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New technology and possible advances in energy storage ☆

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ABSTRACT

Energy storage technologies may be electrical or thermal. Electrical energy stores have an electrical input and output to connect them to the system of which they form part, while thermal stores have a thermal input and output. The principal electrical energy storage technologies described are electrochemical systems (batteries and flow cells), kinetic energy storage (flywheels) and potential energy storage, in the form of pumped hydro and compressed air. Complementary thermal storage technologies include those based on the sensible and latent heat capacity of materials, which include bulk and smaller-capacity hot and cold water storage systems, ice storage, phase change materials and specific bespoke thermal storage media.

For the majority of the storage technologies considered here, the potential for fundamental step changes in performance is limited. For electrochemical systems, basic chemistry suggests that lithium-based technologies represent the pinnacle of cell development. This means that the greatest potential for technological advances probably lies in the incremental development of existing technologies, facilitated by advances in materials science, engineering, processing and fabrication. These considerations are applicable to both electrical and thermal storage. Such incremental developments in the core storage technologies are likely to be complemented and supported by advances in systems integration and engineering. Future energy storage technologies may be expected to offer improved energy and power densities, although, in practice, gains in reliability, longevity, cycle life expectancy and cost may be more significant than increases in energy/powerdensity per se.

1. Summary of anticipated scientific and technological advances

Technology	Advances	Likelihood	Implications
Electrochemical	Incremental development of: • Electrodes • Plates • Current collectors • Seals • Membranes • Electrolytes	High	• 10–20% improvements in energy density • Enhanced cycle and chronological lifetimes • Reduced manufacturing costs
	Improved cell packaging and design	High	
	Improved battery pack make-up, thermal and electrical management	High	• Ability to construct and engineer larger battery packs • Enhanced reliability and tolerance to misuse
	Development of lithium sulphur/sulphide electrochemistries	Medium	• Potential three-fold increase in energy density
Flywheel storage	• High-performance composite fibres • Low loss, high-performance bearings • Enhanced design tools	Medium/high	• Improved energy and power densities • Reduced manufacturing costs • Enhanced reliability levels
Thermal storage	• Development of bespoke phase change materials • Improved systems integration	Medium/high	• Enhanced market application and uptake

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☆ While the Government Office for Science commissioned this review, the views are those of the author(s), are independent of Government, and do not constitute Government policy.

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2. Energy storage

Energy storage embraces a wide range of energies, technologies, scales and applications. Energy may be converted to stored form in chemical, electrical, kinetic, potential or thermal media. It can be converted for final use directly, for example when heat is taken from a thermal energy store, or indirectly via an energy conversion system, for example when electricity is generated via the turbine generator of a pumped hydro storage system.

Energy storage systems are generally described as either electrical or thermal. Electrical energy storage embraces all the technologies and systems where the external interface is electrical. The energy storage medium itself may use one of a number of technologies, including electrochemical systems, kinetic energy storage and potential energy storage.

The electrical interface is an essential element of electrical energy storage systems and is provided by a power conversion system (PCS). The PCS can represent more than 25% of the overall cost of a complete electrical energy storage system.

In contrast, thermal energy storage systems utilise either the sensible or latent heat capacity of materials to provide a heating or cooling resource, which can be replenished as required.

Electrical energy storage systems find ready application in a diverse range of markets. They include traction and propulsion, the ubiquitous automotive starting, lighting and ignition (SLI) sector, standby power, remote area power supplies (RAPS) and in electrical power systems. This last-named sector is of most interest in the present paper.

In contrast, thermal energy storage has a somewhat more restricted applications domain, principally embracing the built environment, industry and certain other niche markets. Applications in the built environment are of principal interest in the context of this paper.

3. Current status: electrical energy storage

Electrical energy storage embraces a broad range of technologies, which either directly or indirectly provide electrical energy storage via an electrical input and output. The principal technologies of interest within the context of the present paper are:

- electrochemical systems (embracing batteries and flow cells),
- kinetic energy storage systems, more commonly referred to as flywheel energy storage,
- potential energy storage in the form of either pumped hydro or compressed air storage.

Further developments are in hand in relation to hydrogen storage systems in which the electrolysis of water is used to generate hydrogen to power fuel cells, but these are outside the scope of this paper.

