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Superconducting Magnetic Energy Storage System – Commercialisation and Marketing Challenges

Final Report

Abstract

SMES is a direct electric energy storage technology that is only in the early commercial phase in the energy storage market. It is characterised as having high power, high-energy conversion efficiency and instantaneous response times. With the emerging and rapidly growing energy storage market being driven by renewables, carbon emission targets, smart grids and electrification of transport, this report looks into the commercialisation and marketing challenges that SMES faces in order to be a competing technology in the market by analyses of various journals, reports and data based around SMES and the energy storage market.

The superconductor is an integral part of the SMES with 2G HTS currently the most promising superconductor for the commercialisation of SMES however the cost of the wire is the main limiting factor. Yet, the energy storage market will provide many opportunities for SMES to achieve commercialisation particularly as use as FACTS or for power quality applications for which the SMES characteristics are ideal. In turn, this and competing technologies will drive innovation of SMES as well as the other superconductivity applications driving innovation in superconductor materials and manufacture.

Introduction

Energy storage is a rapidly growing market thanks to a number of trends. The increase in decentralised renewable energy, the advent of smart grids, smart micro-grids and smart houses, the electrification of transport, the increasing demand on the ageing electricity infrastructure and climate change targets are all helping to drive the energy storage market. Research and development, innovation and commercialisation of energy storage continues to grow.

Superconducting Magnetic Energy Storage (SMES) is just one type of energy storage and it is only at the demonstration and early commercial stage with only a few projects worldwide. Thus, with a rapidly emerging energy storage market, the aim of this report discusses the commercialisation and marketing challenges that SMES faces in order to become a competitor within the market. The objectives of this report will be:

- SMES as part of the superconductivity and cryogenic environments
- What cost of superconductors will make SMES competitive
- What sectors of storage will SMES make a difference and why SMES is required in future planning of energy needs
- SMES SWOT analysis
- Competing energy storage technologies
- The energy storage market
- Factors affecting the market

Discussion

SMES utilises a simple concept; energy is stored in a magnetic field created by the flow of direct current (DC) in a superconducting coil, which has been cryogenically cooled below its critical temperature. The stored energy can be quickly and efficiently released by discharging the coil into a connected power system. To convert the AC supply to DC for charging and DC to AC for discharging a SMES requires a power conditioning system connected to the coil. Thus, a typical SMES is made up of four parts: superconducting coil, power conditioning system, cryogenically cooled refrigerator and a protection system [1].

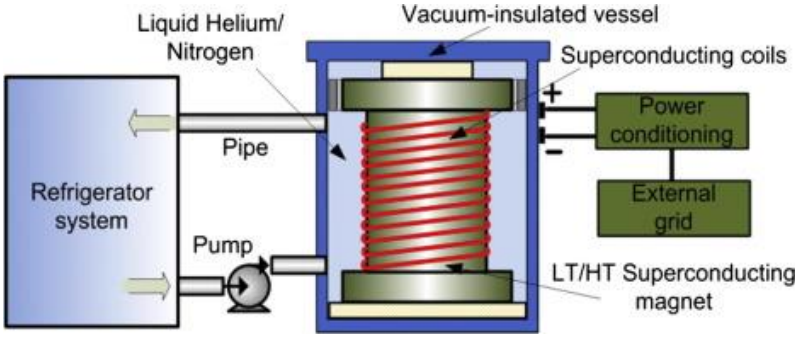


Figure 1: SMES Schematic [2]

The use of a superconductor and the fact that superconductors currently need a cryogenic temperature to operate means SMES is part of the superconductivity and cryogenics industry. There are a number of superconducting materials that are either low temperature superconductors (LTS) or high temperature superconductors (HTS) and fall into either the ceramic, organic materials or metals categories, only a handful are currently commercial such as NbTi (LTS), Nb_3Sn (LTS), YBCO (HTS) and MgB_2.

According to Scanlan [3], the superconductivity market can be split up into two distinct markets. The first market is for low temperature magnet applications such as particle accelerators, nuclear magnetic resonance (NMR), magnetic resonance imaging (MRI) and plasma containment magnets for fusion power and there are no competing technologies to superconductors. The second market however, is that for electric power equipment and this includes SMES as well as motors, generators, transformers, fault current limiters and power transmission cables, where there is plenty of competition from alternative technologies. Furthermore, Scanlan [3] continues to state that this second market is an emerging market with the potential to be much larger than the first market. There are several estimations for size of the superconductivity market with different sources using varying criteria in their estimations and projections, however the main consensus it that the market is around a billion dollars [4] [5] [6].

