Electrical Energy Storage & Smart Grid Technologies to Integrate the next generation of Renewable Power Systems

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Electrical Energy Storage & Smart Grid Technologies to Integrate the next generation of Renewable Power Systems

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Abstract: The growth of renewable power sources, distributed generation and the potential for alternative fuelled modes of transport such as electric vehicles has led to concerns over the ability of existing grid systems to facilitate such diverse portfolio mixes in already congested power systems. Internationally the growth in renewable energy sources is driven by government policy targets associated with the uncertainties of fossil fuel supplies, environmental issues and a move towards energy independence. Power grids were traditionally designed as vertically integrated centrally managed entities with fully dispatchable generating plant. Renewable power sources, distributed generation and alternative fuelled vehicles will place these power systems under additional stresses and strains due to their different operational characteristics. Energy storage and smart grid technologies are widely proposed as the tools to integrate these future diverse portfolio mixes within the more conventional power systems. The choice in these technologies is determined not only by their location on the grid system, but by the diversification in the power portfolio mix, the electricity market and the operational demands. This paper presents a high level technical and economic overview of the role and relevance of electrical energy storage and smart grid technologies in the next generation of renewable power systems.

Keywords: Distributed generation, electric vehicles, power system balancing, renewable energy source

1. Introduction

Due to increasing environmental constraints associated with greenhouse gas emissions (GHG), uncertainty in the price and security of supply of fossil fuels, power systems of the future will become more reliant on renewable power and inflexible base load plant such as nuclear and coal. World electricity demand is projected to grow at 2.5% annually. Non-hydro renewable power sees the fastest increase to 8.6%, while coal will contribute the largest share of power at 44% and nuclear power is also expected to grow in most regions except Europe by 2030 [1]. At the same time a rapid increase in the demand for digital quality power is expected. Modern electrical equipment used in the home, industry and for commercial activities such as computers, the internet, wireless phone systems, fibre optic telecommunications and security etc. are dependent on high quality power. Power interruptions and disturbances lasting longer than one cycle, which is less than 1/50\textsuperscript{th} second, are enough to crash servers, automated equipment and so forth. Power must be available to a high quality as well as in large quantity. Digital quality must be available 99.9999999\% of the time also referred to as ‘9-nines reliability’ [2]. In the United States of America (US) alone it is estimated that digital quality power represents about 10% of electrical load and may be up to 30% by 2020 [3 and 4]. Digital quality and more reliable power can only be delivered with electrical energy storage (EES) and smart grid technologies (SGT) [5]. It is estimated that power outages cost electricity consumers in the USA approximately $79 billion annually and it is reported that two thirds of these outages last less than 5 minutes [6]. There is also the addition of potentially uncontrollable loads from electric vehicles (EV’s) which may change the expected load demand curve by flattening and widening peaks and increasing base load [7]. Then there is the issue of installed capacity and power demand, the average level of power production is only 40% to 55% of the peak capacity that is
installed [8 and 9]. Is this a valuable use of our resources within the context of an increased demand for dwindling fossil fuel supplies?

In addition most renewable energy sources have some element of variability and intermittency. Currently renewable power prediction and forecasting is limited [10]. Traditional power sources such as coal, gas or oil thermal also have certain levels of intermittency either through forced or planned outages. However, thermal generators are considered favourable and reliable by system operators because they are more dispatchable than renewable sources of power. Table 1 shows the operational characteristics of a number of thermal generators [11 and 12]. Studies have been undertaken to quantify the additional system balancing costs, if any, of variable intermittent renewable power [13, 14, 15, 16 and 17]. However, the overall results are not comparable as no two power systems are the same. Table 2 identifies the technical implications for the electricity system as a result of increased wind power penetrations [18, 19, 20, 21 and 22]. Next to electrical, EES demand response (DR), geographical dispersion of renewable power sources and interconnection with other grids can reduce the effects of variability of renewable energy sources (RES).

