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Estimating the capital costs of energy storage technologies for levelling the output of renewable energy sources

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Abstract

In remote areas and islands North and West of Scotland, and in many other parts of the world, the high cost of connecting wind farms and other renewable energy converters to the grid may make energy storage an attractive alternative. We estimated the installed capital costs of advanced adiabatic compressed air storage (ACAES), vanadium redox flow cells (VRB) and Li-ion batteries, in the range 0.5-50 MW and 0.7-30 MWh. These costs were all of the order of £ 1 million per MWh, confirming that they already compared favourably with that of network improvements and connection to mainland. VRB and Lithium ion batteries had similar capital costs, with VRB being more competitive at lower power output and higher energy storage. Cost reductions of 30-50% would be required for ACAES to be competitive, which may be achieved by the use of reversible compressors that can also be operated as expanders.

Keywords: adiabatic compressed air energy storage; batteries

1. Introduction

In remote areas North and West of Scotland, the cost of connecting wind farms and other renewable energy converters to the grid is not cheap, especially on an island. For example, the Orkney archipelago already hosts more than 50 MW of installed onshore wind capacity and 4 MW of wave and tidal, but the output from these is curtailed by a limited local grid and connector to the mainland, and this costs an estimated £ 4 million per year to generators in lost income. A simple shore-to-shore improvement of the connector to the mainland could cost about £ 28 million, but the necessary overhaul to the whole island system would be ten times this amount. Other areas in Europe and the world will face similar issues, including with other energy sources for example solar energy.

As an alternative, or to reduce the constraints on connectors to the mainland grid, energy storage in various forms is an option. Ideally this could be pumped hydro storage (as with the 1 MW scheme on the Isle of Jura), but this is limited to specific sites. Recently, electrochemical technologies have benefited from improved footprint and costs which makes them sufficiently competitive to be considered for this application. These options may also have advantages including conversion to services where the energy may be used directly, such as transport or heating. In addition, adiabatic compressed air energy storage has also been proposed for this application, perhaps because electrochemical technologies are seen as expensive. In any case, costing these options is fraught with difficulty, not least because the technologies that may be employed have often not reached full commercial or even technical development at the appropriate scale for this type of application.

This paper considers storage for small scale generators, in the range 0.2-10MW and up to several hours of stored energy using Li-ion batteries; Vanadium redox flow cells; and adiabatic compressed air energy storage (ACAES). The first two have reached commercial stages, with further cost reductions still expected through technology and mass production. The last (ACAES) seems promising. A working plant might require only a combination of existing technologies; but uncertainty regarding suitability of components may make it more expensive to build and less efficient to run [1]. We will attempt to compare and estimate costs for all three technologies.

2. Methodology

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The present study focuses on installed capital costs for a given output in MW and MWh. A more detailed analysis would require consideration of operating and maintenance costs (with significant impact of round-trip efficiency), and also footprint. The Chemical Engineering Plant Cost Index was used for adjusting all cost estimates for inflation up to year 2013, with the following values: 395.6 in 2002, 575.4 in 2008, 584.6 in 2012 and 567.3 in 2013.

2.1   Lithium ion batteries

Lithium batteries were developed for consumer electronics; their high volumetric energy density and light weight was a great advantage. They are now produced in billions of units for powering a wide array of devices from phones to laptops and toys, etc. Li-ion or $LiFePO_4$ batteries make electric vehicles a practical proposition, and they are also now serious commercial contenders for stationary applications including uninterruptible power supply, grid balancing and energy storage [2]. Their main weakness is with the necessary coupling of power rating and energy storage capacity, since the energy is stored within the electrodes themselves, a constraint which might limit the total energy capacity that could be economically reached.

