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Shifting demand and supply over time and space to manage intermittent generation: The economics of electrical storage[☆,☆☆]

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ABSTRACT

The literature on electrical energy storage (EES) is technical and complex, which this paper aims to simplify. It quantifies the current scale, costs and value of different types of mature EES and compares them to peaking generators, interconnectors and demand-side response. Worldwide, dams have 2700 times the storage capacity of pumped storage, which accounts for 99% of conventional EES, batteries making up most of the rest. Indirect use of hydro power, and in future, electric vehicles, adds to their value and if accessible at reasonable cost, would be cheaper than conventional EES. EES, peakers and DC interconnectors can offer flexibility services which considerably enhance their value, but hopes of a battery revolution enabling a smarter electricity system should not be exaggerated.

1. Introduction

The electricity system has to balance supply and demand every second, a task that becomes increasingly difficult as intermittent renewables increase their penetration and the amount of inertia on the system falls. Wind and solar PV can be both highly variable over short time periods and hard to forecast accurately more than a few hours ahead, making storage appear increasingly attractive as a key element in a renewables-dominated electricity system. Much of the discussion of electrical energy storage (EES) is technical, reporting results from small model networks or individual experiments. More ambitious studies of future EES requirements (e.g. Pudjianto et al., 2014) summarise complex simulation/optimal dispatch models at a rather high level based on generic storage devices.

This paper takes a bottom-up approach to compare the likely ranges of costs and benefits of different solutions to the various problems facing the evolving electricity system. It describes different solutions to balancing supply and demand, their costs and value, as well as constraints on their supply. It draws on market price data to assess the arbitrage benefits of EES, comparing that with alternatives such as back-up generation and interconnection, to assess the role that EES might play in shifting demand and supply over time and space.

The paper argues against the simplistic assumption that batteries, and indeed building more storage generally, offers the natural solution to balancing an increasingly renewables-dominated electricity system, by providing relevant evidence in an accessible form. This is not to deny that storage can provide increasingly valuable services, nor that batteries, particularly at specific locations on distribution networks, can be a cost-effective solution to managing constraints and deferring investment, but their total contribution of managing high levels of renewables is likely to be modest. The main point of this paper is to provide evidence, not just on EES but on alternatives that can offer other shifting options that are often cheaper.

Section 2 sets of the methodology adopted for measuring cost and value, followed by a discussion of the characteristics of different types of storage, their value (Section 4), the value of indirect storage in Section 5, alternative sources of flexibility (Section 6), ending with conclusions and policy implications.

2. Measuring the cost and value of electrical energy storage

Different technologies have different characteristics that lend

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[☆] *"This article is part of a Virtual Special Issue entitled 'Economic Analysis of Recent Energy Challenges: Technologies, Markets and Policies'."*

[☆☆] This paper was presented at the Paris meeting of CEEPR/MIT on 8 July 2016, at which time the author was a research associate in the Electronic and Electrical Engineering Department of Imperial College London. Its approach is much influenced by David MacKay's (2013) demonstration of the power of simple quantification to test the plausibility of options for decarbonizing economies in *Sustainable energy without the hot air*. His chapter 26 on storage covers similar ground but without the economic assessment. I am indebted to excellent comments from colleagues and the Journal's referees, and support from Goran Strbac.

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themselves to different applications. Luo et al. (2015) surveys current EES technologies, their operation, characteristics and applications, with some cost information. Of the 18 technologies surveyed, most are only at demonstration stage. The mature technologies are discussed below.

2.1. Measuring cost and value

Storage and its competitors have a number of characteristics that affect cost and value. Different technologies typically have a comparative advantage in one dimension, and may not be able to offer some of the others. The three most important are maximum output (kW or MW), capacity (kWh, MWh) and speed of response (milliseconds for batteries and interconnectors, tens of seconds for pumped storage, minutes for combustion turbines, longer for other fossil plant). Other factors influencing cost are lifetime (years, or number of charge and discharge cycles), whether they need to convert from AC to DC and back, their accessibility, and capital and operating costs. For balancing and fast frequency response, output and response time are critical, so measuring their capital cost in £/kW is the natural metric; for diurnal load smoothing, storage capacity becomes important and the appropriate metric is £/kWh. Capital and fixed operations and maintenance (O&M) costs are naturally measured in £/kWyr or £/kWhr.yr – the latter meaning the annual cost of being able to provide 1 kWh of storage.

2.2. The value of storage

The benefits of storing currently excess or very cheap electricity for later more valuable use is not new. As Britain (and other countries) developed significant shares of nuclear power, it became clear that the opportunity cost of night-time nuclear power was zero (or negative, given the costs of stopping and restarting), while meeting peak demands the next day involved high variable cost power. Storage could shift surplus supply to later periods, and many pumped (hydro) storage plants, or PSPs, like Dinorwig in Wales,[2] were built to allow nuclear power to run at full capacity while facing variable demand.

