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Energy Storage

A key technology for decentralised power, power quality and clean transport

ENERGY, ENVIRONMENT
AND SUSTAINABLE DEVELOPMENT

EUR 19978

"Energy storage is a key technology for an efficient and sustainable use of energy..."

Importance of energy storage is too often overlooked and taken for granted; yet it remains a major technical challenge.

Renewable energy sources need energy storage to adapt the intermittent, seasonally and daily varying supply to the demand.

Energy storage is the key to the hybrid-electric vehicles and helps to reduce fuel consumption.

Energy storage is indispensable for high-quality electricity supply.

E-commerce, Internet and mobile communications are all unthinkable without energy storage.

Optimal use of fuel cells in co-generation requires energy storage.

Energy storage is needed to ensure uninterruptible supply of electricity to essential services, such as hospitals, industry and commerce.

Energy storage can reduce the number of stand-by power stations needed for reserve capacity, hence reducing costs.

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Introduction

Energy storage is the most promising technology to reduce fuel consumption in the transport sector. Reliable and affordable electricity storage is a prerequisite for using renewable energy in remote locations, the integration into the electricity system and the development of a future decentralised energy supply system. Energy storage therefore has a pivotal role in the effort to combine a future, sustainable energy supply with the standard of technical services and products that we are accustomed to and need.

The vast majority of today's technology products rely on components or sub-systems to store energy. Electricity, heat or cold, compressed air and mechanical energy has to be made available when and where required by the application. A delayed response to a power requirement and inadequate or excessive power levels are unacceptable to industrial, commercial and private consumers and can lead to application failures. Energy storage systems match the requirements of applications to the energy supply. Power stations, compressors, heating systems etc. all have different performance characteristics concerning their response time to changing demand, their lead times for starting up or shutting down and their most efficient point of operation. Without energy storage the timely availability of energy is compromised and operation of energy generation and conversion devices at low efficiency levels has to be accepted. The decision to use an energy storage system depends on the demands of the application and the cost of competing solutions In renewable energy systems, for instance, the use of fossil fuel based generation and grid connection are competing solutions.

Energy storage systems can usually be replaced by conventional energy generation. However, this can lead to an inefficient use of fossil fuels and a need for investment in additional energy generators with high power output and fast response time. Where this is acceptable and cost efficient, energy storage systems will not be used. Conversely, low cost and efficient energy storage systems can lower fuel consumption and emissions and can reduce the overall capital investment for an energy system. Hybrid transport systems are an example of this.

The target action of the European Union's RTD is focussing on storing energy which is available in its useful form, e.g. as electricity or heat, and reconverting it back to useful forms of energy. Non-rechargeable batteries, fossil fuels, biofuels or hydrogen will not be considered in this target action although they, too, can be looked at as energy storage media. The target action includes all integral and necessary parts of an energy storage system such as power electronics, control equipment and software to implement operating strategies. Separate target actions have been established for biomass and hydrogen.

Energy storage technologies are based on different scientific principles. Electrochemistry for batteries and reversible fuel cells, electromagnetic fields for capacitors and superconducting magnetic energy storage systems (SMES), physicochemistry for the storage of heat and cold and mechanical engineering for flywheels, compressed gas and pumped hydro storage. Some energy storage systems are commercially available and well proven. The driving forces for RTD&D are both economical and technological in nature: reducing size, cost of

Picture of installation in Berlin, Pris or London

The need for energy storage is not new. Large battery energy storage systems (BESS) existed in some European cities around 1930. The largest was installed in Berlin and had 186 MWh capacity. None of these systems exist anymore, because the energy supply system is now based on much larger grids, three-phase power transmission has replaced direct current and the cost of generation is lower. Today, utilities are again considering the construction of large battery energy storage systems because they may offer a cost-effective solution for the problem of balancing electricity generation and consumption quickly and cost-effectively. The driving forces for this rediscovery of battery energy storage systems are not technical but economic in nature: the real price of short-term grid stability tends to get higher with liberalised markets. Also, the electricity customers have to pay the real cost of extending the grid, e.g. in remote areas.

Energy sources		Use of energy		Energy storage
• *Conventional fossil fuels* • *Nuclear fuel* • *Renewable energy: Biomass, wind, water and solar energy*	***Generation processes*** →	• *Electricity* • *Heat* • *Cold* • *Transport* • *Kinetic energy* • *Compressed gas*	***Storage and recovery*** ↔	• *Batteries* • *Flywheels* • *Reversible fuel cells* • *Electromagnetic fields* • *Compressed air* • *Thermal energy* • *Pumped hydro*

Diagram of energy sources, use of energy and energy storage

operation and investment, increasing efficiency to lower fuel consumption and emissions, and minimising the impact on the energy infrastructure. When looking at the list of energy storage technologies it can be clearly seen that progress in all of them depends heavily on progress in the properties and cost of specific materials. Research of this type is usually risky and takes a long time. It therefore requires public support to reap the benefits of the technology quickly.

Certain EU policy objectives, such as: meeting the Kyoto obligations to reduce greenhouse gas (GHG) emissions from fossil fuels; lowering consumption of primary energy; creating a sustainable supply of electricity with an increasing share of renewable energy; and supplying low cost reliable electricity in remote areas of Europe, can only be achieved if energy storage systems are improved further. The RTD target action on energy storage of the European Union together with national RTD programmes is therefore a key element in achieving the EU environmental goals.

A brief overview of energy storage technologies

Different energy storage technologies coexist because their characteristics make them attractive to different applications. From a user point of view there are both technical and commercial criteria for selecting the most suitable technology:

Energy and power density
The available energy and the maximum power per litre or per kilogram is an important figure for most applications, but particularly for transport applications and mobile communication. Here weight and volume are either an absolute limit or a determining factor for the design and performance of a system.

Response time
Some applications have very stringent requirements concerning the speed with which the energy has to be released or absorbed. In UPS applications, a few milliseconds may sometimes be the maximum response time that is acceptable.

Cost and economies of scale
The auxiliary components required by some energy storage systems determine the total system costs and are often independent of system size. For these reasons, some storage systems are only economically feasible above a minimum energy content and power output.

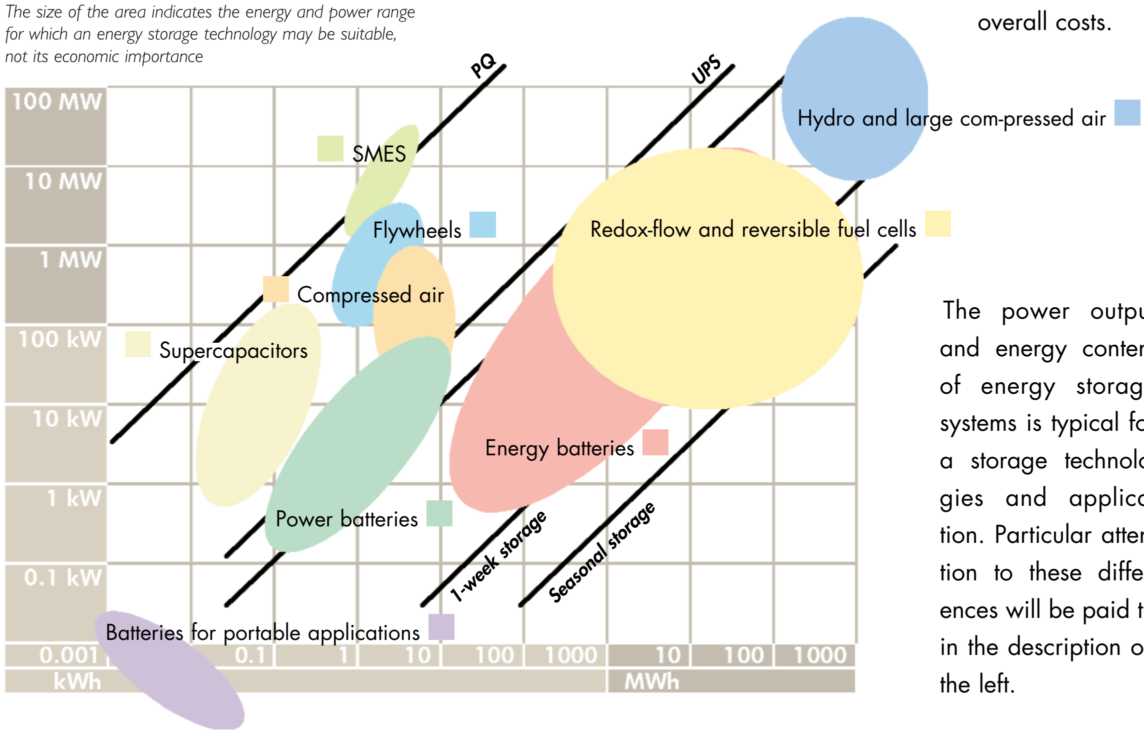
Lifetime
The overall energy storage cost is determined by the original investment costs and its projected lifetime. The accuracy with which the lifetime can be estimated is a particularly important problem for all electrochemical storage systems.

Monitoring and control equipment
The performance of some systems can be monitored extremely easily and cheaply whereas in some other systems a considerable effort has to be used to monitor the available energy content and the safety of the energy storage.

Efficiency
The process of storing and withdrawing energy can cause considerable losses (round trip or in-out efficiency). These are often application specific. Many auxiliary components of the energy storage system have a constant power demand, and in addition, there are energy losses inherent in the storage principle, such as self-discharging of batteries or heat losses. These losses can be very high in relation to the energy content.