A recently published DOE/EPRI handbook [2] contains quotations for a number of Li-ion energy storage plants spanning a wide range of power and energy storage ratings, including some detail on the balance of the plant. We analysed these data to develop cost correlations for this type of plant, taking into account the most basic of their physical characteristics. Thus, the cost of the batteries as delivered was taken to be proportional to their energy storage rating E, divided by the depth of discharge DoD. Figure 1 shows that a linear correlation applied for battery capacities in the range 0.028 to 30 MWh (i.e., spanning four orders of magnitude), with $R^2 = 0.937$.

[FIGURE 1 GOES HERE]

The handbook also provides estimates for design and construction, connection to the grid, commissioning etc. [2] in the range 0.25 to 30 MWh from the same data that were used for plotting Figure 1. The resulting correlation giving installed costs for Li-ion batteries was

Installed cost = 1,170,000 x (MWh rating) x 100/DoD + 49,500,000/DoD   in 2013 $ m.   (1)

Figure 2 compares the result from Eqn. 1 with the data from the handbook [2]. It can be seen that the model overestimates the quoted prices for the larger installations (capital expenditure greater than $ US 5 million) by up to a third, and that it is accurate to within 20% for the rest, with one exception out of nine data points.

[FIGURE 2 GOES HERE]

2.2   Vanadium redox batteries

Vanadium redox flow batteries (VRB) have been commercially available since the early 2000s for voltage regulation and grid balancing [3]. Unlike Lithium batteries, they did not enter a rapidly expanding market of applications to stimulate their development and reduce costs. At present, typical round trip efficiencies are of the order of 75%, compared with 90% for lithium. Nevertheless, like all flow cells they offer an advantage over conventional batteries since their energy is stored within their electrolyte and not their electrode. This allows their energy rating to be decoupled from their power rating and hence makes the storage of energy potentially much cheaper (by storage of electrolyte rather than increased size or number of batteries). The technology is attracting attention. Renewable energy generation is growing, and challenges to distribution and the matching of supply and demand are becoming more acute, as illustrated by announcements of demonstration projects for the technology in 2013. For example, there are a planned 15 MW, 60MWh, demonstration project for Hokkaido island, Japan [3]; and 1.6 MWh, 100kW demonstration project for the island of Gigha, Scotland[4].

Costs for the components that make up the batteries and electrolyte tanks have been determined and used for estimating the cost of VRB before installation [5], from which it is possible to infer the following model:

Cost before installation = 927,200 x P_{out} + 326,000 x (MWh rating) + 23,410 x (MWh rating)$^{0.6}$ in 2013 US $ (2)

The first term is assigned to the electrodes, and therefore is expected to be proportional to power (assuming current density is kept constant when scaling up); the second term is assigned to the electrolyte, hence proportional to the energy stored; and the third term relates to process items like vessels, pumps and piping, and follows a power law familiar to process engineers. This reversed engineered correlation seemed adequate for the purpose of this study, since comparison with all five commercial quotations provided in the handbook [2] gave agreement within 10%. The commercial data covered a wide range of specifications, from 0.2 MW and 0.7 MWh to 50 MW and 250 MWh. Finally, inspection of the same raw data from the handbook [2] indicated that installation costs were on average 1.7 times the cost of the batteries.

2.3   Adiabatic Compressed Air Storage

Barbour, Mignard and Bryden [1] analysed the energy efficiency, design and costs of adiabatic compressed air energy storage (ACAES) with particular consideration given to a small scale marine energy scheme with rating 1MW and 2MWh. The scheme was for multistage compression of 1700 Nm^3 of air, with recovery of the heat after each stage in packed bed heat exchangers (PBHE) filled with granite pebbles, and storage of the compressed air in two 90 m^3 accumulator pressure vessels operated between 20 and 80 atm. Figures 3 shows a simplified diagram of the scheme.