The superconductor industry is closely linked to the cryogenic industry due to operating temperatures required for superconductivity being below 130K. Such cooling comes from cryogens or cryocoolers, Helium is the main cryogen having a boiling point of just 4.2K and is used in most low temperature magnet applications as it is around these temperatures the a lot of superconductors operate best in terms of current and magnetic field. However, the issue of helium supply is a growing problem; it currently costs between £7 and £9 per litre whereas liquid nitrogen is just £0.5 per litre [7] thus to be able to operate at temperatures around 77K would be of great benefit in energy usage, efficiency, refrigeration reliability and cost. In relation to SMES the need for cryogenic cooling is an issue as energy is used up to enable the storage of electricity, therefore the longer the energy is stored in standby by the SMES the less efficient the system is and thus SMES is best for applications where many cycles are required daily. Therefore, the use of HTS in SMES is a promising combination allowing for liquid nitrogen temperature operation, however the issues arises with cost.

One of the biggest disadvantages of the SMES is the cost of the superconducting wire that usually makes up the majority of the capital cost, as well as the accompanying refrigeration operating cost. Now, electrical wires are generally compared on a per kiloamp-meter (kAm) basis, where the kiloamp refers to the operating current level [8]. For HTS wires, copper is the main competitor for many of the electric power applications as it is the most extensively used wire for electrical applications and is generally seen as a benchmark for the comparison of other electrical wires to compete, the price of copper wire is about $24-36/kAm [9]. Scanlan [3] suggests that HTSs in operating range 20-77K could be economical for some applications between $10-100/kAm and states that the price of copper wire is a standard target. Melhem [10] suggests a target of $20/kAm again similar to the price of copper wire. Both Paranthaman [11] and Grant [12] suggest the target price for superconductors is that of copper.

Looking at LTS, NbTi is the cheapest superconducting wire available and it has a price of around just \$1-2/kAm [3] [9] [13] and Nb_3Sn has a cost of around \$11/kAm [9] [13] [14]. However, these LTS superconductors require operation below 4.2K with liquid Helium and cryocoolers, for large-scale operations this gets expensive; hence, LTS superconductors are generally used for NMR, MRI and other low temperature magnetic applications where there is not any other competition technologies. It is a similar situation for MgB_2, even as a MTS its operating temperature is still too low for use with liquid nitrogen even though cost projections predict MgB_2 be just a few \$/kAm in the near future [15]. HTSs are still too expensive; 2G HTS wire costs around \$300-400/kAm [16], while for 1G HTS the costs are around \$140-180/kAm [14] but they are more difficult to manufacture in long lengths. Therefore, there is still plenty of room for improvement on the cost side. There is plenty of research going into superconducting materials finding innovative ways to improve performance both in terms of critical current and critical magnetic field, simplifying of the manufacturing method and processes and finding new superconducting materials [16] and with advancements in superconducting materials the cost of SMES could be reduced by at least 30% [17]. There is also potential for improvement in the power conditioning system to further reduce AC losses and current lead losses making the SMES efficiency even greater [15].Yet, it is going to take a mix of market driving forces, superconductor material development and uptake of commercial applications to make SMES competitive. American Superconductor is one the major companies in superconductor manufacture and having installed a number of SMES systems in order to improve grid stability it will have a big role to play in the future of the superconductivity market and SMES [1].

Two main characteristics of SMES are its high power and fast response time this makes it ideal for power management applications such as power quality and system stability enhancement and this is where SMES could really make a difference [18] [19]. With the rapid increase in decentralised renewable energy into the worlds electricity grids, ageing grid infrastructure and other energy costs and constraints, the world's electricity grids are operating with reduced stability margins. Thus, energy storage systems capable of stability applications in power, voltage and frequency are becoming an ideal solution. SMES can reduce system frequency oscillations in power systems, it can modulate both real and reactive power, increase voltage stability and balance fluctuating loads. An application commonly linked with SMES is flexible AC transmission systems (FACTS) and it was this application that was the first superconducting application installed in a real power grid used at Bonneville Power Authority's Tacoma substation in the late 1970s [1]. Further to this, Baxter [17] states that the largest market potential for SMES technology is that of supporting utility transmission voltage levels against sudden disruptions. SMES systems can compete in this market on both price and capability. In 2000, the Wisconsin Public Service Corporation installed six of American Superconductor's D-SMES units to solve voltage instability problems while additionally increasing the power grid capacity and this system cost less than any of the other solutions whilst also being the quickest to implement [17]. Table 1 is an adapted table from Luo [2], which highlights a few current and past SMES projects, and all the systems are or were used for power management and quality applications. Therefore, SMES is the type of energy storage that is going to be used by utility companies, distribution network operators (DNO) and industry as it is these that require such services that SMES can offer.