Finally, the focus of this paper is to establish the role and relevance of EES and SGT in the next generation of renewable power systems by presenting a technical and economic overview of the current state-of-the-art in technology development. Thermal heat storage such as combined heat and power (CHP), heat pumps and other forms of energy storage associated with transportation, which can also be used to integrate RES are not considered in this paper. References [25, 26, 27, 28, 29, 30 and 31] study CHP and heat pumps in detail as part of an integrated energy system.

2. Smart Grids

There is no internationally agreed standard definition for the term ‘smart grid’ and it can have different meanings from country to country. This can even vary depending on your location in the energy chain. Table 3 compares the existing traditional grid with the smart grid [32]. SGT at the end-user level allows customers use electricity more efficiently and change their usage patterns to less congested times on the system. This can be achieved by dynamic pricing service via access to RTP data and ‘prices to devices’ or smart equipment and appliances in the residential, commercial and industrial sectors, which make intelligent decisions based on pre-defined user parameters. In a broader sense at the distributed and transmission level it enables power producers to manage grid congestion by availing of energy storage, self-healing grid properties, discretionary loads and better grid management [33]. It is estimated that SGT enhancements will ease congestion and increase utilization (of full capacity), sending 50% to 300% more electricity through existing energy corridors [34].

2.1 SGT Activity in the US

In 2002 an architecture for an intelligent grid was first discussed by the Department of the Energy (DOE) in the US, when they identified hundreds of millions of dollars in lost revenues because of transmission bottlenecks and constraints [35]. This led in turn to Grid2030, the GridWise® Initiative, the GridWise Architecture Council, the Electric Research Institute (EPRI) ‘Intelligrid’ and the recognition of SGT in the Energy Independence and Security Act (EISA), 2007 in the US [36, 37, 38, 39 and 40]. The National Institute of Standards and Technology (NIST) is charged under EISA with the development of interoperability standards for the US. NIST started work on an interoperability framework document in April 2009 [41].

2.2 SGT Development in Europe

The term ‘SmartGrid’ was initially coined by the European Technology Platform (ETP) in 2005. The ETP was established by the European Union (EU) at the recommendation of industrial stakeholders at the First International Conference on the Integration of Renewable Energy Sources and Distributed Energy
Sources in December 2004. An ETP referenced short description of ‘SmartGrid’ is ‘an electricity network that can intelligently integrate the action of all users connected to it – generators, consumers and those that do both – in order to efficiently deliver sustainable, economic and secure electricity supplies’ [42]. Perhaps a better description is the National Technology Platform Smart Grids Austria which defines ‘SmartGrids’ as power grids, with a coordinated management based on bi-directional communication between grid components, generators, energy storage systems and consumers to enable an energy-efficient and cost-effective system operation that is ready for future challenges of the energy system [43]. A first step in developing an intelligent electricity system to enable end-users to modify their behaviour and use energy more efficiently is intelligent smart metering, also called advanced metering infrastructure (AMI). Directive 2006/32/EC on energy use and energy efficiency services introduced among other things smart metering in the EU. Reference [44] presents an overview of progress in smart metering, identifies some of the common technical and economic barriers as well as providing a comprehensive list of smart metering programs in the EU and globally.