[FIGURE 3 GOES HERE]

Standard preliminary procedures were followed for estimating shell thicknesses for the packed bed heat exchangers and pressurised accumulators [6]. Based on the required ratings of compressors, as well as thickness and materials of vessels including packed bed heat exchanger pressure vessels (made of chrome molybdenum low alloy steel to withstand the high temperatures of about 420°C) and accumulator (made of carbon steel), cost estimates were performed for the system following published cost correlations [7]. Storage of the compressed air at 80 atm cost 2013 US $ 224,000 per MWh of rated capacity of the ACAES system using the largest size for which the correlation was established. The pressurised vessels containing the packed bed for heat storage cost about 2013 US $ 96,000 per MWh of rated capacity. We assumed linear scaling, i.e., more vessels of the same size when increasing capacity. A quotation was available also for 20 mm granite pebbles at £ 150 for 855 kg in 2013 (US $ 225), of which 50 t is needed in total for thermal storage of 1 MWh [1]. Overall, these figures translated to 2013 US $ 334,000 per MWh.

One correlation for compressor costs was based on power rating at pressures up to 70 atm (stretched to 80 atm), and included drive, gear mounting, baseplate and auxiliaries (filtering, soundproofing, cooling) [7]. Another one was based on volumetric rate with three compression stages [7]. Quotations from one supplier were obtained for multistage compressors to 100 atm rated at 100 and 200 Nm^3/hr, and were found to be within a few percent of that predicted by the correlation based on power requirements, which itself was some 50% larger than the one based on volumetric flow rates. It was decided to retain the correlation based on power rating as a conservative one; heat exchangers for cooling would have to be discounted but their contribution was neglected here, and in any case they might still be needed to finish off cooling the compressed air exiting the PBHE before further compression [1]. The correlation we used was then

Compressors F.O.B, O.E.M cost = 953,000 x MW + 57,400   in 2013 US $ (3)

where 'F.O.B, O.E.M' is for "Free on Board" as supplied by "Original Equipment Manufacturers".

Costing turbines was made more realistic by considering gas turbines (GT) including controls and generator, i.e., the whole plant minus the compressor. Appropriate data for this were provided in Pauschert [8] in the range 2-51 MW for simple cycle aeroderivative GT units. (An alternative approach would be making use of the compressor in the gas turbine and adding further stages of compression). The resulting cost correlation for gas turbines was as follows:

$$\text{Turbines F.O.B, O.E.M cost} = 950{,}400 \times P_{out,\,GT}^{0.7} \qquad \text{in 2013 US \$,} \qquad (4)$$

in which $P_{out,\,GT}$ is the power output of the commercial gas turbine, within 14% of quoted price for plants rated at 2, 3, 4, 10, 14, 22 and 51 MW. This correlation was an overestimate in the sense that the net power output would represent the gas turbine output minus the power required for compressing the air supply, but on the other hand it failed to take account of the higher inlet pressure. It seems that on account of the smaller specific volume of air at higher pressure, the second factor is expected to be minor [9], whereas compressor requirements for a gas turbine are of the order of 55-60% [10]. On this basis, and given that the costs of compression were estimated for the whole compression train, a suitable estimate of the installed costs of turbines decoupled from compressors for ACAES would be as follows:

$$\text{Turbines F.O.B, O.E.M cost} = 950{,}400 \times (0.5P_{out})^{0.7} \qquad \text{in 2013 US \$,} \qquad (5)$$

in which P_{out} is the delivered power.

Finally, installed costs [8] suggested that Free on Board costs supplied by Original Equipment Manufacturers be multiplied by 2.25 to give installed costs, and the same factor was assumed to apply to compressors and storage.

3. Results

Figure 4 compares the installed capital costs of ACAES with those of VRB using the following formula:

$$\text{\% difference} = (\text{CAPEX of ACAES} - \text{CAPEX of VRB})/(\text{CAPEX of VRB}) \qquad (6)$$

where 'CAPEX' stands for the capital expenditure that is required for the installed plant.

Figure 6 compares the capital cost of VRB with that of lithium-ion batteries in the same fashion. A positive value on Fig. 5 indicates that ACAES is more expensive than VRB, and a positive figure on Fig. 6 that VRB is more expensive than Li-ion.

