Advanced Batteries as Energy Storage Systems
An essential technology for a Sustainable Energy Policy

SUMMARY & CONCLUSIONS

In the context of the European Energy Policy, there is a need for a strong support to renewable energy utility grid integration as well as for the use of intermittent energy storage systems **such as batteries** for "non-grid integrated" renewable energy production.

The impact of batteries on large scale fleet of Hybrid Electric Vehicles should also be considered as a complementary transportation technology for increased mobility with reduced dependence on non-renewable fossil energy.

Specific areas for additional research in the advanced battery field includes

In the stationary sector,

- the relative costs and benefits of different energy storage technologies,
- the potential for intermediate energy storage systems to mitigate wind power generation,
- and to assist the development of delocalized photovoltaic energy production.
- the need for cost competitive battery assisted load leveling of large power plants.

In the mobility sector,

- the improvement of candidates batteries technologies for hybrid electric vehicles,
- the development of cost competitive batteries for Hybrid Diesel Electric Vehicles,
- the impact of the fossil energy price on the incremental cost of using batteries for small and large HEV applications,
- the use of combined technologies such as traffic tele-regulation with hybrid propulsion.

On a more general basis

- the impact of the price of raw materials on the advanced battery cost,
- the development of new electrode materials and battery design,
- the impact of the development of new battery technologies based on thin film- or nano-technologies.

RECHARGE.

May 2008

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CONTENT.

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1. Introduction

There is a need for developing efficient and cost affordable energy storage options to cope with imbalances between demand and capacity, and variable prices in energy markets. An uninterrupted availability of clean energy products at the marketplace at a price that is affordable for both private and industrial consumers is critical in our "energy-based" society.

Energy Storage Systems are engineered systems to hold adequate amounts of mechanical, thermal, physical, electro-chemical or chemical energy for prolonged periods of time. Energy Storage Systems should be quickly chargeable and should have a large energy storage capacity, but at the same time they should also have high rates of energy delivery and high energy conversion efficiency.

2. Electricity Storage

Apart from the use of secondary batteries, electricity storage is predominantly carried out in form of mechanical energy. Large-scale electricity storage systems are suitable to balance differences between power supply and demand. Power must be deliverable in short (minutes) or long (hours) time intervals and sometimes days or months to balance seasonal changes. Large-scale electricity storage systems supply peak-load power using previously stored base-load electricity, or make it possible to integrate renewable energy technologies characterized by intermittent resource availability (e.g. solar and wind). In addition, large-scale electricity storage systems can supply regulating power for proper transmission and distribution of electricity through the grid. Finally, experience has been gained for more than ten years in the use of hybrid energy storage and supply in the transportation sector.

The following storage technologies are often used for large-scale electricity storage systems:

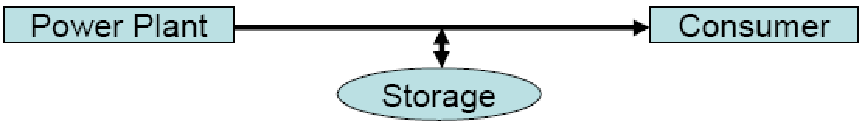
- Pumped storage hydropower reservoirs
- Compressed air energy storage
- Large-scale secondary batteries and large fuel cells

Other, smaller scale applications of electricity storage provide power for mobile systems or upgrade power quality and reliability (including emergency supply). Electricity storage for these applications has varied capacity and time-scale characteristics. The following technologies are available:

- Batteries and fuel cells
- Super-conducting (magnetic) energy storage (SMES)
- Super-capacitors and ultra-capacitors
- Flywheel energy storage

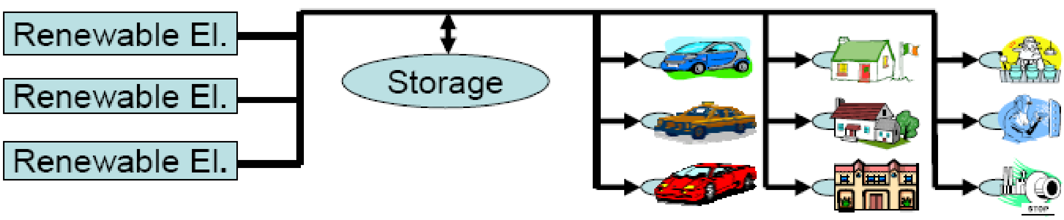
Need for Dispersed Electricity Storage

In addition to large centralized two-way storage facilities, there is a need for …