2.3. SGT Standardisation

References [45 and 46] give a summary of SGT existing 20th century grid and future SmartGrid standards. In the current market environment, smart metering in itself will not enable the vision of a carbon efficient smart grid, which includes dynamic pricing, smart appliances and the electrification of transport. However, modernisation of grid systems using information communications technology (ICT) within the framework of international standards is needed to deliver energy efficiency in the entire electricity chain so that reliability is improved, safety levels are increased and that the flexibility and quality of service is enhanced. In early February 2010 the Institute of Electrical and Electronic Engineers (IEEE) with the Society for Automotive Engineers (SAE) formed P1809 Working Group on Grid Infrastructure for Electric Sourced Transportation to implement best practice and establish draft standards. The IEEE has also produced comprehensive draft SGT standards. The review of current literature indicates that Japan and the US are far more advanced in the preparation of standards for SGT and EV’s than the EU. This is more related to policy at a government level rather than the market structure. A number of electricity market types exist. The traditional government controlled or heavily regulated investor owned electricity market is often referred to as a monopoly or vertically integrated utility. In a monopoly customers have only a single electricity supply company whereas in a liberalised market there is more than one electricity supply company. Restructuring, deregulation or privatisation refers to the introduction of consumer choice and different levels of competition into the electricity market, often called a liberalised electricity market [47 and 48]. There exist a large number of market types including forward markets and spot markets, also called real-time markets on power exchanges. Electricity markets can embrace bilateral contracts, power pools, futures, options, power exchanges, power derivatives and ancillary services type arrangements. Most markets in the USA use bilateral contract agreements for forward contracting, whereas restructured markets, such as the PJM region uses nodal pricing (NP) or locational marginal pricing (LMP) for day-ahead and real-time trading, respectively. In Europe System Marginal Pricing (SMP) as well bilateral agreements are used. In the Nordpool market in Scandinavia and Denmark an implicit auction, which uses supply and demand to balance electricity in the region is in operation, called a ‘pool’ price [49]. The Japanese market is very unusual as the national market (except for Okinawa prefecture) is divided into nine (plus one) service areas, with each served exclusively by a regional electric power company. This system is unique; no other country has such a regional monopoly system [50 and [51]. Finally, there is little or no information available in relation to real empirically collected or measured energy savings or the actual cost of SGT, either in terms of capital or operation and maintenance costs.

3. ENERGY STORAGE TECHNOLOGIES

Following the introduction Directive 2001/77/EC on Electricity Production from RES in 2001, subsequently superseded by directives 2003/30/EC and 2009/28/EC respectively, the EU identified energy storage and SGT as valuable tools to integrate RES, assist in security of supply, enable green transport and reduce GHG emission [52]. Ironically at a US DOE convened meeting of 65 top executives from across the electricity industry in April 2003 energy storage emerged as one of the top five concerns in achieving the main goals of ‘Grid 2030’ which include an increase in RES and distributed generation [53].

Figure 2. EES Systems Groups

Figure 2 groups the various EES technologies. In general terms EES are categorised as magnetic, mechanical, kinetic, electrical, and chemical technologies. References [54, 55, 56, 57, 58, 59, 60, 61, 62, 63, 64, 65, 66, 67, 68, 69, 70, 71, 72, 73, 74, 75, 76, 77, 78, 79, 80, 81, 82, 83, 84 and 85] describe, classify and present the state-of-the art, benefits and challenges of EES. Table 4 lists all the power and
electricity market benefits and Table 5 presents a technical, economic and environmental comparison of EES based on a review of all available published literature and clearly shows the range of expectations.

3.1. EES Modelling & Applications

Many studies have been carried out to evaluate the role of EST [86, 87, 88, 89, 90, 91, 92, 93, 94, 95, 96, 97, 98, 99, 100, 101, 102 and 103]. These studies indicate that the benefits and profitability of EES is dependent on the following:

1. the design, performance and technical capabilities of the EES including power and energy rating, round trip efficiency, ramp rate and any constraints on response rate, cycle life under different applications,
2. the electricity market regime including ability to participate in energy arbitrage, ancillary services including regulation and operating reserves, capacity markets and demand response programs,
3. the financing related factors such as risk, return on investment, cost of borrowing, variations in capital expenditure (Capex), construction and permitting period, uncertainty in operational and maintenance expenditure (Opex),
4. Other factors such as fuel prices, government and regulatory policies such as environmental regulations, carbon tax, energy efficiency initiatives, and location issues can also play a major role can affect EES,
5. and competition from other choices such as better wind forecasting and prediction methods which can provide improved unit commitment and dispatch planning. EES also competes with cheap gas peaking plant, thermal plant upgrades and grid reinforcement.