Operating constraints
The cost of providing the correct environment and operating constraints such as temperature and safety systems etc. have to be considered for proper estimates of the lifetime expectations and overall costs.

The size of the area indicates the energy and power range for which an energy storage technology may be suitable, not its economic importance



Energy content and power output of different storage technologies

The power output and energy content of energy storage systems is typical for a storage technologies and application. Particular attention to these differences will be paid to in the description on the left.

Batteries and advanced batteries

Rechargeable batteries or accumulators are the oldest form of electricity storage and are extremely widely used. A lot of today's products are unthinkable without them.

Batteries store electric energy in a chemical form. Their performance is linked in a complex manner to the materials used, the manufacturing processes and the operating conditions. Lifetime tests take many years. Consequently, progress in battery technology is slow and the transfer of laboratory results into commercial applications is risky. Lithium ion and nickel-metal-hydride (NiMH) batteries are the only new battery technologies, which have reached a significant market penetration in the last decade. Other new battery technologies such as sodium sulphur and sodium nickel chloride have failed to deliver on their promises as yet although the technical performance achieved in ongoing research is quite remarkable.

Batteries can respond to changes in power demand within microseconds. Only supercapacitors equal their response time. Batteries usually have very low standby losses and can have a high energy efficiency dependent on the application and the details of the operation. The energy content and maximum power output of a battery are linked. In stationary applications requiring very high power outputs for a short time only, batteries face competition from flywheels, supercapacitors and SMES.

The rational for the development of new battery systems is an increase of energy density, power density and lifetime under the actual operating conditions of an application. It is now usual to make a distinction between power batteries capable of delivering and storing short bursts of power and energy batteries capable of delivering large amounts of energy, but at a much lower rate. Battery research currently focuses on new and improved materials and manufacturing processes as well as on their operating conditions.

- In stationary applications commercially available lead acid batteries will be difficult to replace for a long time to come due to the fact that weight is not an important factor in such applications. They are the cheapest energy storage system currently on the market, have a very high recycling rate and fulfil most specifications. Research centres on specific improvements for specific applications and the overall system design. Major improvements are still possible especially concerning their lifetime. However the lifetime of lead acid batteries in severe climatic conditions and remote outdoor installations is unsatisfactory so that NiCd batteries are used and other storage systems, e.g. lithium-ion batteries may be able to compete in the future.

- For portable applications the focus of the research is on lithium-ion and lithium-polymer batteries and also nickel metal hydride batteries. Nickel cadmium (NiCd) batteries are still the battery-of-choice for applications requiring high power output, e.g. for power tools and some industrial applications. However, the use of cadmium in industrial and consumer products poses an environmental hazard[1] and restricts research into new applications and technical improvements.

- For electric and hybrid vehicles, the research focuses on NiMH, lithium-ion and lithium-polymer batteries due to their high energy density. Despite the much higher weight, lead acid batteries are still considered a serious contender for hybrid vehicles due to their much lower cost.

Energy and power density	*20 – 100 Wh/kg depending on type, target 170 Wh/kg; power levels for very short power pulses exceed most requirements; 150 W/kg and target of 400 W/kg. Energy to power ratio is a design characteristic and only small variations are possible.*
Cost/economy of scale	*Most battery types with economic potential are already produced in large quantities. The cost of material and processing are the driving factors. For power batteries in hybrid applications, the cost target is most crucial and is 100 Euro/kWh*
Lifetime	*Mostly application dependent but perfectly acceptable for most conventional applications under laboratory conditions. Particular problems exist for energy batteries in RES and power batteries in hybrid vehicle applications.*
Monitoring and control	*Complex, no adequate solution exists*
Efficiency	*Higher than 90 % in some PV applications, very sensitive to application, standby losses in most batteries are negligible*

Most batteries contain toxic materials so that the ecological impact from mining the materials to recycling them and the uncontrolled disposal of batteries always needs to be considered. There is agreement that no unacceptable hazards arise during use but also a high percentage of batteries have to be collected and recycled. Collection rates for batteries used in portable applications are not considered acceptable.

Supercapacitors

Supercapacitors store electrical energy in the electric field between two electrodes made of carbon. Electron conducting polymers are now also tried as electrode materials. The fundamental design and the electrical properties are those of conventional capacitors used throughout the electrical and electronics industry. The design of the electrodes and the choice of electrolyte allow a very high charge density on the electrode surfaces, but limits the voltage to approx. 2.7 volts per cell. Despite the low voltage the energy content is much higher than in conventional capacitors and can reach the scale of a few Wh for some of the largest supercapacitors which are now commercially available. Supercapacitors are connected together to form larger modules with up to 1 kWh energy content and can be further joined together for larger energy storage units.

Supercapacitors have a very high power output and energy storage systems now under trial reach approx. 50 - 100 kW. In most applications, the energy stored will supply the load only for a few seconds to minutes. The number of charge and discharge cycles is for all practical purposes nearly unlimited but the energy throughput in fast cyclic operation is limited. Control circuit to balance the individual voltages of each supercapacitor is necessary for safe and reliable operation if supercapacitors are connected in series to achieve a higher output voltage. The lifetime of supercapacitors will probably be in the range of large conventional capacitors, e.g. 10 years. The in-out efficiency is very high, but the self-discharge rate is considerable compared with batteries.

Supercapacitors have proven their performance in demonstration projects and are now entering the commercial stage. Target applications are uninterruptible power supplies (UPS) and hybrid vehicles. In UPS applications they compete both with batteries and flywheels when there is a high power requirement. In hybrid vehicles they would offer a design option because high power but only a low energy content is required. Future research has to concentrate on cost, manufacturing process and lowering internal resistance. The principle target for RTD is meeting the costs of competing systems such as SMES, flywheels and batteries.

Supercapacitors

Energy and power density	*Single module up to 0.5 kWh and 15 kW; Energy and power density for a module in the range of 1.5 Wh/kg and 1.2 kW/kg, for a single supercapacitor in the range of 2 Wh/kg and 2 kW/kg.*
Cost/economy of scale	*Still very high costs mainly due to low production quantity, no commercial applications yet*
Lifetime	*No practical limits of number of cycles, but calendar life limited to approx. 8 – 10 years*
Monitoring and control	*Simple monitoring but complex control electronics is still required for operation*
Efficiency	*In-out efficiency is above 95 %. The self discharge rate is significant – approx. 5 % per day.*

Reversible fuel cell systems and redox flow batteries

Fuel cells convert hydrogen from a storage tank or reformer and oxygen from the air to water and generate a current from the electrochemical process. The electrochemical reaction itself is reversible. However, the materials and the design of a fuel cell need to fulfil conflicting requirements when the direction of the reaction is reversed. Such systems exist and are called electrolysers. However, electrolysers are not as developed as fuel cells. For energy storage, the requirements of fuel cells and electrolysers need to be combined in one system, a reversible fuel cell, to make it a cost efficient proposition.

Instead of hydrogen and oxygen, other materials can be used too, e.g. zinc/bromine and zinc or vanadiumoxides. The active materials react when they have the opportunity to exchange protons through a non-electron-conducting electrolyte and generate a current through a load from the electrochemical reaction. These systems have been called redox flow batteries. Their energy efficiency is likely to be higher than those of reversible fuel cells, but still below the energy efficiency achieved by most batteries.

Energy and power density	*Approx. 75 Wh/kg; Energy content and power density are independent design parameters. Storage with a few 100 MWh energy content are planned.*
Cost/economy of scale	*Only large systems (for electric vehicles or utility type storage) will probably be cost effective. Increasing the energy content is much cheaper than increasing the power output*
Response time	*In principle similar to batteries, but probably a few seconds*
Efficiency	*50 - 60 %, but low standby losses*

Reversible fuel cells

Small redox flow batteries may find an application in electric vehicles. Large redox flow batteries in the range of hundreds of MWh have been proposed and are now under development. The aim is to use them for large wind farms and electricity storage systems for load levelling with a discharge time of approx. 2-4 hours. The materials used in reversible fuel cells and redox flow batteries are usually hazardous and special care will have to be taken when large tanks for MWh energy storages are built.

Reversible fuel cells and redox flow batteries allow the separation of energy content and maximum power output. Energy capacity is determined by the size of the storage tanks for the active materials and the power by the area of the electrodes and design of the reactor. Standby losses are low because the active materials are kept physically separate. The overall efficiency is likely to remain low and these energy storage systems may therefore remain unsuitable for PV applications, where the cost of every kWh produced is high. At high power output the efficiency decreases considerably. The response time of reversible fuel cells is in principle very short.

The technology of fuel cells and electrolysers and redox flow batteries is proven in principle. Long term tests are still necessary, the effect of outside temperatures, the maintenance-free operation of pumps, valves and other auxiliary components needs to be tested. Key issues in the development of reversible fuel cells will be the development of suitable membranes, reducing the cost of manufacturing and increasing the efficiency. Commercial success will also depend on meeting cost targets. Potential applications are characterised by a high energy content in relation to the power requirement and the availability of cheap surplus electricity. Prototypes for UPS have been built with 100 kWh energy content and 25 kW power rating.

Lead acid batteries, pumped hydro and in some cases, strengthening the grid, are competing solutions in stationary applications.

SMES *(Superconducting magnetic energy storage systems)*

SMES store energy in the magnetic field of a coil made from special alloys. By cooling the conducting wires down to - 269 °C the resistance of the material to electrical current disappears making it possible to conduct very high currents without electrical losses. When looking at the total system, however, it is clear that there is considerable energy requirement for refrigeration. Also, the current has to flow through non-superconducting components and solid-state switches, which cause resistive losses. Despite this, the overall efficiency in commercial applications in the MW range is very high.