NB: Storage = Hydropower

…"Decentralized" storage in many smaller Energy storage units connected to applications



Intermediate Electrical Energy Storage

Energy economy relies on efficiency and service life of intermediate storage systems (cycle efficiency, initial and operational costs, etc…)

Examples	Service Cycles	Efficiency Energy Conversion
Hydrogen	1,000	45%
Lead acid batteries	1,000	70%
Nickel-Cadmium batteries	>1,000	85%
Nickel-Metal Hydride	>1,000	85%
Sodium-Sulfur batteries	>1,000	80%
Compressed air	>100,000	5%
Hydro	>100,000	75%
Flywheels	>100,000	85%
Li ion "batteries"	>10,000	90%
Super capacitors	>100,000	95%

3. The role of Batteries.

Batteries are commonly used in mobile applications and systems where reliability with low maintenance is important. They release power instantaneously. They operate with very low emissions to air, water and soil. Batteries can also deliver power over prolonged period as compared to some other technologies. Batteries are suitable for improving power quality, integration into emergency backup systems, and peaking in mobile systems when short-time power demand is high. Flexibility in power delivery is one of the major advantages for using batteries as intermittent energy storage media.

Still in the testing phase, fuel cells may also be suitable for providing power over long periods of time, and for continuous operation at various power ranges.

Capacitor and flywheel energy storage have rather different discharge characteristics, releasing high power in a short time frame.

Both the capital costs of power and energy are important in evaluating the economics of storage systems. Typically the capital cost component of power is related to the output capacity, while the cost of energy deals with the storage capacity of the system (Table 1). The various energy densities of storage technologies are presented in Table 2.

Table 1: Estimates of power capacity cost and energy capacity cost for different storage systems. Annual costs assume a discount rate of 9% and a 10-year life cycle.

Electricity storage system	Power capacity costs [US$/kW/a]	Energy capacity costs [US$/kWh/a]
Compressed air energy storage in tanks	120	100-1500
Underground compressed air energy storage	90	5-100
Large scale batteries	70	10-700
Pumped storage hydropower	50	3-90
Super-conducting magnetic energy storage	40	9-150
Flywheel energy storage	30	80-1200

Source: EESAT. "Proceedings of the International Conference of Electrical Energy Storage Systems: Applications and Technologies." *International conference Electrical Energy Storage Systems*, Chester, UK, 323.

TABLE 2: Energy Densities of Energy Storage technologies

Media	Wh/kg (a)
Hydrogen	38000
Gasoline	13000
Flywheel Fused Silica	870
Flywheel Carbon Fiber	215
Advanced battery systems	100 - 200
Flywheel Steel	48
Lead-acid battery	25

(a) weight of motor and generator and energy conversion efficiency not included.

Source Ristinen R.A. and Kraushaar J.J. in Energy In the Environment John Wiley & Sons. (NY (1999).

4. Energy Storage in Batteries

The oldest and best-established way of storing electricity is in the form of chemical energy in batteries. As with the energy stored in fossil fuels in form of chemical bonds formed originally via photosynthesis, batteries also use the principle of chemical bond formation to store energy. Electrochemical storage is characterized as the ability to convert chemical binding energy directly to electricity. The process can be reversed for secondary (or rechargeable) batteries or accumulators in order to recharge the storage media.

Because batteries can release their power virtually instantaneously, they can significantly improve the stability of an electricity network. For instance, after the Second World War, a large-scale battery storage plant with a capacity of 9.3 MWh and an output of 8.6 MW was constructed in Berlin to operate the city's island electrical system. Another system with an output of 10 MW and a four-hour grid capacity was constructed in California during the 1980s. The largest system currently in operation have been supplied by SAFT S.A:, it is based on nickel-cadmium technology and is designed to supply 27 MW of back-up power for 15 minutes. Installed in Alaska, the system operates from 2003.

There are many more battery energy storage systems in operation today. Smaller-scale storage options probably become more important in the future due to increasing capacity of intermittent renewable energy sources such as wind and solar.

5. Application fields for Batteries as Energy Storage Systems.

5.1. History.

Early in the 20th century vehicles using lead-acid batteries traction batteries out-numbered internal combustion (IC) powered vehicles. With the invention of the self-starter and development of a refueling infrastructure along the commercialization pathway of the car, the combustion engine using the higher energy densities of fossil fuels rather than electricity showed a far greater range per charge of energy. A lead-acid battery of a given weight could only store electricity equivalent to 1% of its weight in gasoline, which has a heat content of 13,000 Wh/kg in contrast to 25 Wh/kg of an early lead-acid battery. We should note that in the last 100 years batteries have improved only by about a factor of two (Ristinen and Kraushaar 1999). Even taking into account the low energy conversion efficiency of gasoline to power, compared with the efficient end-use of electricity, the battery still severely limits electric vehicle range.