Electrical energy storage, principally in the form of large-scale pumped hydro systems, has historically been used in electrical power systems to even out imbalances between supply and demand. For example, base load power stations can be used at times of low demand, typically at night, to charge the energy store, which can be discharged at times of peak daytime demand. Such large pumped hydro systems also provide system operators with reserve generating power that can be brought into use quickly, for example when there is a surge in TV viewer figures or when conventional power stations are unexpectedly ‘tripped’, or taken off the system.

Applied at a smaller scale within the power distribution network, electrical energy storage is attracting increasing interest for applications such as distribution asset deferral, peak lopping, voltage support, the assurance of power quality and the integration of renewables into power systems.

Electric power systems will need electricity storage for systems balancing if forecasts of large-scale take-up of time variable or intermittent renewables such as wind prove accurate. Energy storage can reduce the need for conventional generating plant to be kept in reserve for times when renewables are unavailable, and would involve lower carbon emissions than fossil-fuel standby plant.

Electrical energy storage technologies include some that provide short duration, high-power discharges, such as flywheels, and others that provide a bulk storage capability and which discharge over extended time periods of several hours or more, for example pumped hydro. The following sections describe the principal electrical energy storage technologies. Although complementary developments in PCS technologies also contribute to improvements in overall system performance, these are not specifically covered in the present paper.

3.1. Battery storage

Batteries are a long-established means of storing electricity in the form of chemical energy. They are classified as primary batteries, which are not rechargeable, or secondary batteries, which can be recharged. Only secondary batteries are considered in the context of the present review as primary batteries are not viable for bulk energy storage.

A battery comprises one or more electrochemical cells, with each cell comprising a liquid, paste or solid electrolyte, together with positive and negative electrodes. During discharge, electrochemical reactions at the two electrodes generate a flow of electrons through an external circuit. During the charging process, the electrochemical reactions are reversed via the application of an external voltage across the electrodes.

Battery technologies range from the mature and long-established lead-acid system (Pb-acid) through to various more recent and emerging systems and technologies, where advances are occurring in relation to sodium–sulphur, sodium–nickel chloride, and lithium ion systems. The last of these is attracting increased interest for possible use in power systems, having achieved market acceptance and uptake in consumer electronics in the so-called 3Cs sector: cameras, cellphones and computers.

Table 1 provides a summary of the essential performance characteristics of the principal battery electrochemistries currently of interest in the context of electrical power systems.

Important performance characteristics for batteries intended for use in power systems include:

- power rating and energy storage capacity,
- whole life cost,
- cycle and calendar lifetimes,
- safety and licensing considerations,
- size,
- round-trip energy efficiency level,
- operational and maintenance requirements.

3.2. Lead-acid systems

Lead-acid batteries have been used in electrical power systems for more than a century. Indeed, lead-acid accumulators were used in early municipal power systems to provide the power at night, when demand was low and the generating plant was shut down. They provide a cost-competitive and proven solution to a

Table 1
Performance of different battery electrochemistries

	Lead-acid	Nickel–cadmium	Sodium–sulphur	Sodium–nickel chloride	Lithium ion
Achieved/demonstrated upper limit power rating	Tens of megawatts	Tens of megawatts	Megawatt scale	Hundreds of kilowatts	Tens of kilowatts
Specific energy (Wh/kg)	35–50	45–80	100	115	160

range of storage requirements. But they have some disadvantages including relatively limited cycle life, low-energy density and a resulting large footprint, which can be a limiting factor in urban applications. This technology has been used successfully in a number of large-scale storage installations and is also of interest for smaller-scale applications, including those associated with micro-CHP development.

3.3. Nickel–cadmium

Nickel–cadmium (NiCd) battery systems rank alongside lead-acid batteries in terms of their maturity. In the past they have been the technology of choice for power tools and portable devices and they found various applications in the electric vehicle field in the mid-1990s. They have been largely displaced from these markets, not least because of concerns about cadmium toxicity and associated recycling issues. Such concerns are a barrier to planning and gaining consent for future large-scale storage systems based upon NiCd technology.