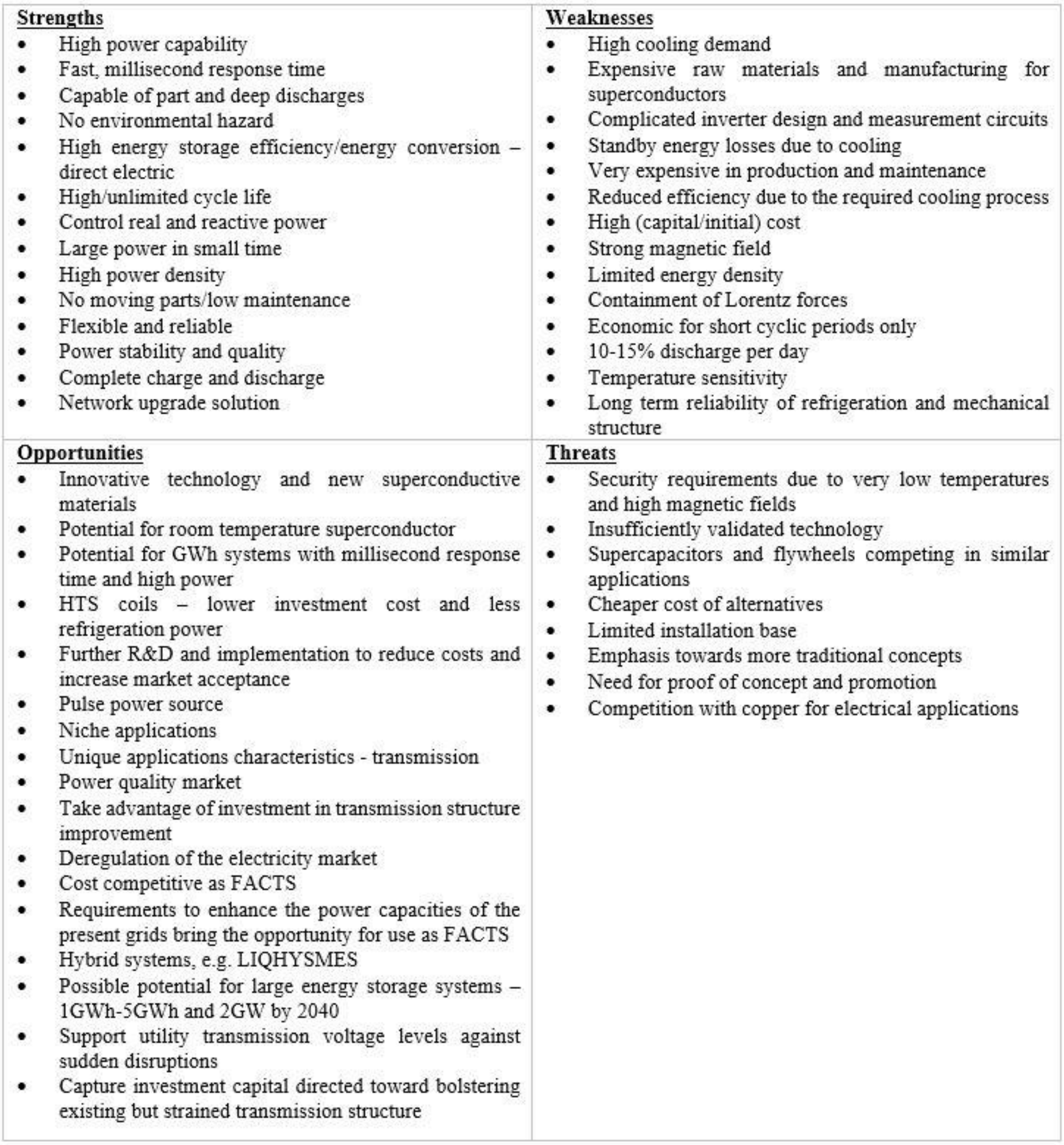
Table 1: Some SMES Projects [2]

Location/Company	Technical Data	Application
Principle Grid Test, Germany (American Superconductor)	5kJ, 2s to max 100A at 25K	First Commercial HTS-SMES
Nosoo Power Station, Japan	10MW	System stability and power quality
Upper Wisconsin (American Transmission)	3MW/0.83kWh, 8MVA each	Power Quality and reactive power support
Korea Electric Power Corporation (Hyundai)	3MJ, 750kVA	Power Supply quality
Chubu Electric Power Co., Japan	7.3MJ/5MW and 1MJ	Provide comparison to transient voltage
University of Houston, USA (SuperPower)	20kW, up to 2MJ class	Voltage distribution

By having SMES systems in the energy sector there are a number of associated benefits, firstly there are improved power system capabilities and advance power qualities with SMES systems able to control both real and reactive power a characteristic not many energy storage systems have. Secondly as SMES systems can absorb fluctuations in demand and ramp at fast rates, it allows generating units to operate and maintain an optimal and efficient operating condition leading to less maintenance and extended operating life. Thirdly, the deployment of SMES would defer the expensive requirement to build new or replace existing conventional capacity and transmission capacity and finally SMES systems would aid in the further integration of intermittent renewables being able to deal with grid instability and decentralised generation [1] [20].