Recent rapid falls battery costs have raised hopes that chemical rather than water storage offers an attractive alternative storage option. Batteries are typically of modest size (up to 10 MW) and likely to be connected to distribution networks, where improved network management (smart grids) allows them to realise a variety of services locally and to the national grid. 454 MW of batteries secured capacity agreements in the 2016 British T-4 capacity auction (for delivery of capacity 4 years later in 2020/21 to ensure security of supply), receiving the clearing price of £22.50/kW.yr,[3] (Ofgem, 2017). Smart metering offers the prospect of accessing smaller decentralised EES units, e.g. those in electric vehicles (Newbery and Strbac, 2016).

2.3. The magnitude of wind variability

Intermittent power from wind and PV makes storage more attractive, as there may be excess power relative to demand in some periods and a shortage in others. The Single Electricity Market (SEM) of the island of Ireland is exemplary, with a higher wind share consumed locally and lower interconnections than almost anywhere else. Eirgrid (2017, A.6) gives 2016 total wind capacity at 2740 MW when average demand was 3150 MW (27.6 TWh/yr) and peak demand 5110 MW. The 2020 target of 40% renewables is estimated to require a total of 3800-4100 MW, likely to be comfortably met at recent installation rates. The 2020 forecast is 31 TWh (+/− 1 TWh), averaging 3540 MW (Eirgrid, 2017, p. 25). Clearly there will be many hours in which wind output will exceed domestic demand. Even to accommodate the 40% target will require 75% non-synchronous generation (such as wind) in lower demand hours while retaining sufficient inertia and flexibility to maintain the required quality of service (in terms of voltage and frequency stability).

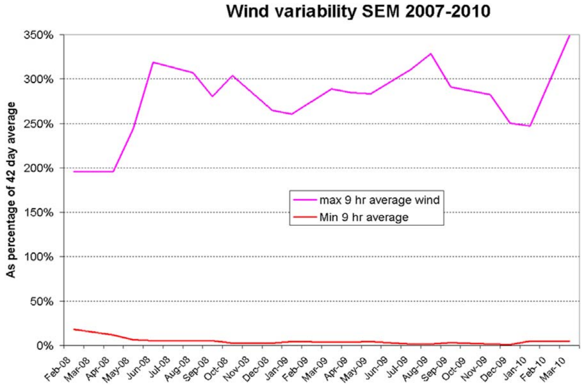

Fig. 1. Wind variability on the island of Ireland, 2007-10.
Source: Single Electricity Market Operator (SEMO)

Fig. 1 demonstrates the significance of wind variability. It shows the maximum and minimum average wind output over successive periods of 9 h within a 42 day window relative to average wind output over that same 42 day period for the first three years of SEM operation. Nine hours is roughly the capacity of a PSP, while the 42-day mean wind output corrects for the rapid growth in installed wind capacity over this period. The figure shows that in any 6-week period there will be at least one 9-hr period when wind output is 1–6% of its average value, and at least one 9-hr period when it is nearly three times the average. At target levels of wind, there will be many periods in which wind output alone exceeds domestic demand, although with 950 MW export capacity some of this surplus can be exported. Nevertheless, over the period 2010-16 2.4% −5.1% of wind was curtailed (Eirgrid, 2017, p43). Given the considerable revealed variability and unreliability of wind, electrical energy storage (EES) might seem an attractive solution to this problem.

2.4. The magnitude of solar variability

The output of solar PV varies predictably diurnally and seasonally, and unpredictably over periods as short as a minute as clouds cover the sun, during which irradiance can fall by a factor of five (MIT, 2015). These rapid fluctuations can cause frequency problems, particularly for grid-scale arrays, unless such arrays are dispersed over a sufficiently wide area and strongly interconnected. Otherwise very fast response EES may be valuable, although as frequency is a system-wide phenomenon, fast frequency response need not be strongly coupled to the PV arrays. The need here is for high output but low storage volumes.

PV'S predictable diurnal fluctuations can dramatically alter the pattern of net (of PV) demand to be met by flexible generation. Fig. 2 shows the famous Californian “duck” curve, and the need for fast ramping to replace the solar PV output as evening approaches. Prices are already strongly depressed in the sunny hours and can be particularly high in the evening peak, again suggesting potential storage arbitrage opportunities over time periods of about 4–6 h, with the need for moderately high output but higher storage volumes.

3. Characteristics of different forms of EES

Table 1 shows the overwhelming (99%) share of conventional EES is provided by pumped storage plants (PSPs), in which water is pumped to an upper reservoir to be released through turbines to generate electricity when needed. PSPs require massive amounts of concrete and tunnelling and a suitable mountain, of which there only are few in a

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[2] See e.g. http://www.fhc.co.uk/dinorwig.htm and https://www.theregister.co.uk/2016/05/16/geeks_guide_electric_mountain/.

[3] All prices are adjusted to £(2015) prices using the CPI. Figures in US$ are first adjusted to 2015 US prices in $ and then converted at $1.5/£.