Notwithstanding this, NiCd is a robust and proven alternative to lead-acid batteries, with higher energy density, a longer cycle life and low-maintenance requirements. It has achieved prominence in the recent Golden Valley project in Fairbanks, Alaska, where it formed the heart of a battery energy storage system, providing quickly-available reserve power to what is effectively an electrical island. The Golden Valley scheme is claimed to be the world's most powerful battery, with the complete system rated at 40 megawatt (MW) discharge capability over 7 min. The NiCd batteries themselves are expected to complete 100 complete and 500 partial discharges in the system's 20 year design life (Fig. 1).

3.4. Sodium–sulphur

Sodium–sulphur (NaS) battery technology involves high temperatures, operating at 300 °C. The cell construction uses liquid sulphur as the negative electrode and liquid sodium as the positive electrode, separated by a solid electrolyte of beta-alumina. The battery delivers 100% coulombic efficiency, meaning that all the electricity put into it can be recovered. But its operating temperature must be maintained, by routine operation or by external heating.

NaS technology has been developed over a period of more than 30 years. The Japanese company NGK brought it to market in year 2002, working in conjunction with the Tokyo Electric Power Company (TEPCO). To date, the installed capacity base is in excess of 200 MW across some 150 sites, principally in Japan, but with a developing North American market base. An 8 MW, 58 MWh system installed at a Hitachi automotive plant in Japan is currently the world's largest battery in terms of storage capacity, while the Golden Valley installation discussed above has the highest power rating of any battery energy storage system.

3.5. Sodium–nickel chloride (ZEBRA)

The Sodium–nickel chloride battery, otherwise known as the ZEBRA battery, is another high-temperature battery system, developed and proven in various traction and propulsion applications. Its cell construction comprises sodium and nickel chloride electrodes, separated by a beta-alumina electrolyte, which is able to conduct sodium ions but not electrons. It offers a number of advantages relative to sodium–sulphur systems, including better safety characteristics, higher cell voltage and the ability to withstand limited overcharge and discharge. Although this electrochemistry has been extensively developed and validated for automotive use, it remains in its infancy in power utility applications.

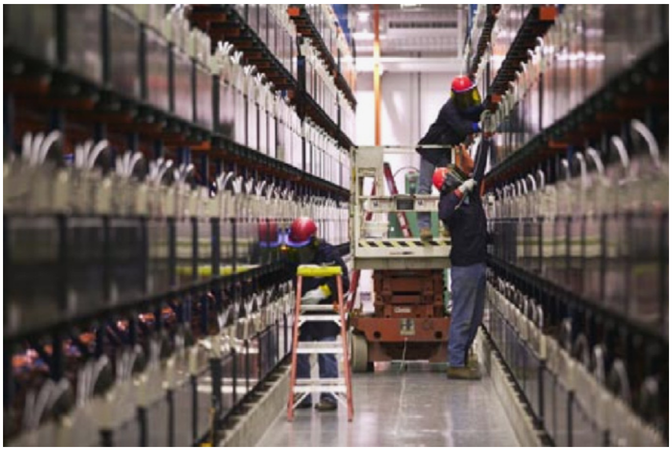

Fig. 1. The world's most powerful battery, at Golden Valley, Alaska, provides back-up to an isolated electric power system. Picture courtesy of Golden Valley Electric Association.

3.6. Lithium ion

Lithium ion battery technology has progressed from developmental and special-purpose status to a global mass-market product in less than 20 years. A highly competitive market is driven mainly by the demands of the 3Cs sector, worth some US$ 6 billion per year at the present time. The technology is especially attractive for its 3Cs market applications because lithium ion batteries offer high-power densities, typically 110–160 watt hours per kilogram (Wh/kg) and generally acceptable cycle life. They have effectively displaced other electrochemistries from this sector.

The basic modus operandi of the lithium ion system involves the reversible transfer of lithium ions. During charging, lithium ions move out (de-intercalate) from the lithium metal oxide cathode and intercalate into the graphite-based anode, with the reverse happening during the discharge reaction. The non-aqueous ionically conducting electrolyte takes no part in the reaction except for conducting the lithium ions during the charge and discharge cycles.