The problem with electric vehicles is clearly the storage of electric power. No battery can have the energy density of gasoline, and battery recharging is far slower than filling a tank. Battery lifetimes also require improvement.

Despite those facts, a battery remains the best energy source for starting an IC engine. The specific property of providing high power in a relatively short time is also necessary for **starter batteries,** for instance for vehicle engines. These must supply a broad load profile with up to 20 A and 70 A during idling or slow drive and 300 A for up to 3 sec during the starting operation.

5.2. Industrial applications for battery powered vehicles.

Battery powered motive systems for indoor use are a major area of application that take an increasing part in organized transport systems in automated industries. **A good example is the fork-lift truck**. The battery system provides flexible power for the traction vehicle, which is equipped with a recharging unit. The battery system design must include the energy supply system for recharge and is dependent on the kind of vehicle operation needed, i.e. capacitive operation with one full discharge/recharge cycle per mission, or cyclic operation with multiple synchronized missions, and combinations thereof. For internal transport tasks, electric traction equipment also provides a low noise, low emission, and clean mobility environment.

For road traffic, electric buses for public transport and electric cars are becoming more popular for environmental reasons. A possible increase in fossil fuel costs may favor electrical motive power including the application of **high energy density batteries and fuel cells** for cars.

5.3. Recent developments.

An interesting concept now being tested is a hybrid vehicle with a smaller, efficient internal combustion engine to recharge batteries and to drive the vehicle after the electric motor has accelerated it. Regenerative braking also helps to charge the batteries; and because of the reserve electric motor, the IC engine can be quickly restarted after every stop and need not idle, thereby resulting in high fuel efficiency. This application is further discussed in § 7.1..

6. Stationary systems.

6.1. History.

For large on-site immobile battery systems mostly lead-acid or nickel-cadmium based batteries are used today in power plants and solar installations, signal transmission (Telecom, radio) and uninterrupted power supply (UPS) systems, switchgear installations, annunciator and traffic lights, safety or emergency lighting, and air conditioning installations. Because of the characteristics of their application, high reliability is required. For telecom equipment, batteries need long operating times to balance electricity supply outages of several hours. For UPS systems, batteries must be able to instantaneously release very high currents over short times (minutes) until the back-up system responds. Less than a 0.25% failure rate has been observed with lead-acid and nickel-cadmium batteries in such systems. Safety and durability are most important criteria. In addition, sealed valve-regulated batteries are often chosen also due to their low maintenance requirements.

6.2. Uninterruptible power supply (UPS).

Stationary battery systems are widely used in **the information and telecommunications technology business**, often as back-up safety systems to compensate for loss of electricity supply from the grid. These systems must be designed to close the supply gap for several hours and in some cases high power outputs must be available immediately or within minutes. As back-up systems for power outages, the systems must be durable and reliable even if they are rarely put to use.

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6.3. Recent Developments.

Intermittent storage of solar energy is another area of application. For example, for autonomous photovoltaic systems, the battery sub-system must be designed to cope with wide fluctuations of input and output currents. The average electricity consumption of powered units and the average availability of solar radiation need to be balanced using site and application specific battery systems. This application of electrical energy storage with batteries will be discussed in § 7.2..

7. Development areas.

Three areas for Battery Technilogy development in the Energy Storage field have been selected.

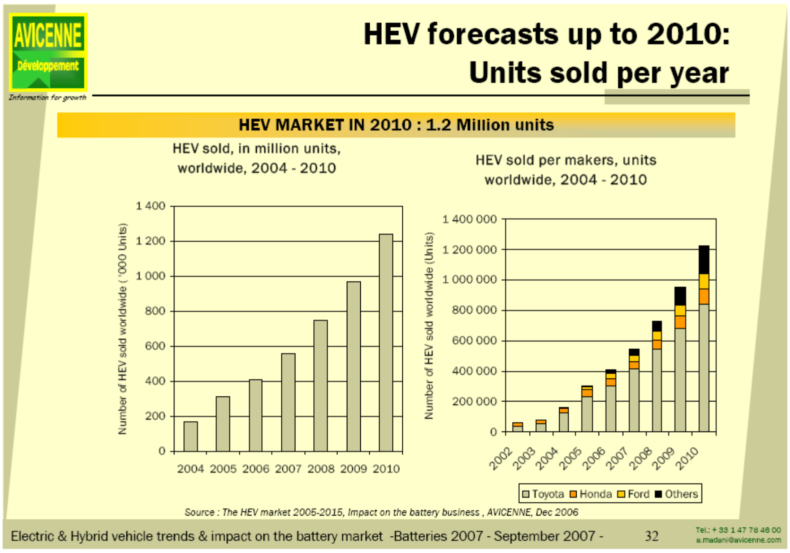
1. The Hybrid Electric Vehicle
2. Photovoltaic and Wind Energy Storage
3. Large Scale Load Leveling in Power Plants.