3.2. Pumped Hydro Energy Storage (PHES)

PHES is by far the most mature, large scale (>100 MW) and widely used method of EES with over 300 plants worldwide with an installed capacity of greater than 95 GW. In PHES water is pumped from a low level reservoir to a high level reservoir via an over-ground pipe or underground tunnel (called a penstock) using pumps. The water at the high level reservoir is, in effect, stored energy in the form of potential energy which is converted to electrical energy using generators when the water at the upper level is released through the pipe to the lower reservoir. There are three types of PHES; pure, pump back and underground. Internationally PHES has been recognised as a technology that can integrate RES with over 20 GW either in planning or well advanced in terms of construction. For example the Federal Energy Regulatory Commission (FERC) in the US has issued 23 preliminary permits for new PHES plants, representing approximately 15 GW of new pumped storage capacity. Another 15 applications for preliminary permits pending before FERC could provide an additional 16 GW of capacity [104 and 105]. Costs are very site specific and caution is needed as, often the prices available are based on construction costs during the monopoly era. Technically PHES plants offer system operators a vast array of services. PHES are not suitable at a distributed level due to their scale.

3.3. Compressed Air Energy Storage (CAES)

A CAES facility compresses a gas (usually air) in a reservoir (either in underground salt mines, abandoned mines in hard rock or natural aquifers or above ground in tanks and pipes) using electricity to between 70 and 100+ bar. When electricity is required the compressed air is reheated prior to combustion to produce power in a generator. In a regular natural gas turbine approximately 75% of the energy produced is used to pressurise the air for combustion. Therefore CAES enables improved natural thermal efficiencies because of the pre-compression and decompression phases, as well as reduced heat losses. The amount of natural gas required is so small that a gas turbine working simultaneously with CAES can produce three times more electricity than a gas turbine operating on its own using the same amount of natural gas. A number of CAES configurations have been envisaged including:

1. a liquid piston, which uses a fast running shaft,
2. an air to oil interface system,
3. a direct air to shaft link [106].

Maintenance and operational issues have been recorded at Huntorf in Germany, which was the first of the only two fully operational CAES plants in operation today [107]. Caution is needed when quoting capex for CAES as the two in operation were subsidised. Technically CAES plants offer system operators a similar array of services as PHES. Like PHES, it is not suitable at a distributed level, again due to the scale.

3.4. Battery Energy Storage (BES)

BES systems are classified as secondary (meaning unlike primary they can be recharged), flow or redox and metal air batteries as follows:

1. Flooded and valve regulated (VR) include lead acid, nickel cadmium (NiCd), sodium sulphur (NaS), sodium nickel (also called the ZEBRA) and the lithium ion (Li Ion),
2. Flow or redox batteries, include zinc-bromide, vanadium redox flow (VRB) and polysulphide bromide (PSB) (e.g. Regenesys ™),
3. Metal-air batteries, for example the zinc air fuel cell battery.

BES systems are mostly used at the distributed level and at commercial, industrial facilities for emergency back-up and uninterruptible power supply (UPS). More
recently BES activity has increased due to the drive to electrify transport. The costs associated with BES projects are very project specific and caution should be taken when using published data.

3.5. Flywheels

Flywheels store energy by accelerating the rotor/flywheel and maintaining the energy in the system as kinetic energy. Flywheels release energy by reversing the charging process so that the motor is then used as a generator. There are low speed and high speed flywheels and they are categorised by the type of material used in their construction as either a speed flywheels and they are categorised by the type of material used in their construction as either a conventional steel rotor type or an advanced composite machine respectively. Like BES systems, flywheels are mostly used at the distributed level and for commercial and industrial applications associated mostly with UPS. More recent flywheel activity is like BES due to the drive to electrify transport. Research indicates that flywheels are suitable in train and bus applications, particularly because of the large mass available to carry the flywheel containment. The costs associated with flywheel projects are very project specific and once again like BES caution should be taken when using published data.