However, there are also challenges to having SMES in the system; firstly, there is only a small installation base and thus limited understanding in installation requirements and operational capabilities of SMES systems [21]. Secondly, this leads to the fact that SMES is a relatively unproven technology giving concerns about its long-term reliability and operation; this is compounded by the markets emphasis towards traditional concepts. Thirdly, SMES systems require constant refrigeration, which requires energy and maintenance and again this raises concerns with long term reliability. Finally, a SMES needs to be in constant use discharging and charging as there are standby losses due to the cooling requirement [22]. Thus, this needs to be a consideration when employing a SMES system.

Table 2: SWOT Analysis for SMES [21] [22] [23] [24].



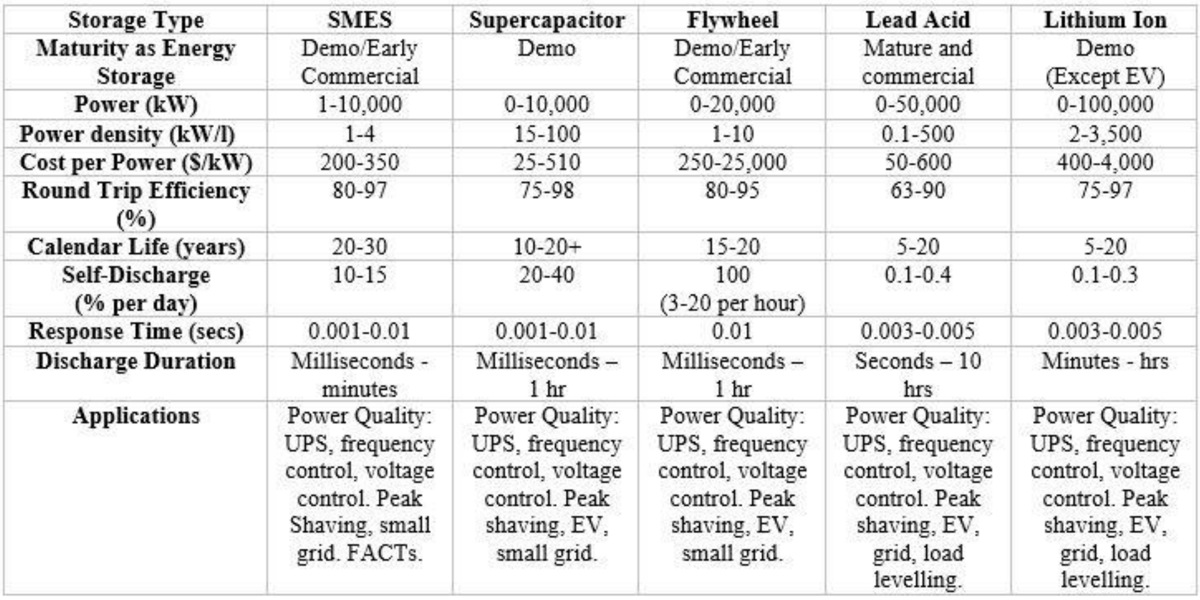
Strengths	**Weaknesses**
• High power capability • Fast, millisecond response time • Capable of part and deep discharges • No environmental hazard • High energy storage efficiency/energy conversion – direct electric • High/unlimited cycle life • Control real and reactive power • Large power in small time • High power density • No moving parts/low maintenance • Flexible and reliable • Power stability and quality • Complete charge and discharge • Network upgrade solution	• High cooling demand • Expensive raw materials and manufacturing for superconductors • Complicated inverter design and measurement circuits • Standby energy losses due to cooling • Very expensive in production and maintenance • Reduced efficiency due to the required cooling process • High (capital/initial) cost • Strong magnetic field • Limited energy density • Containment of Lorentz forces • Economic for short cyclic periods only • 10-15% discharge per day • Temperature sensitivity • Long term reliability of refrigeration and mechanical structure
Opportunities	**Threats**
• Innovative technology and new superconductive materials • Potential for room temperature superconductor • Potential for GWh systems with millisecond response time and high power • HTS coils – lower investment cost and less refrigeration power • Further R&D and implementation to reduce costs and increase market acceptance • Pulse power source • Niche applications • Unique applications characteristics - transmission • Power quality market • Take advantage of investment in transmission structure improvement • Deregulation of the electricity market • Cost competitive as FACTS • Requirements to enhance the power capacities of the present grids bring the opportunity for use as FACTS • Hybrid systems, e.g. LIQHYSMES • Possible potential for large energy storage systems – 1GWh-5GWh and 2GW by 2040 • Support utility transmission voltage levels against sudden disruptions • Capture investment capital directed toward bolstering existing but strained transmission structure	• Security requirements due to very low temperatures and high magnetic fields • Insufficiently validated technology • Supercapacitors and flywheels competing in similar applications • Cheaper cost of alternatives • Limited installation base • Emphasis towards more traditional concepts • Need for proof of concept and promotion • Competition with copper for electrical applications

Table 2 is a SWOT analysis for SMES and Table 3 gives a summary of the characteristics of SMES and the competing energy storage technologies (See Table 5 in the appendix for a full characteristics breakdown) [2] [15] [21] [22] [23] [25] [26] [27]. Like SMES, Supercapacitors have a high efficiency, high power capability and long cycle life and is a direct competitor in the market. Disadvantages are they have low energy density and a high cost per installed energy. Most characteristics of supercapacitors are similar to SMES as well as the applications except supercapacitors have electric vehicle applications. Supercapacitors are only at the demonstration stage in the energy storage market but capacitors are a proven technology.