[FIGURE 4 GOES HERE]
[FIGURE 5 GOES HERE]

Figure 4 clearly shows that ACAES with above ground storage (i.e., relying on pressurised vessels rather than underground caverns or aquifers or subsea membranes) struggles to compete with redox flow batteries. The penalty decreases with increased storage capacity, however. This is in line with the second and third coefficients on the right hand side of Equation (2) for VRB adding up to slightly more than the $ US 334,000 /MWh we found for ACAES. Therefore it may be possible to improve the figure for ACAES by using larger storage vessels or underground or subsea storage, but the development of cheaper electrolyte systems for flow cell batteries (e.g., Iron/Chromium) could offset this.

Another observation for Figure 4 is that for any fixed capacity greater than about 4 MWh, the cost penalty on ACAES is lessened when power rating is decreased. This is due to the cost of added power being greater for compressors than it is for batteries, as can be seen when comparing the sum of Equation (3) and (5) with Equation (2). This explains why the capital cost of ACAES seems to be at least 40% more expensive than VRB. In order to compete, ACAES would require cheaper compressor technology. To a large extent, this could be achieved by using reversible compressors that can be used also as expanders. Recent, exciting developments [11], [12] suggest that it is always possible to improve on compressors' construction or energy efficiency; the critical point will be the capital cost. It is also worth noting that we chose the most conservative estimate of compressor prices (reciprocating, high pressure multistage) since even the actual type and arrangement of stages depending on rating and duty may vary.

Figure 5 clearly shows the capital expenditure advantage of flow cell batteries over Lithium based batteries for storage of more than about 4 hours' worth of supply of energy. Nevertheless, VRBs would benefit from cheaper electrodes as they are outcompeted by Lithium based batteries when storage is less than 4 hours.

4. Conclusions

Currently, VRB flow cell batteries and Lithium ion batteries for small scale storage of energy in the MW and MWh range have similar capital costs, with Li-ion being more competitive at higher power outputs and lower storage capacity, and VRB at lower power output and higher energy storage. Cheaper electrodes for flow cell batteries and cheaper metals for the electrolyte would strengthen their advantage.

In order to compete with batteries with respect to capital costs, ACAES must benefit from further development of the technology of its components, in particular cheaper compressors and turbines, or possibly the dual use of reversible machinery that can be used as both compressor and expander given that cost reductions of at least 30-50% are required.. Underground or underwater storage of the compressed air could also decrease this cost penalty

Finally, it is worth noting that the installed capital costs of all these technologies are of the order of £ 1 million per MWh of storage. This compares favourably with the cost of network improvements and connection to mainland in island networks. The renewable energies industry and local communities can look forward to further progress in storage technologies. They are a more affordable way of increasing the share of renewable energies in the energy mix.