The energy content of SMES in commercial use today is only approx. 1 kWh but the maximum power output is in the MW range and only limited by the rating of the power electronics. Due to the complexity of the cooling system, SMES cannot be

Superconducting magnetic energy storage

Energy and power density	*Negligible energy content (up to 1 kWh) but very high power output (3 MVA). Data on energy or power density are meaningless for PQ applications*
Cost/economy of scale	*Smallest unit available has higher power output than any competing technology except pumped hydro and large compressed air storage. The cost of auxiliary equipment and the low numbers sold prevent cost competitiveness for smaller power levels.*
Response time	*A few milliseconds because of the control circuits and power electronics*
Lifetime	*No limitations of number of cycles, easy monitoring*
Efficiency	*99 % are guaranteed for PQ applications, mostly caused by standby losses*
Operating constraints	*Large self contained unit (trailer) which ensures that all constraints are met*

built cost effectively for low power outputs. The lifetime of the superconducting coil and the number of charge and discharge cycles are very high and probably exceed all competing technologies although there is mechanical stress in the components leading to material fatigue. The response time of a SMES is limited to a few milliseconds by the speed with which the need to release energy is detected and the speed of the subsequent switching operations of the power electronics. In practice that is a few milliseconds.

SMES have proven their technical performance in a number of installations and are now a commercial product in applications where an extremely high power rating is required but the amount of energy needed is small, e.g. UPS applications and power quality applications in the utility grid. Key development areas are a reduction in cost, possibly achieved by the design of high temperature superconducting materials and low temperature power electronics. Costs are also a function of the number of units which will be sold in the future.

Superconducting magnetic energy storage systems compete with flywheels and batteries optimised for high rate applications in power quality applications. The main research target is meeting the costs of these competing energy storage technologies.

Flywheel

The energy is stored as kinetic energy in a rotating mass. The amount of energy stored increases with the square of the rotational speed, which is limited by the tensile strength of the material used. Lightweight materials allow higher speeds than heavy materials of the same tensile strength and therefore can store more energy. Rotors made from plastic re-enforced with high tensile strength fibres with up to 100 000 revolutions per minute (rpm) can store more energy per volume or weight than rotors made from high tensile steel with approx. 10 000 rpm (slow speed flywheel). The flywheel is coupled to a conventional electric generator, which generates electricity when braking the flywheel.

Flywheels are capable of delivering a very high power, limited only by the rating of the generators and power electronics. The biggest commercially available flywheel can supply 1.6 MW for 10 seconds. This corresponds to an energy content of approx. 4.5 kWh. The response time is limited to a few milliseconds for the same reasons as for a SMES. The number of charge and discharge cycles of a flywheel is limited only by the cooling efficiency of the electrical system and power electronics. Friction with the surrounding air is the main cause of loss. Slow flywheels with a speed of up to approx. 10 000-rpm are therefore contained in vessels filled with helium to reduce friction and high-speed flywheels are kept in a vacuum. The standby losses are considerable, but the in-out efficiency is very high. The lifetime depends on the bearings used. In low speed flywheels with up to 10 000 rpm the bearings are commercial products with many years of service life and easy monitoring of their operation. In high-speed flywheels non-contacting magnetic bearings are investigated.

A few hundred low speed flywheels are used in Europe commercially, e.g. for the uninterruptible power supply for Internet providers and special production machinery. High-speed flywheels are used in transport applications because of their much lower weight. They offer little advantage in stationary applications. Research focuses on improvements in the materials and manufacturing processes to achieve long-term mechanical stability, improved low loss bearings and reduction of costs. Also safety aspects and containment for mobile applications are a research issue.

Flywheels compete with SMES in applications requiring one MW or more for one or two seconds and they compete with batteries in applications where the backup time needs to be longer than some 15 seconds.

Flywheel

Energy and power density	*Energy density approx. 0.01kWh/kg; 1 - 10 kWh and 300 kW up to 2 MW; Power to energy ration is in the range of 1: 100*
Cost/economy of scale	*Smallest unit with approx. 100 kW output*
Lifetime	*No limitations of number of cycles, simple monitoring and long overall life time*
Efficiency	*Above 95 % but standby losses are 100 % per day*

Thermal storage (heat and cold)

Conventional heat and cold storage systems simply store excess energy in a large tank using the working medium at the temperature required for later use. Virtually every cooling and heating sys-

Energy content	*Energy content is determined by the size of the tank and the power by the size of the heat exchanger. Typical energy density is up to 0.1 kWh/kg.*
Cost/economy of scale	*Due to the diversity of applications, planning and installing large systems carry a very heavy cost penalty; small storages are standard products.*
Allowable investment cost	*The allowable investment cost is very low and competes with the direct fuel cost.*
Lifetime	*In excess of 10 years for most systems, thermal stability of advanced material is the limiting factor. For water systems > 20 years.*
Standby losses	*Important to be considered carefully (except for thermochemical systems). Careful insulation required.*

Heat and cold storage

tem has such storage tanks. Advanced heat or cold storage systems also use the latent heat required for a change of state, e.g. water to ice or crystallising salt solutions[2] , or they use heat of absorption and desorption. A much higher amount of energy can be stored per unit volume at the temperature at which the physicochemical processes take place. To be useful, this temperature must be above the temperature level of the application in the case of heat storage and below the temperature of the application in the case of cold storage. For very large storage systems, e.g. to store seasonal energy demand, geological structures such as underground aquifers or large sand filled basins are used. Heat pumps or absorption cooling systems make it possible to store thermal energy near the ambient temperature. Thermal losses can then be kept at a low level. The thermal power rating of a heat and cold storage is mainly determined by the size of the heat exchangers, but also pumps or other auxiliary components have an influence. The energy content is determined by the volume of the storage tank.

The temperature levels required in each application limit the use of heat and cold storage systems and the difficulty and cost of transporting heat, even for short distances. As a result, the amount of waste heat and cold at slightly the wrong temperature, or generated only a few hundred meters away from another application, is huge.

Research targets for heat and cold storage are the integration of different applications, and more cost efficient methods to increase or decrease the temperature level. Basic research is focussing on new storage materials for either latent heat or thermochemical storage systems.

Compressed gas storage

Compressed air tanks are widely used in industry to provide a constant source of compressed air with uniform pressure in the range of 8-10 bar. The compressed air is used for cleaning, moving parts and driving tools. For energy storage applications, air or gas has to be stored at a much higher pressure, e.g. in the range of up to 300 bar at ambient temperature, or at a pressure of approx. 30 bar at a temperature of up to 300-400 °C. The compressed air can then be used to drive a compressed air motor to generate electricity. There is one very large underground compressed air storage system in operation in Germany since 1980, providing 250 MW of peak shaving power for a large German utility.

There is renewed interest in compressed air storage for small wind/hybrid systems, where the energy to power ratio of batteries is unsuitable, either because the energy content is very high but the power requirement low (e.g. wind systems with long periods of low wind) or the energy throughput is very high compared to the energy content. These are unfavourable operating conditions for batteries. The energy to power ratio of compressed air storage can be chosen freely. The size of the tank, a conventional industrial product, determines the energy content and the size of the motor gen-

Compressed air

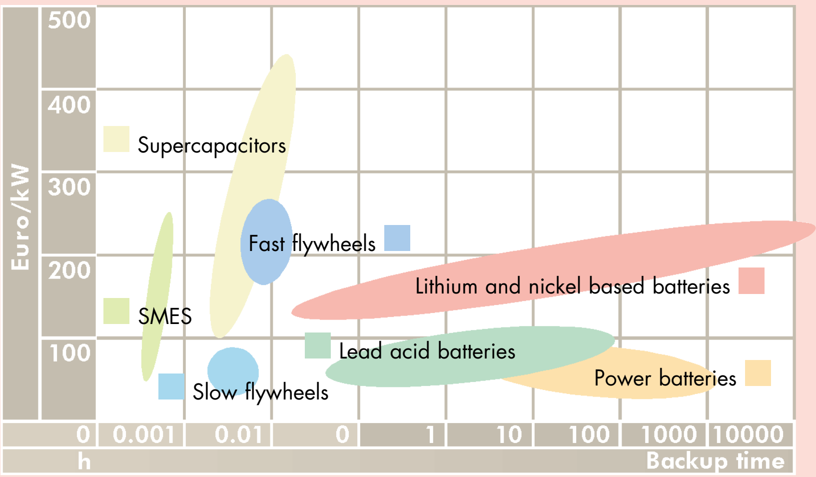
Energy and power density	*Energy and power density not relevant for large geological structures; for compressed gas tanks approx. 1 m^3 is required per kWh; the energy to power ration is approx. 1 : 10 and covers a range which is not covered by other storage technologies.*
Cost/economy of scale	*Smallest unit with approx. 20 kW*
Response time	*Approx. 0.1 second*
Lifetime	*No limitations of number of cycles, long overall life expectancy*
Efficiency	*75 %, with negligible standby losses*

erator the power output. Research needs to focus on the systems design, the control strategies and the temperature stability of the components.

Another new development of compressed air energy storage is the development of a storage system for a car with a compressed air motor. Prototypes with approx. 20 kWh energy storage for a range of up to 300 km and the performance of small light vehicles do exist.

Pumped hydro storage

Pumped hydro storage is a conventional energy storage technology in the electricity industry. Water in a basin at the top of a mountain is used to drive a generator in a reservoir at a lower level. When surplus energy is available, the water is pumped back up again. The power output and the cost efficiency of a pumped hydro storage depend on the difference in height. Installations with more than 1000 MW power output and a few hours of runtime exist and provide power for load levelling and reactive power. Due to the size of these systems, its conventional character and its dependence on geological formations, this energy storage technology is excluded form further discussion in this brochure.