Practical data are supplied below in order to illustrate the potential for development of Batteries as Energy Storage Technologies.

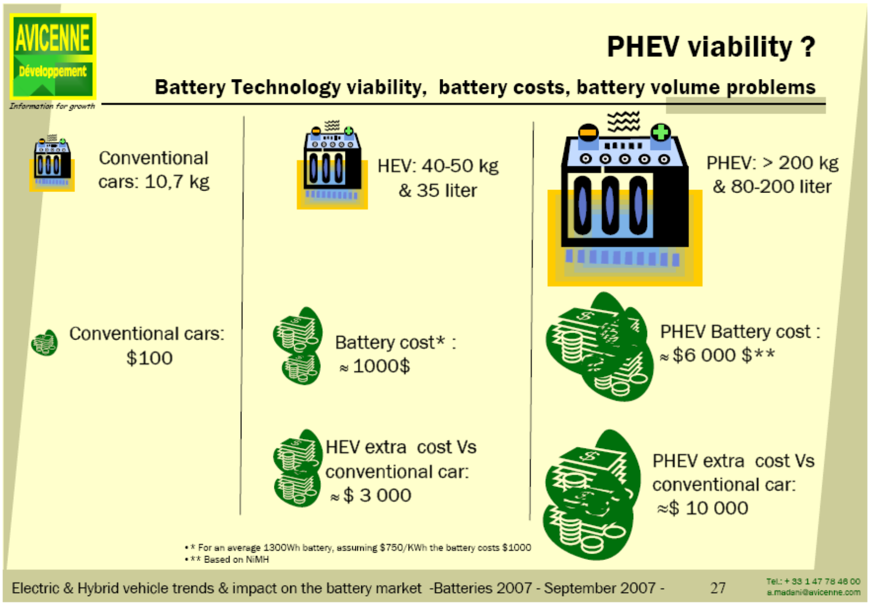
7.1. The Hybrid Electric Vehicle.

An interesting concept now being tested is a hybrid vehicle with a small, efficient internal combustion engine to recharge batteries and to drive the vehicle after the electric motor has accelerated it. Regenerative braking also helps to charge the batteries; and because of the reserve electric motor, the IC engine can be quickly restarted after every stop and need not idle, thereby resulting in high fuel efficiency (Dresselhaus and Thomas 2001). The recent development of the **Hybrid Electric Vehicle (HEV)** has demonstrated its practicality with a reduction in fuel consumption equivalent to 25 % when using the battery for the peak demand in city driving mode.

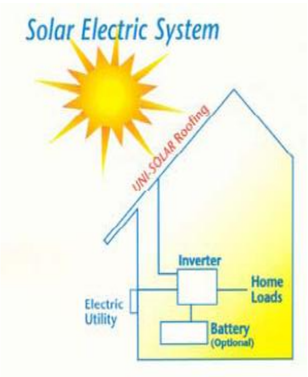
The market development for HEV is presented in the next Figure.



The challenge in technological evolution for shifting from an Internal Combustion engine powered car to an full electric vehicle is presented in the next Figure which shows the technological requirements for shifting from the conventional IC technology to the HEV technology an to the full electric power (PHEV).



7.2. Photovoltaic and Wind Energy Storage.



The general principles of intermittent Energy Storage capacity requirements will be illustrated for the Photovoltaic application.

Energy storage has always been closely associated with solar installations, including both solar heating and photovoltaic (PV) applications. Although today photovoltaics can be grid-adapted, the problem of the intermittent nature of solar energy can be solved either through energy storage or by system back-up, such as the use of natural gas burners at night or on cloudy days (Owen 2001; Witt et al. 2001). For rooftop solar power systems, possible **applications include battery storage systems** with the option to expand the power output from a standard 2.4-kilowatt to 3.2 kilowatts.

Table 6 lists many more storage applications for PV supply technologies.