Flywheels have a fast charge, are low maintenance and long-life but they have low energy density, require a vacuum chamber and have high safety requirements and suffer from very high self discharge. Again, due to similar characteristics to SMES the applications are also similar. Although at the early commercial stage, the first large scale grid storage flywheel was built in 2011, they are well established as UPS and used for frequency control.

Lead acid and lithium ion are not direct competitors to SMES being more suitable for energy management; however, with their wide range of possible applications and the potential for GWh SMES as an energy management system around 2040 it provides a good comparison [28].

Table 3: Characteristics comparison between energy storage technologies.



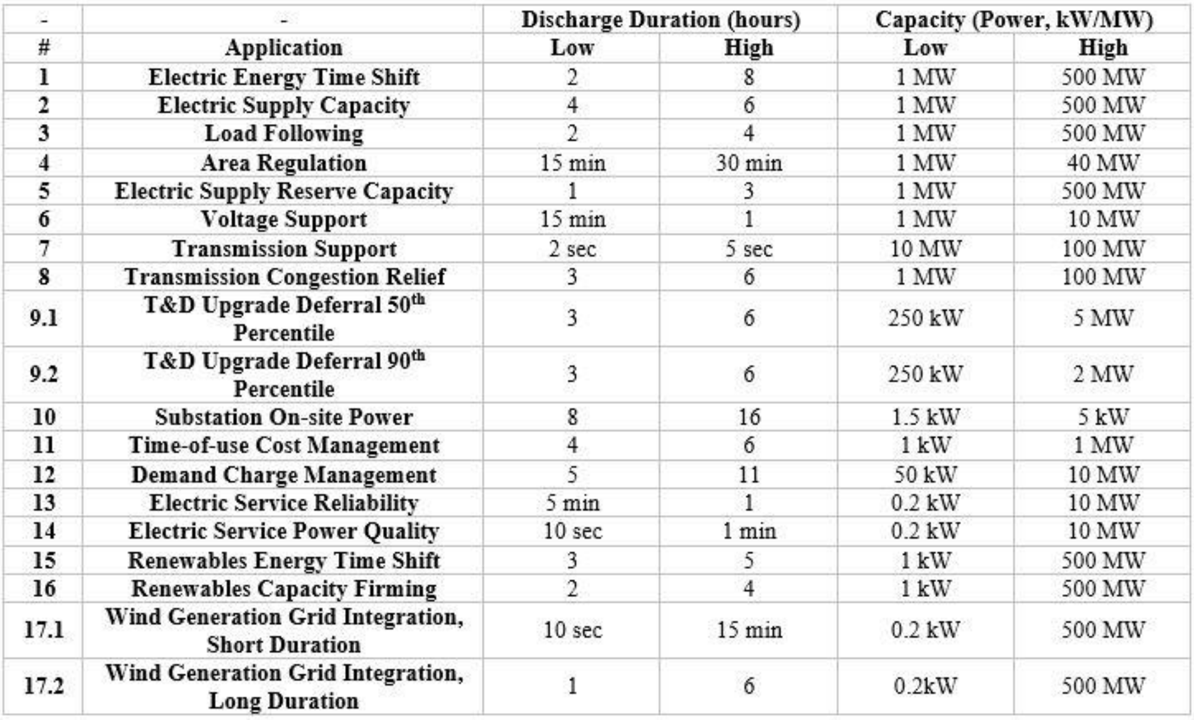
Storage Type	SMES	Supercapacitor	Flywheel	Lead Acid	Lithium Ion
Maturity as Energy Storage	Demo/Early Commercial	Demo	Demo/Early Commercial	Mature and commercial	Demo (Except EV)
Power (kW)	1-10,000	0-10,000	0-20,000	0-50,000	0-100,000
Power density (kW/l)	1-4	15-100	1-10	0.1-500	2-3,500
Cost per Power ($/kW)	200-350	25-510	250-25,000	50-600	400-4,000
Round Trip Efficiency (%)	80-97	75-98	80-95	63-90	75-97
Calendar Life (years)	20-30	10-20+	15-20	5-20	5-20
Self-Discharge (% per day)	10-15	20-40	100 (3-20 per hour)	0.1-0.4	0.1-0.3
Response Time (secs)	0.001-0.01	0.001-0.01	0.01	0.003-0.005	0.003-0.005
Discharge Duration	Milliseconds - minutes	Milliseconds – 1 hr	Milliseconds – 1 hr	Seconds – 10 hrs	Minutes - hrs
Applications	Power Quality: UPS, frequency control, voltage control. Peak Shaving, small grid. FACTs.	Power Quality: UPS, frequency control, voltage control. Peak shaving, EV, small grid.	Power Quality: UPS, frequency control, voltage control. Peak shaving, EV, small grid.	Power Quality: UPS, frequency control, voltage control. Peak shaving, EV, grid, load levelling.	Power Quality: UPS, frequency control, voltage control. Peak shaving, EV, grid, load levelling.