Energy storage costs for different technologies (without power electronics to connect the storage device to the application, but including all auxiliary components necessary for safe and reliable operation of the storage device, e.g. cooling systems, temperature and voltage equalisation, etc.)

Cost of energy storage systems

The cost of energy storage systems differ greatly. Investment costs per kilowatt of maximum power output can be compared with some caution. Total systems costs including power electronics which is often needed, can be more than twice the value given in the diagram. The cost of energy (kWh) delivered cannot be compared because the cost depends too much on the use of the energy storage in different applications. For a typical PV system for a remote residential application, the cost per kWh delivered from a battery is in the range of 0.5 € per kWh and more.

The costs of SMES, supercapacitors and fast flywheels are influenced by low production quantities. In addition, supercapacitors are not yet sold commercially except for demonstration projects. Please note that the power levels of the energy storage technologies, which are shown here, are very different and often do not compete with one another.

[1] A directive from the European Commission is under preparation concerning the use of lead, cadmium and other substances. It would lead to severe restrictions in the use of NiCd batteries, if accepted by the Council of ministers.

[2] Water to steam is also a change of state, which stores and releases a large amount of energy. Steam tanks are a conventional energy storage system in power stations and industrial processes, which is not considered here.

Future challenges

Impact of electricity market liberalisation on energy storage

The directive of the European Commission to open the gas and electricity markets in Europe has had two effects: the commercial re-orientation of utilities and the push to optimise the electricity generation, transmission and distribution system technically. The key requirement that has to be met now is "no cross subsidies" between generation of electricity, operation of the transmission and distribution grid and sale of electricity. In the long term, the electricity market may be one of the largest markets for energy storage systems world-wide.

One of the major misconceptions about the electricity industry is that prices are low for every customer, reasonably uniform in different areas and fairly constant over time. Deregulated markets allow and force the determination of prices and help to establish a realistic cost basis for prices.

- The price of electricity fluctuates more than that of any other commodity. Peak prices in the United States have been as high as 7.5 € per kWh for a few hours in 1999.
- Ancillary services[3] , which are required by grid operators to maintain the stability of the grid, are now priced on the open market. Prices for some ancillary services are in the range of up to 0.5 € per kWh of delivered energy or approx. 10 000 to 15 000 € per MW standby power per year.
- The cost structure of the grid and extending or strengthening it, is becoming an issue. Each European country has to decide to what level they will allow price differentiation for the cost of the grid between densely populated industrial centres and sparsely populated areas and islands on the rim of Europe. Also the balance between the quality of supply guaranteed by the grid operator for all, and the power quality needed only by some industrial and commercial customers, has to be newly established.

It is these three points which have the biggest impact on the future of energy storage systems in grid connected electricity supply.

The real cost of the grid

Typical size: 0.1 – 1 MW and 0.1 to 1 MWh

The cost structure of distributed versus central electricity generation has changed due to deregulation. Building new large power stations and high voltage transmission lines to connect them is costly, requires long planning periods and may in the case of long transmission lines not even be permissible. As a result, distributed generation and/or large energy storage units may become cost effective alternatives. The plan to build a 70 MW/17 MWh battery energy storage system in Fairbanks, Alaska stems from the difficulty of building a new 400-kilometre long transmission line across unspoilt and protected countryside.

Energy storage systems for this application are likely to be very large. Small pumped hydro, conventional lead acid batteries and in future redox flow batteries and reversible fuel cells will be the systems of choice.

The cost of electricity on the low voltage grid and in remote areas with low average demand per square kilometre is determined by the cost of the grid. Regulated and in some cases state-owned utilities did not distribute the cost of the grid properly to the different customers. In today's economic environment, the question of uniform grid prices for industrial centres, urban and rural areas has to be raised again and a new answer found. It is clear that any subsidy to the cost of making, extending or strengthening a grid connection is the same as a subsidy for power generation in large central power stations. When costing a grid extension properly, PV modules with a small battery will probably provide electricity to very small loads in any large park or square in a European city cheaper than grid based electricity. Similarly, the installation of a wind hybrid system will be cheaper than extending the grid to remote islands in regions like Ireland, Scotland or Greece.

Wind turbine in the Central Massiv/Vergnet

The cost of strengthening and extending the grid for new housing developments or commercial centres can also be prohibitively high. Over the last two decades, a number of energy storage systems for this application have been investigated, but have never been commercialised in Europe. The new cost sensitivity of grid operators to the cost of long term investment into the grid is likely to rekindle interest.

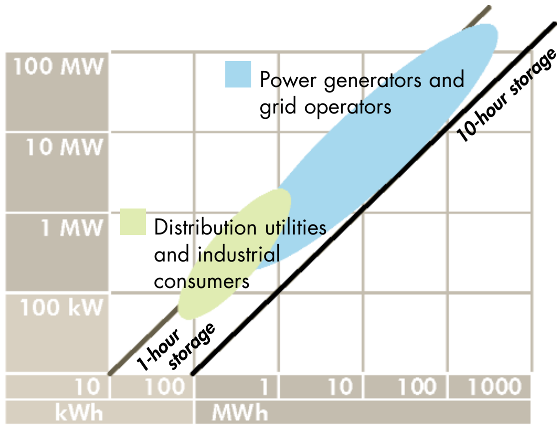
Energy storage systems on the low and medium voltage level will probably be quite small, e.g. up to e.g. 500kW/1000kWh and probably need to be modular in size. They will be charged and discharged daily and their installation must be easy, without any major regulatory requirement similar to the upgrading of a transformer in a substation.

Peak load shaving/load levelling

Electricity generation and consumption must balance at all times to maintain the supply of electricity. The generation capacity, therefore, has to exceed the maximum short-term demand during a year while still maintaining the additional back-up levels laid down in the grid code of the UCTE (Union for the Coordination of Transmission of Energy). If the overall generation capacity is insufficient even for a few minutes, loads will have to be switched off, the voltage reduced (brownouts) or rolling blackouts[4] carried out. Peak load generation is expensive because the capital cost of the power station and the cost of maintaining it in a standby mode have to be borne by very few hours of operation. Also, fuel efficiency is low.

In deregulated markets, there is no statutory requirement to maintain standby power for peak load generation. The financial incentives must be high enough to maintain a power station in standby mode for possibly only a few hours of operation per year.

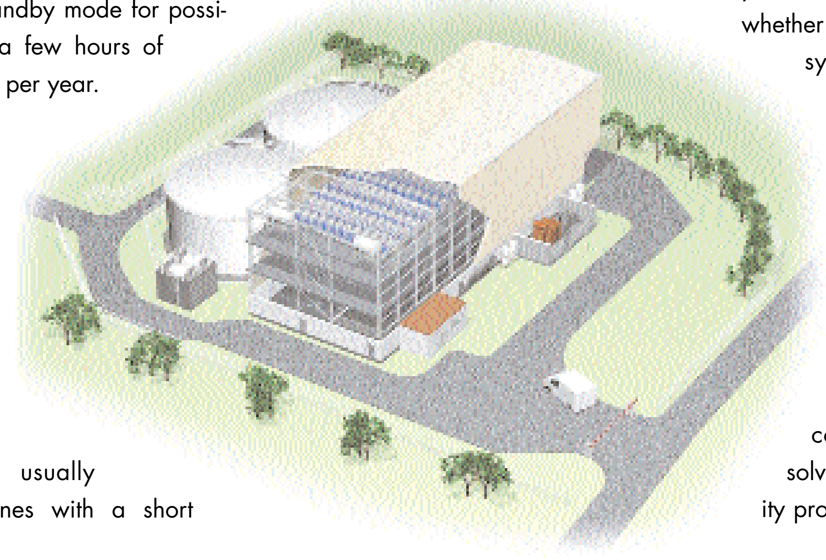
Today, peak load generation is carried out by special power stations, usually gas turbines with a short



Peak load shaving and load levelling

start-up time, or by altering the power output of power stations where this is easily possible, e.g. using hydro or pumped hydro power stations, the largest energy storage systems in use. Energy storage for peak load shaving simply tries to store electricity produced at times of low demand and low cost of generation and excess electricity from weather dependent sources such as wind power. It is released at times of high demand and high cost of generation or when there is no more generation capacity available. Energy storage systems for peak load shaving have to compete against the present over-capacity of power stations and power generators with short start-up times, such as gas turbines and gas or diesel motors with the appropriate emission controls. Their disadvantage is restricted number of start-ups and minimum run time. The technically best and most cost efficient solution could be the organisation of energy storage and gas turbines as a virtual power station.

Of all the energy storage systems described above only batteries and reversible fuel cells would be capable of storing enough energy. Energy storage systems depend on a consistently very high price differential between buying and selling electricity and it is unclear whether energy storage systems for this application will ever be capable of competing, unless they are linked to other issues such as relieving grid constraints and solving power quality problems.


Picture of Model of Regenesys 100 MWh redox plant

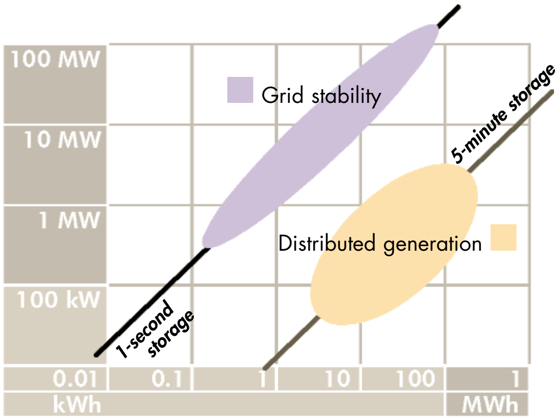
Courtesy of Innogy Technology Ventures Ltd.