3.6. Supercapacitors (SC)

A SC EES device consists of layers of capacitors and hence the name supercapacitor. SC’s operate in a similar manner as BES systems except there is no chemical change. In a SC electrical energy is stored in the form of an electric charge between plates. Small capacitors have been used for years in electronic equipment. SC devices exist which are capable of providing up to 3 MW of instantaneous power for up to 1.5 seconds. Like BES and flywheels their use is also under scrutiny for transport related applications.

3.7. Superconducting magnetic energy storage (SMES)

In an SMES energy is stored in a magnetic coil. SMES devices are available as small prototypes and demonstration projects. There are no commercially available SMES devices above 3 MW’s.

3.8. Hydrogen Fuel Cell (HFC)

A HFC converts chemical energy of a fuel source into electrical energy. Generally a HFC consists of two electrodes separated by an electrolyte and electricity is produced by an electrochemical reaction using hydrogen and oxygen as the primary reactants. A number of fuel sources such as natural gas and reacting steam with methane are used in HFC with water and heat as the only by-products. Once again like BES, SC and flywheels their application is mainly seen at a distributed level with applications in the domestic, commercial and industrial sectors, primarily related to transport.

4. Transport, SGT & EV’s

EV’s have been identified as a possible EES opportunity in the form of Vehicle to Grid (V2G) electricity from the EV BES, but development is at a very early stage [108, 109 and 110]. Published data indicates that V2G will be heavily dependent on SGT.

4. Discussion & Conclusion

EES and SGT can play a pivotal, flexible and multifunctional role in electrical power systems by reducing the need for reserve power plant, managing the transmission and distribution grid in a more efficient manner, decreasing the cost and number of power failures, smoothing out fluctuations in power supply and enabling more RES by improving capacity factors (i.e. by changing the demand curve using either load shifting or through energy conservation incentives by intelligently linking all market participants). As can be seen from the literature review there is a wealth of experience, knowledge and research in the area of EES and SGT. However, the weakest links in terms of delivering a sustainable RES future using EES and SGT is the lack of the following:

1. international standards,
2. real competitive market environments,
3. government and regulatory policy and
4. limited product realisation and commercialisation, particularly at the distributed level.

If the fossil fuel market price and volume fluctuate and carbon taxes are introduced the price-elasticity of the wholesale electricity price may rocket. This may be the catalyst for EES and SGT. Furthermore, if standards do not converge, then EV’s will be fitted with country-specific connectors, and possibly highly customised country-specific charging circuits. Obviously this will have to happen to some extent anyway due to differing mains voltages and frequencies, but there is potential for confusion and lack of conformity in technology if the EV and of course SGT deployment is not co-ordinated properly. This lack of ‘standardisation’ will impede cross-border trade in EV technology and mobility of the actual EV’s and may result in unnecessarily complicated charging infrastructure designs.

Either way without EES and SGT there cannot be the smart grid and the full integration of RES and the deployment of EV’s to the current levels envisaged by policy makers for 2020. Politicians have identified the green energy economy for employment opportunities in research and development, product manufacturing and associated construction, operation and maintenance services. However, the weakest links must be dealt with in order to deliver on this green energy economy. Therefore the authors recommend that a working group be formed by the European Commission. Internationally the International Energy Agency (IEA) should be given the task of co-ordinating a common set
of approaches and standards for both EES and SGT for mass production to ensure a better unit cost. In conclusion the authors have presented a technical and economic assessment of the role and relevance of EES and SGT in the next generation of renewable power systems.

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Appendix A.

