (NiCd), Nickel–Metal Hydride (NiMH) and Lead Acid (PbA) batteries. As a second contribution, several key engineering parameters with regards to the PbA battery-based storage solution are examined, such as cell charge distribution, cell string configuration and battery capacity fade. Finally, as a third contribution, an ES system operating criterion is discussed and proposed to manage the inherent rapid aging of the batteries due to their cycling activity. The simulation results are supported on real data from two non-interconnected power grids, namely Crete (Greece) and São Miguel (Portugal) Islands, for demonstration and validation purposes.



## 1. Introduction

In the last decade and a half $CO_2$ emission reduction has become an item on the political agenda of most developed countries to decelerate the global warming phenomenon. In this sense, renewable energy sources (RES) have a fundamental role towards climate change mitigation, the decrease of negative health and environmental effects and the security of electricity supply [1,2].

Insular power grids (IPG) are encouraging for RES deployment since wind and solar resources are generally abundant. Presently, RES exploitation in insular systems is an increasing reality, although it still has a reduced or moderate contribution to the insular energy mix. However, the gradual changes in insular energy mix will introduce new challenges from the grid operation perspective, mainly due to the intrinsic volatility of renewable generation exacerbated by load variability, inexistent interconnections and reduced dimensions of the insular grids. In this framework, insular grid operators would need to resort to additional reserve margins in order to keep the reliability of the IPG intact [3]. For instance, if wind power integration surpasses 20% of the installed capacity, ancillary services such as frequency regulation would require an increase of 7% of capacity to face the grid instability [4]. For the aforementioned reasons additional sources of flexibility have to be adopted in order to avoid the deterioration of IPG management [5].

ES systems could become in the medium term one the main drivers for RES expansion in insular energy panorama. However, IPGs are indeed heterogeneous in terms of size, RES resources, load demand variability and installed power mix. ES can only become a viable solution if analysed in connection with the challenges associated to RES planning at a large scale [6,7].

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In this paper two real insular systems that serve as the basis for the present study are discussed. The next part targets a comprehensive study of four competing electrochemical storage devices, which are Li-ion, NiCd, NiMH and PbA batteries; their evaluation is performed on basis of merit figures created for this purpose. The third part is dedicated to the PbA battery. The design aspects of this battery sizing are analysed, specifically the charge distribution on a serial cells arrangement and energy capture as function of cells configuration (single or parallel strings). The paper ends with the presentation of an ES system operating criterion with the purpose of extending the battery life. The simulation results are supported on real data from non-interconnected power grids, which are Crete (Greece) and São Miguel (Portugal) Islands. The real data concerning one week of operation were supplied by the Singular EU FP7 project [8]. An ES system operating criterion is proposed and discussed to manage the inherent rapid aging of the batteries due to their cycling activity. A simplified modelling of the capacity fade estimation is also proposed and utilised in this paper.

The remainder of the paper is organised as follows. In Section 2 the background on the studied conventional ES technology is addressed. In Section 3 a summary of the two researched insular systems is presented and the respective case studies are addressed. Section 4 focuses on the analysis of the performance between a set of competing electrochemical ES technologies. The sensitivity analysis of battery design parameters is presented in Section 5. The conclusions are finally made in Section 6.

## 2. Background on the studied conventional energy storage technology

Utility ES applications will play three main roles [9–12]: (1) Stabilizing power which means ES can make an active contribution to the grid power quality with sophisticated services aiming voltage and frequency regulation; (2) High flexibility in balancing power – for filling the gaps between conventional and non-conventional power, e.g., short-time drop in wind power can be replaced by ES resources. Alternatively, it can secure critical energy supply while part of generation is ramped-up or disconnected from the grid. Moreover, high flexibility means the energy discharge time can be chosen according to the application itself; (3) Dispatching energy which allows the possibility to deploy power when it is needed. Such solution offers opportunities to take advantage of time-pricing scheme since the energy can be stored at low demand periods and traded to be deployed at higher price periods, thus, shortening the payback time and increasing the potential profits.