Grid stability and distributed generation

Grid stability has two aspects. The frequency of the voltage supply needs to be maintained in very tight tolerances and the energy flow between the different areas of the grid has to be under control at all times.

The frequency of the electricity supply increases when generation exceeds demand and decreases when demand exceeds generation. In Europe, 3000 MW are available for this purpose within a few seconds. Between 1984 and 1992 the BEWAG battery energy storage system with ±8.5 MW power capability was used to increase or decrease generation. Other large battery energy storage systems (BESS) were used for this application as well. The largest, which is used today is located in Puerto Rico and has a power capability of 20 MW.

The impact of distributed generation on the stability of the electricity system is at the moment low, but will increase with the total power of all systems installed. Distributed electricity generation which supplies power to the grid stochastically leads to greater fluctuations of generation than existed previously. If distributed generation is not organised as a virtual power station, the fluctuations together



Grid stability and distributed generation

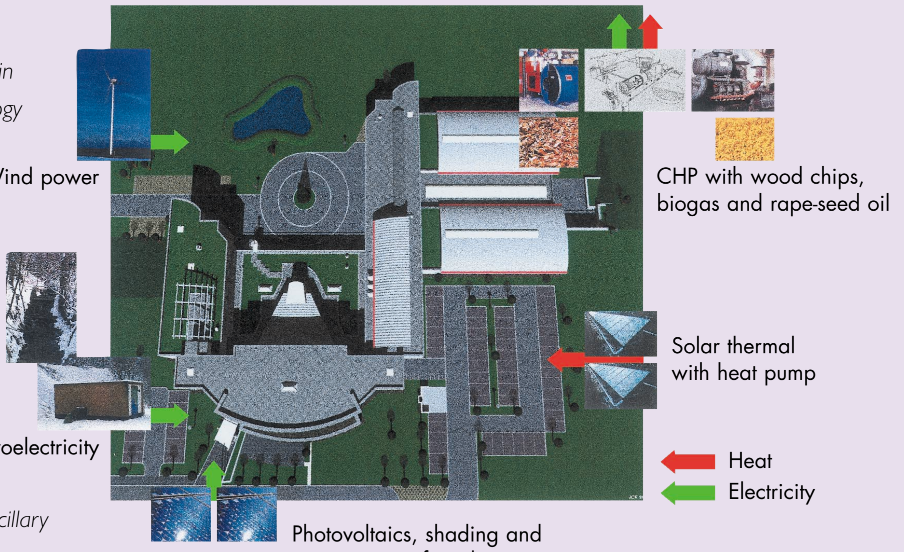
with the fluctuations of the loads have to be balanced by the grid operator and will lead to more reserve power and higher costs for grid stability. Large energy storage units could help in achieving grid stability.

Virtual power station

A conventional power station generates electricity in one location, using one type of generating technology and is owned by one legal entity. A virtual power station is a multi-fuel, multi-location and multi-ownership power station, which generates electricity in many locations in the grid. Both supply energy reliably at the predetermined time. In today's electricity market this means making a supply contract for each hour of the next day. Some power stations, both conventional and virtual stations, must also be capable of changing their power output quickly and sell this capability as ancillary services to grid operators.

For a grid operator or energy trader, purchasing energy or ancillary services from a virtual power station will be equivalent to purchasing from a conventional power station.

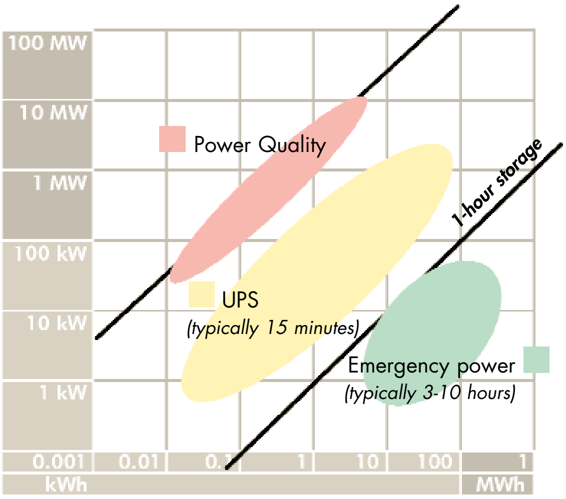
The concept of a virtual power station is not a new technology but a method of organising decentralised generation and storage in a way that maximises the value of the generated electricity to the utility. Virtual power stations using distributed and renewable energy generation and energy storage have the potential to replace conventional power stations step by step until a sustainable energy mix has developed.



Energypark at Clausthal, Germany

Security of supply, power quality and uninterruptible power supply

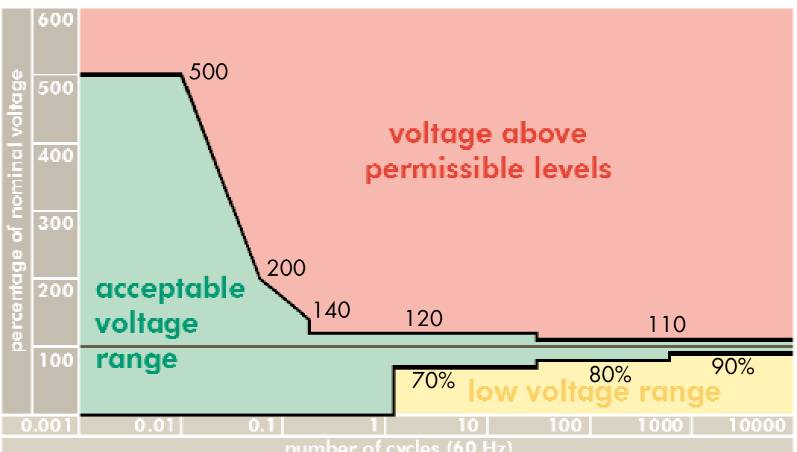
Different groups of consumers associate different quality levels with the term "Power Quality". Private consumers may be concerned with re-connection of the power supply before the heating in their house becomes a problem or the deep freeze thaws, others may think of quality of supply in terms of a few seconds power outage. Some industrial and commercial consumers, however, require that there is no power outages lasting more than a few milliseconds and voltage sags to some 70 % of the nominal voltage last no longer than 50 milliseconds. Examples for such industries are Internet service providers, manufacturers of semiconductor components and paper or fibre manufacturers.



Security of supply

The economic optimum between increasing power quality to all consumers by strengthening the grid and leaving those that benefit most by high power quality levels to pay for their own protection, is an elusive, ever changing goal. Power quality guaranteed by the grid needs to be redefined by the new regulatory authorities in Europe. Setting high technical standards and charging the cost to everyone alike is no longer acceptable. World-wide there are two grid operators who have installed SMES systems in their grid to improve the overall power quality to their customers. The most recent installation is in Wisconsin, where 6 SMES of 3 MW and 7.5 MVAr each have been installed to improve the power quality in a part of the grid, which extends far from generation plants.

CBEMA Curve to demonstrate impact of power quality problems on sensitive loads



The only technical solution for a UPS system is an energy storage with a fast response time, e.g. batteries, flywheels, supercapacitors and SMES. Depending on the long-term supply requirement, either a large battery system or motor generators have to be installed to cover long power outages.

UPS systems are a fast growing market segment of the electrical industry because loads become more and more sensitive, modern power electronics has a detrimental effect on the line voltage and the quality of service becomes a critical issue. The cost of not delivering a service in the financial industry and Internet services justifies very sophisticated and expensive solutions. A typical Internet service provider would be prepared to pay something like 1000 € per kW connected load to ensure a high level of power quality and uninterruptible power supply. The largest UPS systems for these customers have a power rating of more than 24 MW and larger installations are planned.

Energy storage in UPS systems is a commercially available technology.

Integration and storage for RES

Stand alone systems

Typical size: 0,01 to 20 kW; 1 to 100 kWh

The time of energy generation from renewable sources, be they electricity or heat, cannot be matched to the time of demand. Energy storage systems will therefore always be an integral part of any RES system. Even when fuel powered generation is used to cover periods of low RES generation, energy storage is required for economic reasons, as energy storage is cheaper than the frequent use of a motor driven genset. Also, the stability of the electricity system and quality of the voltage supplied will be considerably higher when an energy storage system is used.

The American "Computer and Business Equipment Manufacturers Association" (CBEMA) has developed a diagram to show which kinds of power disturbances should not lead to a failure or malfunctioning of equipment. This is often used as a guideline when discussing possible impacts of power quality problems on loads.

The technical and economic optimum concerning the size of an electricity storage system needs to be defined in each case individually. The systems of choice will consist of storage technologies with a fast response time and a reasonable energy density and power output. Conventional, commercially available lead acid batteries have a very high energy efficiency and all other technologies have to compete with this. Advanced batteries with lower weight and higher power outputs in relation to the energy density offer no advantage over lead acid batteries, indeed they may even be of a disadvantage if their overall energy efficiency is lower. Research areas of particular interest are not so much the battery technology itself, which has reached a high level of maturity but more precise estimates of the lifetime and the definition of good operating conditions. This could result in a much longer lifetime. Batteries are the most expensive item in RES system when the total systems lifetime costs are considered and there are big variations in battery lifetime in different installations.