The market for energy storage is growing rapidly, especially in the last few years. Using data from the US Department of Energy's Global Energy Storage Database [29], there had only been 13 commissioned energy storage systems before the year 2000. Between the years 2000 and 2010, another 73 energy storage systems were commissioned. However, between 2010 and June 2016, 580 energy storage systems were commissioned (All numbers exclude pumped hydro storage (PHS)). This market trend and rapid growth in part has come on the back of the increasing renewable energy market that itself has seen rapid growth in the last 15 years.

With this growth there has been plenty of innovation and competition between the several different types of energy storage each with their own advantages and disadvantages. Along with that, there are plenty of different types of applications for energy storage; Table 4 shows a comprehensive list of different types of energy storage application concerning the electricity grid along with suggested discharge duration and capacity [30]. One other large application of energy storage is electric vehicles; however, that is limited to batteries, fuel cells and supercapacitors.

Initially the energy storage market concerned itself with utility use through conventional power generation, grid operation and services and large industrial consumer use as uninterruptible power supplies. PHS, which accounts for 99% of the world's energy storage capacity, and compressed air energy storage (CAES) are the large stores of energy and are used in the typical way of storing cheap, off-peak electricity at night and discharging it at peak demand times. Whereas sodium sulphur batteries have a number of applications as UPS for industrial consumers. Now, energy storage is starting to have a wider role with several trends in applications driving the energy storage market: decentralised renewable energy generation, smart grids, smart microgrids, smart houses and the electrification of transport and heating [27].

Table 4: Various Energy Storage Applications [30].



-	-	Discharge Duration (hours)		Capacity (Power, kW/MW)	
#	**Application**	**Low**	**High**	**Low**	**High**
1	**Electric Energy Time Shift**	2	8	1 MW	500 MW
2	**Electric Supply Capacity**	4	6	1 MW	500 MW
3	**Load Following**	2	4	1 MW	500 MW
4	**Area Regulation**	15 min	30 min	1 MW	40 MW
5	**Electric Supply Reserve Capacity**	1	3	1 MW	500 MW
6	**Voltage Support**	15 min	1	1 MW	10 MW
7	**Transmission Support**	2 sec	5 sec	10 MW	100 MW
8	**Transmission Congestion Relief**	3	6	1 MW	100 MW
9.1	**T&D Upgrade Deferral 50th Percentile**	3	6	250 kW	5 MW
9.2	**T&D Upgrade Deferral 90th Percentile**	3	6	250 kW	2 MW
10	**Substation On-site Power**	8	16	1.5 kW	5 kW
11	**Time-of-use Cost Management**	4	6	1 kW	1 MW
12	**Demand Charge Management**	5	11	50 kW	10 MW
13	**Electric Service Reliability**	5 min	1	0.2 kW	10 MW
14	**Electric Service Power Quality**	10 sec	1 min	0.2 kW	10 MW
15	**Renewables Energy Time Shift**	3	5	1 kW	500 MW
16	**Renewables Capacity Firming**	2	4	1 kW	500 MW
17.1	**Wind Generation Grid Integration, Short Duration**	10 sec	15 min	0.2 kW	500 MW
17.2	**Wind Generation Grid Integration, Long Duration**	1	6	0.2kW	500 MW

There are a number of applications where energy storage is already commercially deployed, while others such as the smart grid and supporting the further expansion of renewables are only just emerging. With electricity demand set to increase, the further expansion of renewables, ageing grid infrastructures, CO2 emission targets, smarts grids and the electrification of vehicles and heating the need and market for energy storage is only set to increase. Figure 2, is a graph of the projection of the monetary benefit and maximum market of several different energy storage applications for the US. It can be seen that markets with large monetary benefit tend to have a low market potential and vice versa. For SMES the four suitable applications would be voltage support, transmission support, reliability and power quality. Each of those market have a projected market potential of about 10GW and that is just for the US. Another market projection by the IEA is based upon Western Europe and the amount of energy storage required to cope with the massive renewable energy introductions into the grid. For a grid with 25% of generation from wind, depending on the wind variation up to 90GW of energy storage may be required about three times as much as the existing capacity.