Notwithstanding their significant advantages, lithium ion systems must be maintained within well-defined operating limits to avoid permanent cell damage or failure. The technology also possesses no natural ability to equalise the amount of charge in its

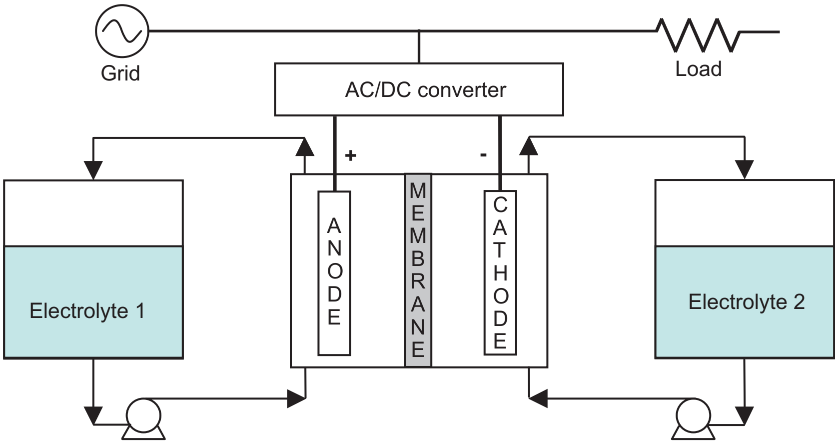

Fig. 2. Illustrative representation of a redox flow cell energy storage system.

component cells. This, and the closely defined operational envelope of lithium ion batteries, essentially dictates the use of relatively sophisticated management systems. The application of the technology to larger-scale systems is relatively limited to date, although various developments are in hand in relation to the automotive, power utility, submersible and marine sectors.

3.7. *Flow cells*

Electrochemical flow cell systems, also known as redox flow cells, convert electrical energy into chemical potential energy by means of a reversible electrochemical reaction between two liquid electrolyte solutions. In contrast to conventional batteries, they store energy in the electrolyte solutions. Furthermore, in contrast with conventional batteries, the power and energy ratings of redox flow cells are independent variables. Their power rating is determined by the active area of the cell stack assembly and their storage capacity by the electrolyte quantity. Fig. 2 depicts a redox flow cell energy storage system.

Over the past 20 years, development and demonstration activities have centred around four principal electrochemistries for flow batteries, namely: vanadium/vanadium, zinc bromine, polysulphide bromide and zinc cerium, although with others under development. Installations to date have principally used the vanadium redox and zinc bromine electrochemistries. Several dozen are in place, mainly in Japan and North America. The polysulphide bromide system was developed for grid-connected, utility-scale storage applications at power ratings from 5 MW upwards, although this development programme ceased in December 2003. Production of flow cell-based energy storage systems proceeds at a slow pace, via the activities of a relatively small number of developers and suppliers.

3.8. *Flywheel energy storage*

Kinetic energy storage systems, otherwise known as flywheel energy storage, rely for their operation on the stored kinetic energy in a rotating drum, the flywheel. Conversion to and from electrical energy takes place via an associated motor/generator set. There are two types: conventional steel rotor systems which run at low speed, and advanced composite machines which operate at high speed. Much current development relates to high-speed devices.

Important considerations in the design of modern, advanced flywheel energy storage systems include the form and make-up of the rotating mass itself, its enclosure within an evacuated containment, which minimises air friction and contains the fragments if there is rotor failure, rotor dynamics and bearing design, and the integration of the motor/generator set and its associated power conversion and control systems.

Flywheel energy storage systems are best suited to short duration, high-power discharges, for example over time periods of several minutes. They have extended cycle lives and higher power to energy ratios than battery systems.

Conventional steel rotor systems are well established in the critical load and uninterruptible power supply (UPS) market, providing short-duration ‘ride-through’, power quality enhancement and load levelling. Early examples of advanced composite machines, sourced from a number of suppliers, are presently installed in various demonstration schemes, including frequency support applications in the North American market.

3.9. *Potential energy storage*

The storage of potential energy is utilised in pumped-hydro and compressed air energy storage (CAES) systems. Pumped hydro is widely adopted in power systems worldwide, with some 90 GW of capacity installed. The basic principle of pumped hydro storage is well established. Water is pumped to an upper reservoir at times of surplus supply and discharged through a turbo-alternator set at times of high demand.