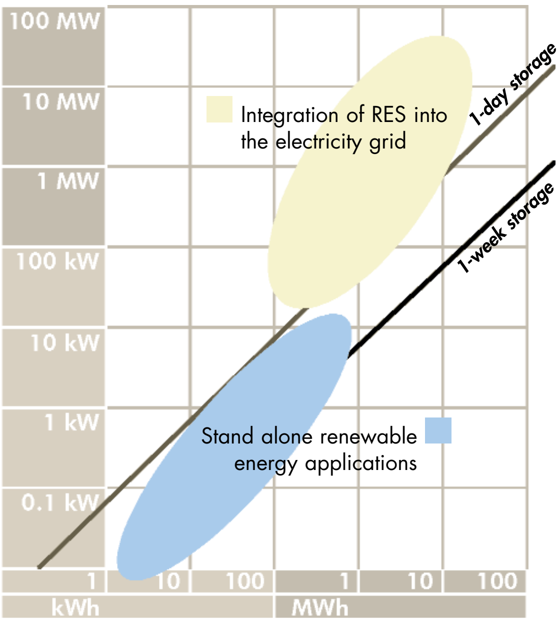
Excess electricity can always be stored in the form of heat cheaply and for a long time. However, the value of heat energy is much lower than the value of electricity.

In solar thermal systems for heating and cooling there is also a necessity to store energy because the heat generation depends on the solar radiation for energy production. The technical and economic optimum depends on the details of the installation and it is likely that the storage size will have to cover in the range of 5 - 10 days autonomy, similar to electricity storage. The basic storage technology for heat and cold is commercially available and questions of the cost of planning, optimisation and cost of market penetration are perhaps the most important to achieve market penetration.

PV installation in Spain.

Courtesy of Trama TechnoAmbiental (TTA), Spain.

Electricity storage for renewable energy



Integration

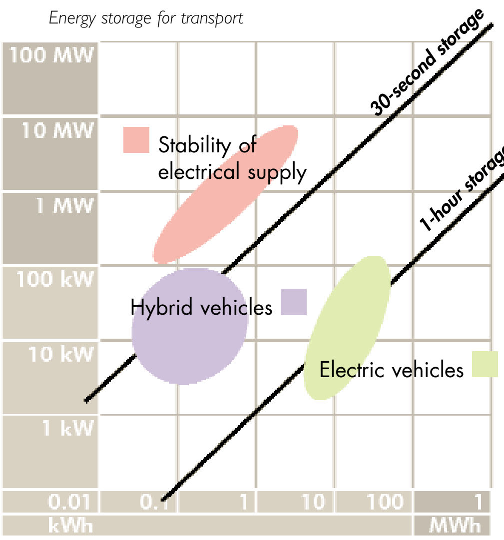
The integration of renewable energy sources into the existing energy system does not usually require energy storage systems. One of the more important exceptions is the power output of wind turbines which changes quickly with large amplitude. Original fears that this changing power output would lead to power quality problems, e.g. flicker (voltage variations with a frequency around 9 Hz) etc. have not materialised because the conditions for connecting wind turbines have been handled with prudence and strict technical requirements have been laid down. However, in areas of Germany and Denmark, where most of Europe's wind power is installed, grid operators face changes in the power output in the range of approx. 100 MW from all wind generators together. The installed power already exceeds the minimum energy demand during times of low demand. The grid operator has to keep base load power stations in a standby mode for reasons of grid stability. This obviously is costly. The only long-term solution to this problem apart from limiting wind power is to store energy either in large energy storage systems or dump it, for instance in hot water tanks. For this reason it is likely that wind energy will have to be stored in large energy storage systems in the range of many tens of MWh if the full potential of wind energy in these regions will be used.

Energy storage for transport

The fuel consumption and emissions of the transport sector continue to increase whereas the energy use and emissions in other sectors diminish. It is therefore necessary to develop solutions, which will combine the wish for and the necessity of mobility with a more sustainable use of energy. This applies to all forms of transport, not only cars and trucks. Batteries for transport applications including starter batteries for cars are already one of the largest markets for energy storage systems world-wide. In the medium term the success of hybrid vehicles could lead to a considerable increase in the size of the market and help to reduce emissions from the transport sector significantly.

Energy storage in grid connected public transport systems, e.g. railway, underground and tram, has been an issue for some time. The braking energy is converted into electrical energy by modern motors and fed back into the grid. However, the electrical supply system of the public transport system is only connected to the electricity supply grid at a few points. During braking at a remote station or a downhill section of the tracks, the surplus energy leads to a voltage increase and no longer allows feeding electricity back into the grid. The same applies during acceleration. In subway systems operating at 750 V DC voltage fluctuations of more than 25 % have been measured. Maintaining the voltage stability would reduce losses and increase the efficiency and lifetime of all the components.

Energy storage for transport



Energy storage and many more connections to the electricity grid are the two solutions available.

An energy storage solution based on a flywheel has already been installed in Hannover, Germany, at a remote extension of the tram system. Flywheels and in future supercapacitors are probably the system of choice for this application as their power output is high and their energy content adequate.

All cars, buses and trucks with internal combustion engines have batteries to start the engine and to stabilise the electrical system of the vehicle during operation. These batteries have already reached a high technical standard. The overall efficiency of internal combustion engines is low because the engines are usually operated outside their optimum point of efficiency and idle when the vehicle is stationary. All car manufacturers work intensively on hybrid systems, which use batteries or supercapacitors to store braking energy and supply power to the motor during acceleration. The internal combustion engine can then work at its optimum point most of the time. First results with such hybrid vehicles, e.g. the Toyota Prius show that the fuel consumption for equivalent driving characteristics and cars is reduced by up to 20 %. The batteries used in this application have to have a high lifetime, a high energy throughput and power density and must be capable of many partial cycles at a medium state of charge. Low weight and a long life expectancy which can be guaranteed and means predictable life cycle costs are the major considerations. Nickel-metal-hydride, lithium ion and lithium-polymer batteries and supercapacitors are the main contenders. Advanced lead acid batteries would have the advantage of allowing to install more power and energy at a lower cost and having the necessary production and recycling capacity in place. Lifetime, however, is a problem. Lithium-ion, lithium-polymer and NiMH batteries in contrast are much lighter, but also much more expensive. It is possible that different market segments requiring different storage technologies will exist.

For larger systems, e.g. trucks, buses and diesel engine operated light railways, high speed flywheels with low weight have been used on an commercial basis and receive wide spread interest at the moment. It is expected that up to 25% of the total energy consumption can be saved in 'stop and go' applications

Developing the drive for a hybrid vehicle leads to major system changes. Instead of a starter motor and a generator only one motor/generator will be required. Excluding the battery, the overall cost of the drive system will not change significantly.

Fully electric vehicles without a combustion engine have been a goal for many years. Their future as an alternative drive is getting clearer and commercial success is now considered to be very likely. The California mandate to have zero emission vehicles on the road by the year 2003 provides a powerful driving force for development. Some major car manufacturers consider fuel cells as the ideal solution and have spent more than 1 billion euro for the development of fuel cell operated cars. The technical risk is substantially reduced as the performance goals have largely been achieved, but risks remain concerning the cost to achieve a high volume and high quality production of certain components, in particular the membrane. Also, the infrastructure for a vehicle fleet operating with fuel cells cannot be built up quickly and cheaply. An alternative to fuel cells are redox flow batteries. In both cases, the fuelling process is identical to filling up with petrol. A liquid, in this case a suspension of charged active material, is filled into a tank and within minutes, the car is 'recharged' and ready to go.

It is by no means clear, whether cars with a fuel cell or a redox flow battery can be operated without a separate energy storage system, as their response time to acceleration may not be adequate for the requirements of traffic. Any energy storage systems for this application would have identical usage patterns compared to hybrid vehicles and would be able to store the braking energy. However, the energy content could be lower than in hybrid systems.

Battery operated vehicles will probably remain a niche market although they would be capable of covering most daily journeys. Both the range and the time that it takes to recharge batteries have developed very satisfactorily. Fast charging to extend the range by up to 100 km within 5-10 minutes is now a technical feasibility and commercially available electric vehicles reach routinely a range of approx. 150 kilometres. The Japanese company Panasonic has recently demonstrated a daily driving distance of 1400 kilometres using lead acid batteries. Rather than technical problems and constraints it is more a matter of consumer awareness and waiting for yet better solutions, which will prevent better market penetration.

Energy storage for small portable applications

Typical size: 1 to 100 W; up to 50 Wh

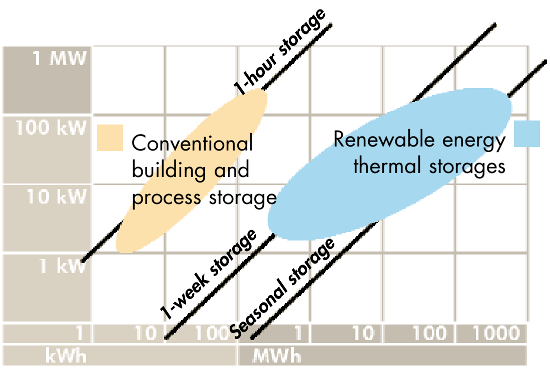
Batteries, the only energy storage system in use for portable applications today are a very large and fast growing market for energy storage systems with many different products. User expectations and applications require an increasing number of features and longer run times of portable electronic devices. Currently high-energy batteries power these devices. Both the maximum power output and the cost are of secondary consideration in most applications. User concern is focused on maximum energy at low weight and a good monitoring system allowing plenty of time to wind down the application and to replace or recharge the battery. Lithium-ion batteries are the system of choice without any serious contender on the horizon to substitute them. There is a wide range of developments in materials and types to improve application specific properties of the battery. For applications requiring high power levels NiCd batteries are still widely used. However, their use will be restricted if the planned EU directive on the use of cadmium in batteries and other products will be adopted by the European Council. Alternatives in this case may be improved NiMH batteries or supercapacitors in the case of short high current pulses.