<table>
<thead>
<tr>
<th>Normal Operating Cycle</th>
<th>Nuclear Base Load Plant</th>
<th>Coal Fired Base Load &amp; Mid-merit Plant</th>
<th>Oil Fired Base Load &amp; Mid-merit Plant</th>
<th>Gas Turbine Peak Load</th>
<th>Pumped Storage Mid-merit &amp; Peak Load Plant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit start-up daily</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>weekend</td>
<td>No</td>
<td>Yes, cold</td>
<td>Yes, cold</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Cycling</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Load Following</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Quick start (10 mins)</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Spinning Reserve</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Frequency Regulation</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Load Management</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Black Start</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Table 1. Capabilities of Power Plant to Provide Dynamic Services [9 & 10]

<table>
<thead>
<tr>
<th>Increase in Wind</th>
<th>Technical Implications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Up to 5%</td>
<td>None</td>
</tr>
<tr>
<td>5 – 10%</td>
<td>Occasional instances when some wind rejected and more part-load required with grid reinforcement</td>
</tr>
<tr>
<td>10 – 20%</td>
<td>As above, plus more use of existing pumped storage to balance</td>
</tr>
<tr>
<td>20 – 50%</td>
<td>Storage, or peaking plant and retain old coal plant, depending on relative costs</td>
</tr>
</tbody>
</table>

Table 2. Infrastructure Implications of Increased Wind Penetration [16, 17, 18, 19 & 20]

<table>
<thead>
<tr>
<th>20th Century (Existing Grid)</th>
<th>21st Century (Smart Grid)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analog &amp; Electromechanical Communications</td>
<td>Digital</td>
</tr>
<tr>
<td>One-way Communication</td>
<td>Two-way Communication</td>
</tr>
<tr>
<td>Totally Centralised</td>
<td>Accommodate Decentralised</td>
</tr>
<tr>
<td>Radial &amp; Hierarchical Topology</td>
<td>Network Topology</td>
</tr>
<tr>
<td>No World Wide Web</td>
<td>World Wide Web Enabled</td>
</tr>
<tr>
<td>Centralised Generation</td>
<td>Distributed &amp; Centralised Generation</td>
</tr>
<tr>
<td>Few Sensors &amp; Blind</td>
<td>Sensors Throughout &amp; Self-Monitoring</td>
</tr>
<tr>
<td>Manual Restoration</td>
<td>Self-Healing</td>
</tr>
<tr>
<td>Failures &amp; Blackouts</td>
<td>Adaptive &amp; Islanding</td>
</tr>
<tr>
<td>Manual Checks &amp; Tests</td>
<td>Remote Checks &amp; Tests</td>
</tr>
<tr>
<td>Limited Control</td>
<td>Persuasive Control</td>
</tr>
<tr>
<td>Generally Average Price</td>
<td>Real-Time Pricing</td>
</tr>
<tr>
<td>Commodity Based</td>
<td>Service Based</td>
</tr>
<tr>
<td>Little or No Consumer Choice</td>
<td>Many Consumer Choices</td>
</tr>
</tbody>
</table>

Table 3. Comparison of Existing & Smart Grid Technology [22#2]

#2 = adapted from Reference [22]

<table>
<thead>
<tr>
<th>Application</th>
<th>Power</th>
<th>Energy Storage Time</th>
<th>Duty Cycle Requirements</th>
<th>Response Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>RES Management</td>
<td>Control, Integration &amp; Smoothing</td>
<td>10kW to 100MW</td>
<td>secs</td>
<td>Random but mostly continuous</td>
</tr>
<tr>
<td>End-use Power Applications</td>
<td>Power Quality Issues</td>
<td>100’s kW</td>
<td>secs</td>
<td>Random but occurring many times/day</td>
</tr>
<tr>
<td>Load Management, Generation &amp; Reserve Capacity</td>
<td>Control &amp; Frequency Response</td>
<td>10MW to 100MW</td>
<td>&lt; 10 mins to 1hr</td>
<td>&lt; 1/2 cycle</td>
</tr>
<tr>
<td>Transmission &amp; Distribution Application</td>
<td>Stabilisation (Transient &amp; Frequency)</td>
<td>up to 100’s MW</td>
<td>secs to 2hrs</td>
<td>&lt; 1 cycle</td>
</tr>
</tbody>
</table>