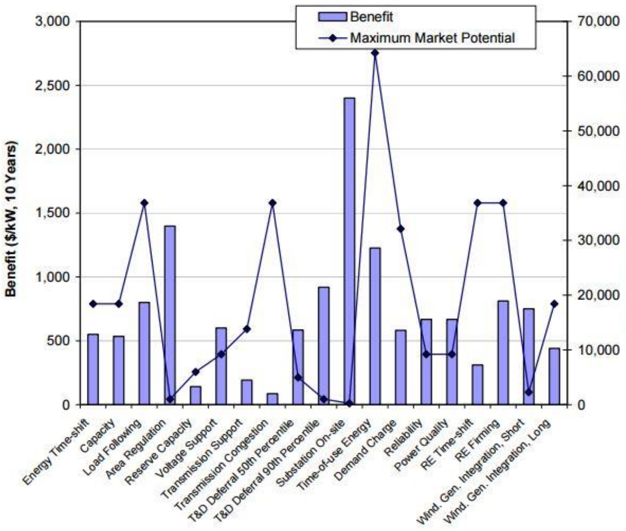


Figure 2: Energy Storage Benefit and market size by Application for the US [30].

One of the main barriers to market growth, particularly in the UK and EU, is the regulation of energy storage. Firstly, there is a lack of definition for storage, as it is both a generator and consumer so operators are often over-charged for services. Secondly, storage cannot be used for multiple revenue streams thus limiting the total benefits energy storage could provide as well as diminishing its economics. Finally, asset owner unbundling restricts who can operate energy storage, again closing off the market to potential users [22] [27] [31].

In addition, there is competition for energy storage: interconnection, demand response and new capacity. Each one has its own set of advantages and disadvantages, but the one that they all have over energy storage is that they are all proven options that work in the electricity market, whereas several types of energy storage are unproven and lack demonstration at a commercial level [22].

Conclusion

SMES is a developing technology with many challenges that need to be overcome to really be competitive in the energy storage market. The superconductor along with the associated refrigeration requirement has always been an issue for SMES and will continue to be in the near future. However, a lot of research and development is going into improving superconductors finding new materials and better process and manufacturing methods. 2G HTSs are starting to get some early commercial projects but with the high price of around $300/kAm and competition from supercapacitors and flywheels, it will currently only apply to niche applications. The target of around $25/kAm, a price similar to that of copper, seems to be a very good benchmark that 2G HTS or the next generation HTS need to achieve.

The sectors SMES can currently have an effect in are as FACTS, an area where it is competitive, or in power quality applications where the high power, fast response time characteristics of SMES are ideal. With the energy storage market continuing to grow due to a number of trends and applications, despite regulatory barriers and competition, the opportunities for commercialisation of SMES systems will continue. With this adoption will come a greater understanding of SMES, its role in the energy market and ultimately a reduction in price due to increased volume.

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Appendix

Table 5: Full Comparative Analysis of SMES, Supercapacitors, Flywheel, Lead Acid and Lithium-Ion.

