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A review of pumped hydro energy storage development in significant international electricity markets

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ABSTRACT

The global effort to decarbonise electricity systems has led to widespread deployments of variable renewable energy generation technologies, which in turn has boosted research and development interest in bulk Electrical Energy Storage (EES). However despite large increases in research funding, many electricity markets with increasingly large proportions of variable renewable generation have seen little actual bulk EES deployment. While this can be partly attributed to the need for technological developments, it is also due to the challenge of fairly rewarding storage operators for the range of services that storage provides to the wider network, especially in markets that have undergone significant restructuring and liberalisation. Pumped Hydroelectric Energy Storage (PHES) is the overwhelmingly established bulk EES technology (with a global installed capacity around 130 GW) and has been an integral part of many markets since the 1960s. This review provides an historical overview of the development of PHES in several significant electrical markets and compares a number of mechanisms that can reward PHES in different international market frameworks. As well as providing up-to-date information about PHES, a primary motivation for this work is to provide an overview about the types of rewards available to bulk EES for the wider storage community including investors, technology developers and policymakers. Observing that bulk EES projects seem to be unattractive investments for the private sector, the paper also includes a brief discussion in terms of public sector investment.

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1. Introduction

In the last decade, interest in bulk Electrical Energy Storage (EES) technologies has grown significantly as a potential solution to some of the challenges associated with decarbonising electrical energy systems. The transition from systems that are primarily reliant on carbon-intensive fossil fuels to those which use greater amounts of lower-carbon energy sources like renewables and nuclear energy is a broadly accepted policy choice of many countries around the world, although the exact technology choices, the speed of the transition and the level of ambition vary widely. The decarbonisation policies are a response to the compelling evidence around the risks of anthropogenic climate change, and the need to decouple economic growth from environmentally damaging impacts.

One of the greatest challenges of many low-carbon generation technologies is that they lack a similar level of load-following flexibility compared to conventional fossil fuel based power generation. This is especially true of renewable generation that is weather dependent. For example, the wind and solar primary energy resources are variable, often unpredictable (when the forecast window to real time is stretched), and crucially lack the *intrinsic energy storage* associated with fuel-based generation. Therefore, while weather dependent renewable generation can generally be turned down (curtailed) if demand is low, it lacks load-following flexibility as it cannot be turned up if the primary energy source is unavailable. Simply put, it is not possible to store these primary energy resources, *e.g.* one cannot store the wind as wind or the sunlight as sunlight. This is a simple but powerful concept as intrinsic energy storage is a defining characteristic of any fuel. Fossil fuels in particular are a major part of the primary energy supply of most electrical systems due to their cost, availability, energy density, ease of storage, ease of handling and ease of transportation. Historically, the low comparative cost of storing electrical energy in fossil fuel stockpiles, prior to its conversion to electricity, has meant that fossil fuel stockpiles are overwhelmingly preferred as the stores of electrical energy [1]. Their use as a source of energy that is converted to electricity as and when required has enabled electrical energy systems to be developed under a 'demand led' paradigm where electrical generation is controlled in order to closely match the demand at any given point in time.

The limited ability of wind and solar technologies to load-follow is one of the main challenges that bulk EES seeks to address. Several academic studies have highlighted energy storage as an important method of adding the flexibility that is required to integrate large proportions of low carbon energy in electricity networks. An extensive report by Denholm et al. [2] for the National Renewable Energy Laboratory, USA concludes that high penetrations of variable generation increases the need for all flexibility options, including energy storage. Eyer and Corey [3] also conclude that renewables integration is one of the major drivers for energy storage while Beaudin et al. [4] concludes that large scale renewables integration will be a more difficult challenge without energy storage. Steinke et al. [5] investigates a 100% renewable Europe and finds that without grid and storage extensions the necessary backup generation amounts to roughly 40% of the demand. Cochran et al. [6] study the best practices for integrating variable renewable generation and concludes that while there is no one size fits all approach, market mechanisms that promote increased storage should be developed. Although it is generally accepted that smaller percentages of renewable generation can be integrated into many electricity systems without very significant operational changes [2,7], the scale of transition required to meet the climate change challenge means that additional flexibility is likely to be universally required. This increasing need for flexibility [8] due to the planned increase in the penetration of variable renewable energy sources is, we believe, a major driver for interest in bulk EES.

The other technologies besides wind and solar which can provide low-carbon electricity on a global scale are nuclear power and fossil fuels with Carbon Capture and Storage (CCS). However, nuclear power also lacks load-following flexibility and historically was deployed alongside significant developments of PHES [9]. This is because frequently turning down the output from nuclear power plants not only increases the electricity cost by reducing the load factor but also strongly accelerates the aging of equipment [10]. Therefore if nuclear is to be deployed in future, without further bulk EES, an important design consideration is load-following ability. This design for flexibility is however likely to increase the cost of the plant, and consequently the cost of the electricity generated from the plant too. On the other hand, CCS technologies have so far failed to gain any meaningful levels of deployment, despite significant research and development [11].

The delays in the development and deployment of CCS or more flexible nuclear technologies in comparison to the speed of recent deployments of solar and wind generation is also a major reason why bulk EES has attracted a growing level of interest from public and private funding sources. Bulk EES also has many other benefits throughout the electrical supply chain, and several studies have discussed these [2–4,12–15]. They include:

- facilitating increased deployment of low-carbon generation
- facilitating time of use energy management
- increasing reliability for end-users
- reducing the volatility of electricity prices
- increasing system reliability
- increasing system flexibility
- reducing the need for transmission upgrades/new transmission infrastructure
- reducing overall pollutant emissions.