Table 4. EES Applications [42 and 46#]

# = adapted from References [42 and 46]

c. = circa
<table>
<thead>
<tr>
<th>EES Type</th>
<th>PHES</th>
<th>CAES</th>
<th>Flywheels</th>
<th>SC</th>
<th>SMES</th>
<th>BES</th>
<th>HFC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Rating</td>
<td>1MW – 4000MW</td>
<td>50MW – 350MW</td>
<td>&lt; 250kW – 2.4MW</td>
<td>&lt; 100kW</td>
<td>10kW – 10MW</td>
<td>1MW – 50MW</td>
<td>&lt; 250kW</td>
</tr>
<tr>
<td>Power Cost, $/kW</td>
<td>600 – 2000</td>
<td>400 – 600</td>
<td>300 – 350</td>
<td>300</td>
<td>300</td>
<td>200 – 1200</td>
<td>1100 – 2600</td>
</tr>
<tr>
<td>Energy Cost, $/kWh</td>
<td>0 – 20</td>
<td>30 – 50</td>
<td>80 – 1000</td>
<td>82000</td>
<td>2000 – 72000</td>
<td>175 – 250</td>
<td>2 – 15</td>
</tr>
<tr>
<td>Balance of Plant</td>
<td>Included</td>
<td>40 – 50</td>
<td>80 – 1000</td>
<td>10000</td>
<td>1500 – 10000</td>
<td>Varies</td>
<td>40 – 50</td>
</tr>
<tr>
<td>Fixed, $/kW-yr</td>
<td>1 – 4</td>
<td>3 – 4</td>
<td>0 – 7.5</td>
<td>5.55</td>
<td>8 – 26</td>
<td>Uncertain</td>
<td>Uncertain</td>
</tr>
<tr>
<td>Variable, $/kW-yr</td>
<td>1 – 4</td>
<td>0.1 – 0.5</td>
<td>Uncertain</td>
<td>0.5</td>
<td>0.5 – 2</td>
<td>Uncertain</td>
<td>1.0</td>
</tr>
<tr>
<td>Operational Worldwide</td>
<td>95</td>
<td>2</td>
<td>5 mostly demos</td>
<td>Uncertain</td>
<td>10</td>
<td>250</td>
<td>5</td>
</tr>
<tr>
<td>Maturity</td>
<td>Fully commercial</td>
<td>Limited commercial</td>
<td>Commercial available but also prototypes</td>
<td>Some commercial but also prototypes</td>
<td>Prototypes, in design and commercial</td>
<td>Prototypes, in design and fully commercial</td>
<td>Prototypes and in design</td>
</tr>
<tr>
<td>Cost Certainty</td>
<td>Very site specific</td>
<td>Very site specific plus initial 2 were built with subsidies</td>
<td>Price lists available but can vary dramatically on application</td>
<td>Project by project</td>
<td>Prices available, but vary project by project</td>
<td>Price lists available but can vary dramatically on application</td>
<td>Prices available, but vary project by project</td>
</tr>
<tr>
<td>Environmental Issues</td>
<td>Reservoir</td>
<td>GHG emissions</td>
<td>N/A, apart from LCA of components</td>
<td>N/A, apart from LCA of components</td>
<td>N/A, apart from LCA of components</td>
<td>N/A, apart from LCA of components</td>
<td>N/A</td>
</tr>
<tr>
<td>Safety Rating</td>
<td>Usual Industrial H&amp;S standards</td>
<td>Usual Industrial H&amp;S standards, but with explosive atmospheres</td>
<td>Usual Industrial H&amp;S standards, with additional containment due to fast moving parts</td>
<td>Usual Industrial H&amp;S standards</td>
<td>Usual Industrial H&amp;S standards, however additional care taken for handling chemicals and in their disposal</td>
<td>Usual Industrial H&amp;S standards, but with care under pressure</td>
<td>Usual Industrial H&amp;S standards, but with care under pressure</td>
</tr>
<tr>
<td>Life Cycle</td>