Utility ES solutions comprise a range of technologies with wide-ranging energy and power handling capabilities [13]. Electrochemical batteries could offer the required flexibility to cope RES intermittency at all levels of the insular power grid [14,15]. The support given by a battery energy storage system (BESS) is that it can recover the wind power curtailment and at same time providing advanced grid services concerning the discharge of electrical energy in a longer period or in a very short time [16]. On the other hand, the reduction of the utilisation of traditional power stations in favour of the use of RES raise questions of performance among the different electrochemical options and the optimal sizing of grid connected battery systems [17]. That said, one of main challenges for grid BESS successful operation is their ability for working for extended periods of time at a partial charge [18].

Currently, the battery universe for grid-scale ES systems as mature and commercially available solutions comprises PbA and Li-ion batteries. Despite their high media exposure and continuous improvement on the performance by many battery manufacturers other electrochemical ES options are available. That is the case for NiMH and NiCd batteries, however their application in the ES market varies greatly [19,20]. Recently, Sodium Sulphur (NaS) batteries have been considered as model candidates for large grid scale BESS applications [21]. Although it is known that this battery is highly efficient and has environmentally friendly characteristics, it has several additional design requirements due to operating conditions and cell configurations [22] which make the project and O&M costs of this BESS expensive for a small electric grid such as São Miguel. For this reason, NaS BESS are not considered in this study. However, a study of modelling and sizing of NaS BESS for extending wind power performance in Crete Island was performed in [23].

From a historical perspective PbA battery is the oldest technology in use. Its discovery goes back to XIX century. The cycling characteristics and energy density of the PbA cell is inferior to other modern electrochemical options, but such issues are balanced in large part by the advanced level of maturity of the PbA battery industry and its low cost [24]. On the assumption that environmental issues and weight do not have an influence on the power generating facility, PbA batteries will likely remain a standard in the BESS field [25]. PbA batteries are utilised in a wide variety of different tasks, each with its own characteristic duty cycle, ranging from combustion vehicles for starting the vehicle to back-up in telecommunications and in other continuous power supplies. Such types of batteries are highly suitable for medium- and large-scale ES operations since they are capable to offer a satisfactory combination of performance parameters at a cost that is significantly below to those of other systems [26] for a large range of production capacity of electricity from RES [27]. In fact, several projects using this chemistry have been deployed in terms of medium- and large-scale grid ES systems, comprising installations of few hundreds of kW to MW. As an example, a 10 MW/40 MW h facility made up of PbA batteries has been running for more ten years [19]. Valve-regulated PbA (VRLA) batteries also known as advanced PbA batteries, which use an immobilised electrolyte, were developed to extend the service life and to minimise the maintenance when compared with conventional PbA batteries [18]. Advanced PbA display several advantages over conventional PbA batteries, such as higher reliability under depth of discharge (DOD) cycles, longer lifetime service and the flexibility of installation in any orientation [28]. Several projects are currently in motion concerning the application of such a BESS technology on islands, such as the Kahuku Wind Farm project - a 15 MW fully integrated ES and power management system designed to provide load firming for a 30 MW wind farm in Oahu, Hawaii, United States [29] or the Kaua'i Island Utility Cooperative in Koloa Hawaii, United States [30].

Li-ion batteries present themselves as an alternative ES technology to PbA batteries and are becoming the main choice for many applications such as portable electronics, power tools, power back-up systems and plug-in hybrids and electric vehicles [31–33]. By the reason of having a long lifetime, higher specific or volumetric power, higher energy density, wide temperature range and decreasing costs have made Li-ion batteries more interesting for the abovementioned applications [34]. As for grid energy storage applications these electrochemical cells are getting increasing attention not only by the companies involved in their development but also the utilities seeking a reliable and lasting solution. The general interest around this chemistry is confirmed by several field trials across the globe. In USA, various pilot programs are conducting utility battery energy storage tests with Li-ion devices, the largest one located in a wind farm in California and featuring an energy storage installed capacity of 8 MW/32 MW h [35].

NiCd batteries have been used from early XX century. Such types of batteries display a significant power density and a lightly higher energy density when compared to other conventional ES technologies. Such types of batteries are able to perform well even in cases of low temperatures, i.e. from −20 °C to −40 °C. A Notable feature of chemistry NiCd is the capability to withstand high cycle