Large CAES systems are far less common. Only two are in existence, Huntorf in Germany (290 MW) and the McIntosh plant in Alabama, USA (110 MW). The modus operandi of such CAES schemes is essentially that of a split gas turbine. High-pressure compressed air is stored in a suitable underground cavern and is used by being expanded through a turbo-alternator set. CAES is presently attracting increased interest in the context of buffering the output of large-scale wind farm developments in the USA and thereby enhancing their financial viability.

4. Current status: thermal energy storage

Thermal energy storage technologies are based on either the sensible or latent heat capacity of materials or, alternatively, upon reversible thermochemical reactions. The time constant associated with thermal energy storage is usually measured in hours, days or even months, so that they can provide for seasonal storage capacity. Such large-scale installations are often deployed in conjunction with renewable energy sources in Germany and Scandinavia.

Systems based on the sensible heat capacity of materials include hot and cold water tanks, underground thermal energy storage (UTES) or specific bespoke materials and structures.

The storage of either hot or chilled water is a well-established technique and is practised over a full spectrum of capacities. It ranges in scale from the simple domestic hot water cylinder, the bulk hot water storage associated with combined heat and power and district heating schemes and through to the bulk storage of chilled water, to reduce the peak loads on air-conditioning systems. Design considerations for such tanked water schemes include the anticipated levels of stratification in the storage vessels, the trade-off between storage temperature and heat losses and gains and the insulation levels employed.

UTES systems exist in a number of countries and use either groundwater or the ground itself as a storage medium. Systems in the former category are referred to as aquifer thermal energy storage (ATES) systems. The second method, borehole thermal energy storage (BTES), uses heat exchangers to transfer heat to and from the ground storage medium.

Perhaps the best-known sensible heat storage system based on a bespoke material is the well-established 'feolite' material used in electric storage heaters. These were introduced to the UK in the 1970s and now account for some 8% of the UK residential heating market. The essential concept of these heaters is that they heat up during the night time, at low-electricity tariffs, and discharge during the day, when the heat is required. The cost-effectiveness of such electric heating systems can also be enhanced by using advanced control technologies, including the industry standard CELECT intelligent control system.

Systems based on the latent heat capacity of materials include the well-established technique of ice storage and the use of various bespoke phase change materials (PCMs).

Ice storage systems are widely utilised in the USA and elsewhere to relieve peak air-conditioning loads in daytime hours. Lower tariff night time electricity is used to generate ice, which in turn provides cooling capacity during the day. Ice storage can be based on static systems, which build and store ice on heat exchanger surfaces, or dynamic systems, where the ice is 'harvested' from the heat exchanger and stored in a separate reservoir.

PCMs based upon various paraffins, esters, fatty acids and salt hydrides have been developed to absorb or reject heat over narrow temperature bands, while providing a thermal storage capacity significantly greater than sensible heat storage. Such materials may be incorporated into building fabrics or contained in free-standing cassettes or storage tanks to provide for various heating and cooling applications, including those in the residential and commercial building sectors, in district heating and for cold storage.

5. Future advances

The essential performance characteristics of any energy storage medium, whether electrical or thermal, may be described in terms of such factors as:

- energy density (Wh/kg),
- power density (W/kg),
- cycle efficiency (%),
- self-discharge characteristics,
- cycle life (cycles),
- chronological life (years).

Other applications-related considerations include the footprint of the equipment, measured in terms of its energy or power rating per square metre of floor area, through-life operational and maintenance requirements, the general acceptability of the materials and chemicals used, including health, safety and environmental related factors and, ultimately, the cost of the technology and its associated balance-of-plant.

Market drivers for improved energy storage technology relate to increasing energy and power densities, improving efficiency, and extending cycle lifetimes and, to a lesser extent, system chronological lifetimes.

For many of the basic storage technologies discussed here, such performance advances call for advances in materials science and in the make-up of these materials to form complete storage systems. For electrical energy storage systems, complementary developments in power electronics and PCSs are also important for systems development.

Potential advances in materials science will also benefit any new storage technologies that may emerge over the next 30–40 years. While it is somewhat speculative to contemplate specific groundbreaking technological breakthroughs, novel electrochemical couples could well emerge over this timescale, together with novel materials for thermal storage. The remaining sections of this paper aim to provide a representative overview of some of the potential future advances over the next three to four decades. It should be remembered that advances in materials science must be accompanied by developments in the systems in which they would be used, including system packaging, balance-of-plant and engineering.