<td>50 yrs</td>
<td>30 yrs expected</td>
<td>20 yrs expected</td>
<td>10000 cycles</td>
<td>30 yrs expected</td>
<td>Varies 5 to 10 yrs 2,000 cycles</td>
<td>10 to 20 yrs expected</td>
</tr>
<tr>
<td>Cycle Efficiency, %</td>
<td>0.7 – 0.85</td>
<td>0.57 – 0.64</td>
<td>0.9 – 0.95</td>
<td>0.95</td>
<td>0.95</td>
<td>0.6 – 0.86</td>
<td>0.34 – 0.40</td>
</tr>
<tr>
<td>Response Time</td>
<td>secs – min</td>
<td>secs – min</td>
<td>&lt; 1 cycle</td>
<td>&lt; 1/4 cycle</td>
<td>&lt; 1/4 cycle</td>
<td>&lt; 1/4 cycle</td>
<td>&lt; 1/4 cycle</td>
</tr>
<tr>
<td>Discharge Duration</td>
<td>2 – 12hrs</td>
<td>1 – 20hrs</td>
<td>&lt;60secs</td>
<td>&lt;30secs</td>
<td>&lt;1sec – 0.5hrs</td>
<td>&lt;1sec – 0.5hrs</td>
<td>&lt;60secs – 20hrs</td>
</tr>
<tr>
<td>Parasitic Losses</td>
<td>evaporation</td>
<td>deterioration in aquifer &amp; salt storage capacity</td>
<td>c. 1% - 3%</td>
<td>unavailable</td>
<td>c. 1% - 4%</td>
<td>Uncertain, but small</td>
<td>uncertain</td>
</tr>
<tr>
<td>Transit &amp; End-use Ride through</td>
<td>N</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y and N</td>
<td>N</td>
</tr>
<tr>
<td>T&amp;D Stabilisation &amp; Regulation</td>
<td>N</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y and N</td>
<td>N</td>
</tr>
<tr>
<td>Peak Generation</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Fast Response Spinning Reserve</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>N</td>
<td>Y and N</td>
<td>N</td>
</tr>
<tr>
<td>Conventional Spinning Reserve</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>N</td>
<td>Y and N</td>
<td>N</td>
</tr>
<tr>
<td>Uninterruptible Power Supply</td>
<td>N</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
</tr>
<tr>
<td>Renewable Integration</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Emergency Back-up</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>Y and N</td>
<td>Y and N</td>
</tr>
<tr>
<td>Renewable Back-up</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>Y and N</td>
<td>N</td>
</tr>
<tr>
<td>Ramping: Load Following</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y and N</td>
<td>N</td>
</tr>
<tr>
<td>Generation: Load Levelling</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>Y and n</td>
<td>N</td>
</tr>
<tr>
<td>Electrical Storage</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>Y and N</td>
<td>N</td>
</tr>
<tr>
<td>Transport</td>
<td>N/A</td>
<td>N/A</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
</tbody>
</table>

Table 5. Economic & Technical Overview of EES

H & S = Health and Safety, LC

1 In reservoir & in vessel type
2 High speed & low speed type
3 Also referred to as electrochemical capacitors and includes ultra
4 Includes micro
5 Includes all types of BES including lead-acid, nickel cadmium (NiCd), sodium sulphur (NaS), zinc bromine (ZBiBr), polysulphide bromide (PSBr), vanadium redox (VR), lithium ion, sodium nickel chloride (Zebra), nickel-metal hydride (NiMH), metal air etc