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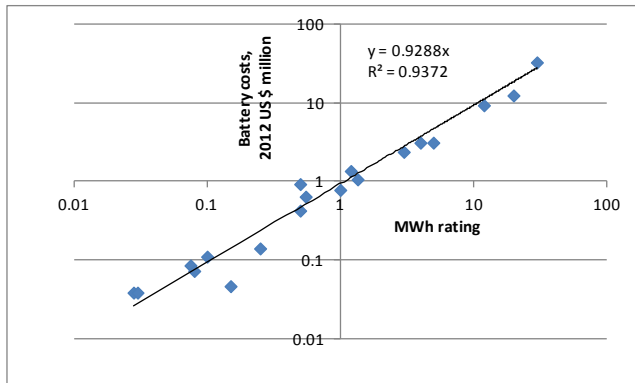
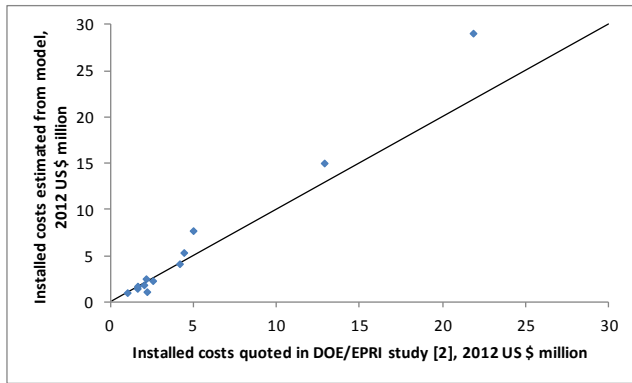[12] Vert rotors, http://www.vertrotors.com, - (accessed 22/06/2014)
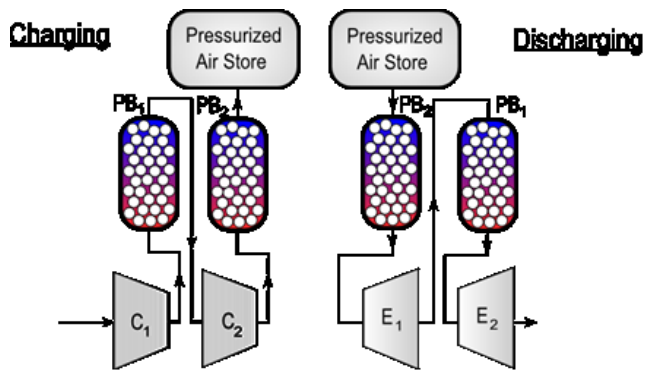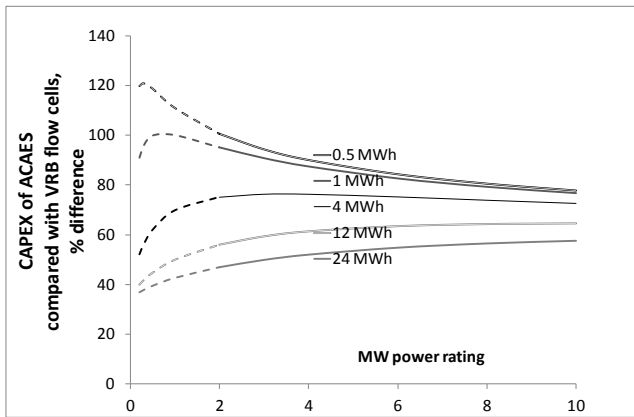
Figure 1

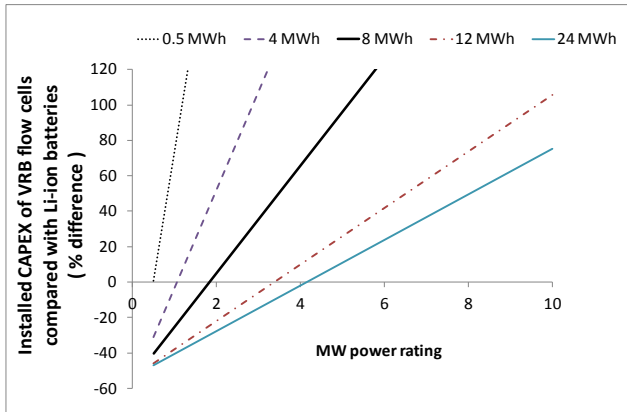Figure 2

Figure 3

Figure 4

Figure 5

Captions to figures:

Figure 1: Cost of Li-ion battery plant correlated against energy capacity

Figure 2: Installed costs of Li-ion energy storage plants as per Eqn. (1), compared with quoted figures from [2].

Figure 3: Basic flow diagram of Adiabatic Compressed Air Energy Storage with Packed Bed Heat Exchangers

Figure 4: Comparing the installed capital expenditure of ACAES with that of VRB. The dashed portion of the curves required extrapolating Equation (5) outside the range of its validating data.

Figure 5: Comparing the installed capital expenditure of VRB with that of Li-ion.