There are commercial solutions available for all portable applications - however major improvements can still be made particularly with lithium-ion, which are still a new system and lithium-polymer batteries. Possibly, the advances made for lithium-ion batteries for hybrid vehicles and their expected power density may make it possible to use lithium-ion and lithium-polymer in the future for power tools and other high power applications. UMTS applications require a particularly large energy storage system and there do not seem to be adequate solutions on the market yet.

Small fuel cells are a competing technology for small portable power applications. They may have the potential to substitute lithium-ion batteries in many applications. Their advantage would be a major increase in run time because only a cartridge has to be replaced and this could be done during operation.

Thermal storage

It is generally accepted that efficient use of energy to provide heat and cold for industrial processes and space heating has an enormous potential for the reduction of greenhouse gases. However, there are very high barriers to any solution. Technically, it must be possible to use proposed solutions for a wide range of different buildings and user requirements. Economically, they have to provide a reasonable pay back time and, from a business point of view, planning, selling and installing them must be attractive to all the professions involved in constructing and managing buildings.



Thermal storage

At present, there is only limited interest in this field and there is a lack of well-thought proposals to generate or upgrade the knowledge base concerning materials and components. The challenges of the EU RTD target action in this important field are therefore mostly non-technical: renew interest and help focus industry and research organisations on this topic. Nevertheless several activities on new technologies related to latent heat and thermo-chemical storage are ongoing. The major goal regarding latent heat materials is to provide stable encapsulation technologies (such as e.g. micro-encapsulation) for well-known phase change materials such as paraffins.

Another technical issue is the integration of thermal storage systems into a larger system with many users. Most thermal applications require energy at a certain temperature to work efficiently. Even small deviations often make it impossible to use thermal energy without altering the temperature levels. Reducing the temperature is often cost effective, however, increasing the temperature is usually not and large amounts of waste heat are discharged into the air, rivers and the sea or the sewage system without further use. Solutions, which would allow the use of low level heat and to transport heat for short distances would therefore make a major impact on the efficient use of energy. Technical solutions as well as planning tools will have to be developed further for this. This is equally important for the use of waste heat generated in conventional heating systems.

Recycling and waste disposal

Batteries, supercapacitors and materials used in advanced thermal storage systems can pose environmental risks during manufacturing, use and recycling. They are special waste and should not be disposed of with normal waste. Certain materials, in particular mercury, cadmium and lead, pose much bigger threats than other metals and their waste stream has to be controlled much more tightly than that of other materials. As a result, the use of mercury has already been banned in virtually all industrial products and the use of cadmium will probably face restrictions, too. The use of lead acid batteries will be linked in future with recycling rates in the range of up to 95% depending on the type of battery. For small portable batteries and consumer products as well as UPS applications these requirements will have to be kept in mind for all future developments. Both lead acid and NiCd batteries used in industrial applications already have a very high recycling rate today.

The recycling processes have proven their technical capability and are in some cases even cost effective because of the value of the materials recovered.

New energy storage technologies will always have to be developed and introduced in such a way that environmental hazards are reduced during use, enable comprehensive collection schemes and safe recycling of the materials.

[3] *Ancillary services are the name given to the capability to increase or decrease power within a very short time. Grid operators need to call upon such services to make sure that power generation and consumption in their region of responsibility is always balanced. Spinning reserve for frequency control, for instance, requires in Europe 3000 MW of power, which must be available within 15 seconds. In addition, large grid operators need in the range of 500 to 1000 MW of power, which needs to be available within a few minutes to balance the power flow within their grid and to and from adjacent grids.*

[4] *Rolling blackout: Small areas of the grid are disconnected for a few minutes to reduce the energy consumption. Before this causes lasting damage or inconvenience, the power is switched back on again and other areas of the grid disconnected. This has happened in California in the winter of 2000/2001!*

An overview of EU energy storage RTD in the Fourth and Fifth Framework Programmes

The overall goal of the Energy RTD programme is to contribute to the development of sustainable energy systems and high quality, low cost energy services for Europe. In pursuing this goal, the aim is to support RTD on technologies that yield:

- substantial reductions in energy consumption and associated greenhouse gas (GHG) emissions and harmful pollutant emissions over the whole energy chain;
- increased security of supply of energy, through diversification of primary energy sources;
- cost-effective integration of Renewable Energy Sources (RES);
- improved competitiveness of EU industry.

Cost-effective, efficient energy storage is clearly a key enabling technology for achieving all of these objectives. The EU has, through successive Framework Programmes (FP2 to FP5), funded RTD on technologies for energy storage for stationary and transport applications. In the JOULE specific programmes in FP2, FP3, and FP4, this included RTD on materials, processes and components for energy storage, as well as energy storage systems integration. Activities such as testing, benchmarking and prototype demonstration of energy storage systems have also received EU support. This approach is continued in FP5 in the Energy part of the Programme "Environment, energy and sustainable development" (EESD).

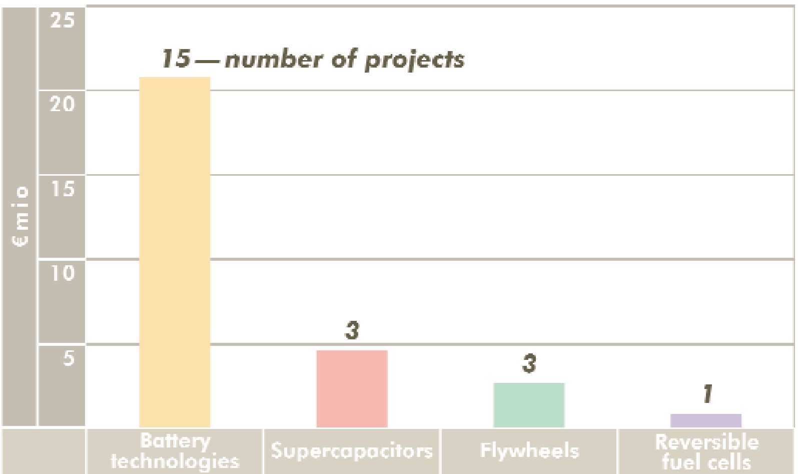
Selected projects are funded in response to open calls for proposals. The above strategic programme goals are realised through calls for proposals for RTD and Demonstration in the following principal domains of energy storage technologies:

- RTD on critical technologies to achieve improved performance, durability and cost reductions; this includes active materials development, materials processing, packaging, etc. for components such as electrochemical cells, modules and complete batteries, super-capacitors, fuel cell stacks, flywheels;
- definition of system specifications, systems integration, systems simulation, energy management and control systems, e.g. for single and hybrid RES and for battery electric and hybrid electric vehicle energy storage;
- demonstration and test of prototype energy storage and converter modules and systems, for hybrid battery and fuel cell systems for stationary and transport applications;
- supporting RTD actions to benchmark technologies and promote cost-effective implementation. This includes definition of standard test procedures for stationary and transport applications, simulation, energy and environmental impact assessment (for the whole life cycle of components from manufacture through operation to recycling and disposal); bench testing (e.g. battery and supercapacitor bench tests) and safety assessment.

Energy storage projects funded under the JOULE III Programme (FP4: 1994 - 1998)

In total, JOULE III funding (only Directorate-General for Research) for RTD on energy storage in FP4 amounted to some 29 M€ (million euro), of which 21 M€ were allocated to 12 projects for research on advanced batteries (mainly lithium ion and lithium polymer). Three supercapacitor and three flywheel projects were also supported (totalling 4.6 M€ and 2.7 M€ respectively). The distribution of funding is shown in the bar chart on the next page.

The RTD on advanced battery systems for pure electric vehicles was aimed at achieving ambitious performance targets (comparable to US Advanced Battery Consortium targets). RTD effort included active materials development, packaging, battery thermal and electrical management systems, safety and economic assessment. Both lithium ion and lithium polymer batteries have been developed. The aim was to develop batteries capable of giving a vehicle range of 200 km.



EC Energy Storage Funding in FP4 (EUR)

A notable development has been the SAFT lithium-ion battery with system energy density of 100 Wh/kg, (around three times that of conventional lead-acid) developed with JOULE support in FP3 and FP4. This battery is now to be tested in both FIAT and Daimler-Chrysler electric cars in the project "Car Integration". It will also be tested in a driveline for an innovative three-wheel, Piaggio vehicle in the project ZED (Zero Emission Driveline). The lithium polymer technology is being exploited in batteries for laptop computers and will also be developed as high power batteries for hybrid vehicles. Other systems such as electrically rechargeable air/metal hydride and zinc/air systems have received support for stationary and traction applications.

Supercapacitors are being developed as power buffers for electric vehicles and UPS, based on conventional carbon and electrically conducting polymer materials, with ambitious energy and power density targets (up to 2kW/kg and 7Wh/kg). RTD includes materials development and optimising the energy management in electric drivelines. At present, supercapacitors are still too costly, though this should be offset by their potential to extend the life of batteries which are used in parallel. The support for flywheel technologies has included a prototype high speed, high power system for automotive application, a 1 MW storage system for RES, and one for small, stand-alone RES applications.