5.1. Electrochemical energy storage

Basic chemistry suggests that lithium-based cell technologies are likely to represent the pinnacle of cell development in terms of specific energy density. The further development of lithium-based cell technologies relates to the ongoing evolutionary development of lithium ion systems, complemented by more fundamental developments in relation to lithium–sulphur and lithium–sulphide technologies.

Lithium-based cell technologies may benefit in future from better electrodes, plates, current collectors and seals, complemented by developments in materials processing, fabrication and manufacturing techniques.

The development of lithium–sulphur and lithium–sulphide cell technologies is presently being pursued by only a limited number of organisations. It has the potential for a further performance advantage over the present generation of lithium-ion technologies, provided that the technology that emerges can compete in terms of cycle life expectancy and cost.

Similar evolutionary development is being pursued for the other principal cell electrochemistries, driven by market needs and by expectations of improved energy density, enhanced cycle life and lower cost.

Various other specific electrochemistries (e.g. silver magnesium chloride) will continue to be developed for specialist niche market applications, such as those in the defence sector, but they are unlikely to find immediate spin-off use in power utilities applications.

Further opportunities for innovation relate to the make-up and management of complete battery packs. Attention is being paid to aspects such as packaging, state-of-charge estimation, interconnectors, thermal management, protection, cell equalisation and control. Such developments provide the potential for the application of lithium-based cell technologies, previously employed in small-scale, low-power applications, to medium and large-scale applications, such as those in electric vehicles.

Flow cell technologies have the potential to provide a cost-competitive alternative to present day batteries for the bulk storage of electricity. Progress will depend upon the engineering development of the present generation of systems. This will be supported by scientific advances in such areas as electrodes, electrolytes, membranes, polymers and seals and advances in manufacturing technology.

Such advances in engineering and science will be supported by developments in materials processing and fabrication. The overall objective is a cost-effective alternative to battery energy storage for applications requiring storage capacity of several hours or more.

5.2. Mechanical systems

The engineering science underpinning flywheel, hydro and CAES systems is well established. But there is potential for specific scientific advances to contribute to the enhanced performance of such systems, especially kinetic energy storage systems. The emphasis is on the development of high-speed machines, with higher specific energy densities, and on reducing the cost of low- and medium-speed machines by the application of more advanced materials and design techniques. Here the key enabling technologies and the underpinning knowledge base are in systems engineering and materials science.

The successful design and engineering of very high-speed flywheel assemblies requires expertise in machinery dynamics, fluid mechanics, bearing design and stress analysis, all complemented by access to, and a good understanding of, the requisite power conversion and control technologies. The development of robust design and modelling tools facilitates many of these system design aspects.

The development of high-directional strength composite materials may be a key enabling technology for improved high-speed rotors. It may allow the configuration of the rotating mass to be optimised to provide higher storage capacity for an installation of given size and mass.

The potential for big advances in science to improve compressed air and pumped hydro systems is more limited. For compressed air energy storage systems, there is the opportunity to employ various derivatives of the basic split gas turbine cycle including, for example, different degrees of intercooling and humidification, and also the development of adiabatic systems. There is also the further potential to realise small-scale CAES, based upon prefabricated storage vessels as opposed to underground caverns. This concept is presently under development in the context of integrated wind/CAES systems. While relatively conventional fabricated steel pressure vessels offer an immediate solution, it may be possible to use high (directional) strength composite fibre materials to facilitate the design of bespoke storage media for specific applications.

Developments in relation to pumped hydro storage include those of the basic turbo-machinery itself, and advances in civil engineering and construction practices that provide the potential for lower cost and higher performance systems.

5.3. Thermal energy storage systems

The potential for major scientific advances in thermal energy storage is also limited. However, there may be opportunities in the development of bespoke PCMs, with the change of phase occurring at an appropriate temperature for the particular application. It is important to ensure that these materials provide adequate heat transfer rates in practice to ensure truly effective functionality.

Developments in relation to the other principal thermal storage technologies are more applications based and relate to the enhanced integration of such systems with their end use.

Further reading

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