Storage Type	**SMES**	**Supercapacitor**	**Flywheel**	**Lead Acid**	**Lithium Ion**
Technological Maturity	Early Commercial [22] Demo/early Commercial [2] Developed technology [25]	Early Demo [22] Developing/demo [2] Developed technology [25]	Demo/early commercial [22] Early Commercial [2] Developed technology [25]	Mature & commercial [22] Mature [2] Developed technology [25]	Demo [22] Demo [2] Developed technology [25]
Round Trip Efficiency (%)	80-90 [21] 90-95 [23] 85-90 [27] 90-97+ [22] 95 [26] 95-97 [25]	90-94 [21] 95-100 [15] 90 [27] 75-98 [22] 95 [26] 90-97 [25]	80-95 [21] 80-85 [15] 80-95 [23] 80-95 [22] 90-93 [26] 90-95 [25]	75-80 [21] 70-85 [15] 65-90 [23] 80-90 [27] 63-90 [22] 85 [26] 70-80 [25]	83-86 [21] 90-95 [15] 90-95 [23] 95-98 [27] 75-90 [22] 90-97 [25]
Energy Density (Wh/l)	0.5-10 [21] 5-6 [27] 0.2-2.5 [25]	2-10 [21] 3-10 [15] 10-20 [27] 10-30 [25]	80-200 [21] 20-80 [27] 20-80 [25]	50-100 [21] 60-100 [15] 50-80 [27] 50-80 [25]	200-350 [21] 150-450 [15] 200-400 [27] 200-500 [25]
Power Density (kW/l)	1-4 [21] 2-3 [27] 1-4 [25]	<15 [21] 35-100 [27] 100+ [25]	10 [21] 4-6 [27] 1-2 [25]	10-500 [21] 0.1-0.7 [27] 0.01-0.4 [25]	100-3500 [21] 2-10 [27]
Power (MW)	0.1-10 [22] 0.001-10 [26] 0.1-10 [25]	0-10 [22] <0.1 [26] 0-0.3 [25]	0.4-20 [22] <1.65 [26] 0-0.25 [25]	0-40 [22] <50 [26] 0-20 [25]	1-100 [22] 0-0.1 [25]
Energy (MWh)	0.0008-0.015 [2]	0.0005 [2]	0.0052-5 [2]	0.00-40 [2]	0.024-10 [2]
Cycle Life	N/A [21] 1,000,000 [23] 100,000+ [25]	< 1,000,000 [21] 500,000-1,000,000 [15] 1,000,000 [27] 25,000-5,000,000 [22] 100,000+ [25]	> 1,000,000 [21] 10,000 [26] 20,000+ [25]	500-2,000 [21] 200-1,500 [15] 1,000-2,000 [23] 1,500 [27] 200-1,000 [22] 500-1,000 [25]	1,000-5,000 [21] 800-3,000 [15] 500-3,000 [23] 5,000 [27] 4,000-100,000 [22] 1,000-10,000+ [25]
Calendar Life (years)	20 [21] 20-30 [22] 30 [26] 20+ [25]	15 [21] 10 [27] 8-20 [22] 20+ [25]	15 [21] 20 [23] 15-20 [22] 20 [26] 15 [25]	5-15 [21] 6-15 [27] 5-20 [22] 5-10 [26] 5-15 [25]	5-20 [21] 5 [23] 5-15 [22] 5-15 [25]
Depth of discharge (%)		75 [21]	75 [21]	70 [21] 80 [27]	≤100 [21]
Self-discharge	10%-15% per day [21] 10-12% per day [23] 10-15% per day [25]	≤25% in first 24 hrs then minimal [21] 20-40% per day [25]	5%-15% per hour [21] 3-20% per hour [23] 100% per day [25]	0.1%-0.4% per day [21] 5% per month [23] 0.1-0.3% per day [25]	5% per month [21] 5% per year [23] 0.1-0.3% per day [25]
Response Time (s)	0.001-0.01 [21] 0.001 [22] ms [26]	0.01 [21] 0.001 [22] ms [26]	0.01 [21] ms [26]	0.003-0.005 [21] ms [26]	0.003-0.005 [21]
Discharge Time	ms-seconds [22] 1sec-30min [26] ms-8s [25]	ms-1hr [22] <1min [26] ms-1hr [25]	1-15 mins [22] secs-1hr [26] ms-15min [25]	Seconds-10hrs [22] Mins-8hrs [26] Seconds-hours [25]	0.15-1hr [22] Minutes-hours [25]
Site Requirements	Refrigeration, switching and inverter system [21]			Ventilation due to gassing [21]	
Applications	Primary frequency control, voltage control, peak shaving, UPS [21] Small grid/commercial UPS [22] Power quality: short duration UPS, flicker management and instantaneous voltage drop [25]	Primary frequency control, voltage control, peak shaving, UPS [21] Small grid/House/EV [22] Power quality: short duration UPS, flicker management and instantaneous voltage drop [25]	Primary frequency control, voltage control, peak shaving, UPS [21] Power quality and [27] UPS Small grid/House/EV [22] Power quality: short duration UPS, flicker management and instantaneous voltage drop [25]	Frequency control, Peak shaving, Load leveling, Island grids, Residential storage systems, Uninterruptible power supply [21] Grid/House/EV/Commercial UPS [22] Power quality: short duration UPS, flicker management and instantaneous voltage drop [25]	Frequency control, Voltage control, Peak shaving, Load leveling, Electromobility, Residential storage systems [21] Grid/House/EV/Commercial UPS [22] Power quality: short duration UPS, flicker management and instantaneous voltage drop [25]
Specific Power Cost	200-350$/kW [22] 300$/kW [26] 200-300$/kW [25]	10-20€/kW [21] 25-510$/kW [22] 300$/kW [26] 100-300$/kW [25]	300€/kW [21] 250-25,000$/kW [22] 300-350$/kW 250-350$/kW [25]	150-200€/kW [21] 50-600$/kW [22] 200-300$/kW [26] 300-600$/kW [25]	150-200€/kW [21] 400-1,600$/kW [22] 1,200-4,000$/kW [25]
Specific Energy Cost	30,000-200,000€/kWh [23] 1,000-10,000$/kWh [22] 2,000-72,000$/kWh [26] 1,000-10,000$/kWh [25]	10,000-20,000€/kWh [21] 300-20,000$/kWh [22] 82,000 [26] 300-2,000$/kWh [25]	1,000€/kWh [21] 1,000-5,000€/kWh [23] 1,000-14,000$/kWh [22] 200-25,000$/kWh [26] 1,000-5,000$/kWh [25]	100-250€/kWh [21] 25-250€/kWh [23] 200-400$/kWh [22] 175-250$/kWh [26] 200-400$/kWh [25]	300-800€/kWh [21] 800-1,500€/kWh [23] >600€/kWh [27] 600-3,800$/kWh [26] 600-2,500$/kWh [25]