Supporting RTD activities include developing test procedures for hybrid, battery-electric, and fuel cell electric vehicles and benchmarking (comparing battery performance and lifetime) of batteries - including both those developed with JOULE support and US and Japanese competitors. The project MATADOR developed test procedures for hybrid vehicles and a manual for information guidance to assist planners /fleet managers in setting up a fleet of electric or hybrid vehicles.

In the stationary domain, a high performance power conditioner is being developed to provide optimised control of charge and discharge currents in RES applications. The aim is to improve the lifetime of lead acid batteries through a better understanding of actual operating conditions and the introduction of active control of charge/discharge to avoid conditions associated with degradation mechanisms. The effectiveness of a mobile battery regeneration unit is also being tested.

Recent developments in the Energy Programme (FP5: 1998-2002)

Following four calls for proposals to date, under the Energy programme in FP5, a total of 17,2 M€ has been allocated to 13 projects in the field of energy storage. This includes 15 M€ funding for 12 projects on electrochemical battery or battery related technologies. One project is working on the carbon nano-structures for hydrogen storage, with the EC funding of some 2.2 M€.

The funding for battery projects include 6.4 M€ allocated to 4 projects on development of active materials and processes for lithium batteries for stationary, transport and small portable applications. Recently, there has been greater focus on developing high power batteries for hybrid electric vehicles – a possible technology for meeting the challenging voluntary EU fleet average target of 140g/km CO_2 emissions by 2008. Other recent projects include improved processes for electrodes for high power nickel metal hydride batteries, a nickel/zinc battery for an electric scooter, a high power lead acid battery for UPS, and the continuation of the battery bench test programme. The later will place greater emphasis on batteries and test procedures for hybrid vehicles and 42-volt systems.

The lead acid batteries are addressed in three other projects, which cover development of new materials and modular design, new charging/discharging schemes and accelerated testing procedures and standards. The battery systems are aimed to be used mainly in RES applications such as PV and wind installations. Some 2.8 M€ is allocated to these projects.

The way ahead: A target action on energy storage

Cost-effective energy storage will be a key enabling technology for the stable operation of a liberalised energy market, for competitive energy pricing and for the introduction of RES. In recognition of this, the Commission has launched a target action on energy storage under the Energy programme. The target action is intended to provide a strategic focus on the medium to long term needs for RTD on energy storage, that is on technologies that have potential for commercial exploitation within a five-year time scale from project commencement. The aim is that projects supported under the target action should together have a significant impact at EU scale. This means meeting the medium and long-term objectives of EU energy policy, in particular GHG reduction, whilst at the same time improving the security of energy supply, through diversification and introduction of sustainable primary sources. The table in annex identifies some of the priority RTD areas.

The European Research Area

The target action will be enhanced through the promotion of the European Research Area (ERA) – a new research policy initiative, which, inter alia, helps to maximise the effectiveness of EU funded RTD actions. The aim is to achieve better co-operation and collaboration between relevant EU Member States' national programmes, and to foster links with international programmes. The target action on energy storage will therefore stimulate actions that are appropriate for EU level co-operation, such as creation of networks and virtual centres of excellence based on complementary competencies. Thematic areas around which such initiatives could be based include:

- mapping technological competencies in energy storage technologies; identification of technological bottlenecks and opportunities for creating virtual centres of excellence founded on key technologies, e.g. fundamental RTD on electrochemistry, low cost materials and processes, heat and cold storage and their transport;
- development of standardised test procedures for performance, lifetime (including accelerated ageing and calendar life) and safety of components and complete energy storage systems for transport and RES applications, enabling benchmarking and comparative assessment;
- life cycle analysis and environmental impact assessment according to EU environment and energy policy criteria;
- pre-normative RTD relating to standards, regulation, safety and certification issues for energy storage technologies (in particular, this may be significant for certain battery technologies and flywheel energy storage);
- "open systems" approach for hybrid systems integration (e.g. hybrid vehicles and hybrid RES), energy management and control systems communications, standardised interfaces for components; this may relate to integration at component level for stand-alone systems, or perhaps the interface at a higher level between energy systems and a centralised supervisory system, e.g. grid connection for RES or traffic management system. Networks in this area would need to be co-ordinated with initiatives in other target actions, e.g. Integration, Clean Urban Transport, etc.
- socio-economic RTD, including cost-effectiveness analysis to compare adequacy of alternative technologies to achieve EU policy objectives, analysis of financial and human resource requirements for commercialisation, analysis of industrial structures and their future capacity needs and suitability for exploitation of new technologies.

The aim is to build appropriate multi-disciplinary networks focused on specific themes. That will on the one hand support technology acquisition, and on the other hand provide the political justification and understanding of what is needed for commercial exploitation and customer acceptance. Such networks will therefore require participation of all relevant stakeholders.

The above themes are suggested for illustration, but it is not intended to be prescriptive. Other themes may be proposed. Instruments available to the target action in FP5 for supporting such collaboration include Thematic Networks, Concerted Actions and Accompanying Measures. Actual RTD is supported through shared-cost actions, which may be for research, demonstration or combined projects. The target action will therefore bring together the instruments for collaboration with the RTD projects, thereby facilitating a more coherent, strategic approach, with a broader scope than EU funded activities alone.

Terms and abbreviations used

AGM: *Absorptive Glass Matting*
BESS: *Battery Energy Storage System*
CHP: *Combined Heat and Power*
NiCd: *Nickel cadmium batteries*
NiMH: *Nickel metal hydride batteries*
RES: *Renewable Energy Sources*
rpm: *revolutions per minute*
RTD: *Research, technological development and demonstration*
SMES: *Superconducting Magnetic Energy Storage systems*
UCTE: *Union for the Co-ordination and Transmission of Electricity*
UPS: *Uninterruptible Power Supply systems*
UMTS: *Universal Mobile Telecommunications System*

EC energy storage research priorities

Storage technology	Application problems and research areas	Targets (to be achieved in field installations)
Batteries – general requirements	Lifetime and monitoring; improvement of operating strategies	Achieving laboratory performances also in field installations
Conventional lead acid batteries (only for RES and utility type storage)	Low state of charge and sulphation; charging efficiency in RES applications	10 years and energy throughput equivalent to 1500 times the nominal capacity [5]
Gel and AGM lead acid batteries using special alloys and designs	Low state of charge and sulphation; charging efficiency; improvements in alloys, materials and design; increasing energy density and lifetime	For stationary applications (energy batteries): 10 years and energy throughput equivalent to 800 times the nominal capacity For hybrid (power batteries) and electric vehicle (energy batteries) applications: fulfilling the ALABC criteria on cost, lifetime and performance
NiMH batteries Lithium-ion and lithium polymer batteries	Power density is limiting factor in some applications, energy density to be improved further; high cost; improvements in materials and material processing; intrinsically safe battery chemistries (Lithium only); cost reductions including safety electronics	For stationary applications (energy batteries): exceeding lead acid batteries in lifetime cost for special environments and applications For vehicle applications (power batteries): comparable to lead acid batteries in cost and performance taking its lower weight into account For mobile applications: higher energy and power density and longer lifetime
Supercapacitors	Cost; high internal resistance and therefore limited energy throughput; high standby losses; improvement in materials and manufacturing processes; cost reductions including monitoring electronics necessary for all applications	Exceeding competing technologies (power batteries, SMES and flywheels) in their relative fields in terms of overall system performance and total systems cost
Reversible fuel cells and redox flow batteries	Field demonstration of system for an application is still necessary; low in-out efficiency; improvement of membranes as regards properties, efficiencies and cost; manufacturing processes for sealing stacks; safety issues; development of infrastructure	Exceeding cost and performance characteristics of energy batteries as competing storage technology; for large scale applications the cost of on-site generation and grid extension have to be undercut
SMES (limited to high power applications)	Cost; improvements in materials, in particular use of "high temperature" superconductors	Exceeding the cost and performance standards of slow speed flywheels as main competing technology in the range of 1 MW power
Flywheels (fast flywheels only)	Long term stability of rotor; safety containment; cost; standby losses; improvements of materials and manufacturing processes for rotors; low loss bearings; cost reduction	For stationary applications: exceeding the cost and performance standards of slow speed flywheels For hybrid vehicle applications (trucks, light railways, etc.): exceeding the cost and performance characteristics of power batteries and supercapacitors
Thermal storage (heat and cold)	Cost of storage and transport of thermal energy; low cost modification of temperature level from storage temperature to temperature of application Cost reduction of heat pumps and heat transformers; systems development and planning tools; encapsulation technologies for latent heat storage; new thermochemical concepts	Cost of storing and recovering heat or cold must be smaller than providing heat or cold from primary energy
Compressed air storage	Viability of concept for RES and transport still has to be demonstrated; control strategies; lifetimes of components	Meeting and exceeding the cost and performance characteristics of competing technologies (energy batteries, reversible fuel cells and redox flow batteries)

[5] Under laboratory conditions this is always achieved. There are a few commercial applications where these values have been reached or even exceeded.

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Energy storage is a key element in achieving the EU policy goals of sustainability, air quality and cost-effective, competitive goods and services. For both stationary and transport applications, energy storage is of growing importance as it enables the smoothing of transient and/or intermittent loads, and downsizing of base load capacity with substantial potential for energy and cost savings.

Reliable and affordable electricity storage is a prerequisite for using renewable energy in remote locations, the integration into the electricity system and the development of a future decentralised energy supply system. Energy storage therefore has a pivotal role in the effort to combine a future, sustainable energy supply with the standard of technical services and products that we are accustomed to and need.

This brochure gives a brief overview of different types of energy storage and their use in various applications, including transport, renewable energy sources and transmission grid stability. There is also a brief review of Community RTD on energy storage.

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