In order to find the optimal system dimensions for the specific storage application, the average electricity consumption and the diurnal consumption profile should be known. Other very important parameters are those of the PV cells themselves, which for instance must be adapted to the seasonal variation of solar radiation. Since seasonal storage is not considered for small systems, additional power installations, for instance hybrid systems, are required to cope with seasonal differences.

Table 6: System power range for PV storage applications.

Power range	Typical application	Examples
µW	Integrated transistors or chips with minimal energy consumption	Solar watches and calculators
mW	Equipment and installation with low energy demand and only periodic use	Portable receivers / transmitter, automatic devices like ticket or vending machines, fire or security alarm systems
W	Installations for communication and measurement, small consumer households or businesses	Devices on buoys or for TV, radio and meteorological stations, electricity supply on boats or in holyday houses, electricity supply for heat pumps.
KW	Stand-alone grids with electric equipment and installations	Remote estates, military

Source: Kiehne, H. A., Berndt, D., Fischer, W., Franke, H., König, W., Köthe, K. H., Preuss, P., Sassmannshausen, G., Stahl, U.-C., Wehrle, E., Will, G., and Willmes, H. (2000). *Batterien: Grundlagen und Theorie aktueller technischer Stand und Entwicklungstendenzen*, Expert Verlag, Renningen (with permission)

The current market of batteries in PV applications is related to energy storage for off-grid (standalone) photovoltaic systems. There si currently a WorldWide Market of approximately 1GWh (annual installed battery market), i.e. about 150M€ in 2005.
His market is likely to double by 2010. (Source: SAFT SA (ML)).

7.3. Large scale battery assisted load leveling for power plants.

An example of such large scale projects can be found in the partnership between Plurion Systems Inc and ITI Energy that are developpoing a large scale Power Storage facility based on High Capacity Electricity (HCES) batteries.

- HCES as a critical value addition and potentially positive "disruptive technology" in the electrical business. The addition of economical storage has roles in the generation, transmission and end use segment of the electricity market

- Plurion will concentrate on the segments where off peak power can be converted to premium power.

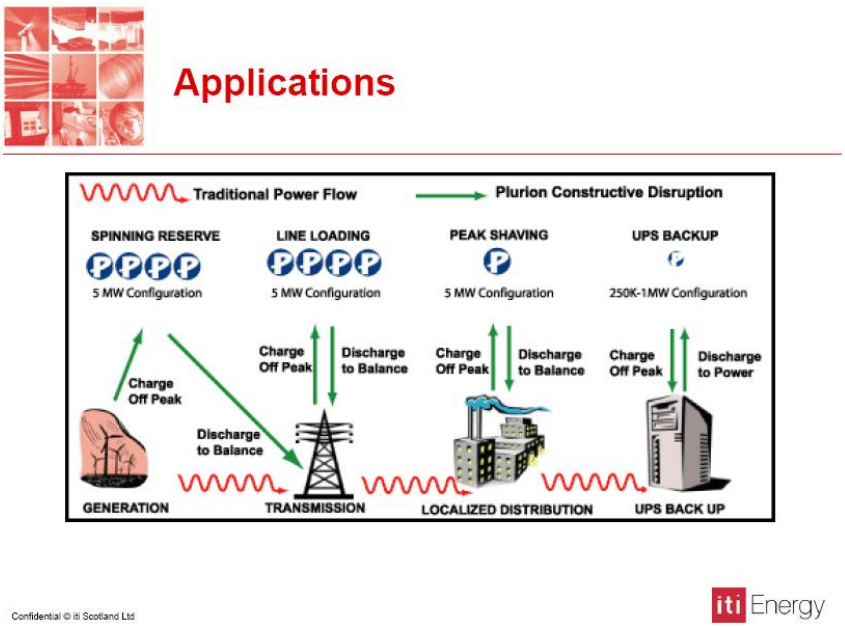
- ITI-Energy is “committed” to funding up to £ 9.3 m over 3 Years

According to Ian Whyte Project manager of the Light House (Glasgow) demonstration plant, the following fdata are characterizing this market.

- Renewables - >$10 billion/year
- Matching time of generation to time of use
- ¼ to 50MW Batteries with 2 – 8 hr discharge capacity

- Industrial Markets - $2-4 billion/year
- Combined Peak Shaver/UPS
- ¼ to 10MW Batteries with 2-10 hr discharge capacity

- Utility Markets - >10 billion/year
- Enabling better use of T&D & base level generation
- ¼ to 50MW Batteries with 4-8 hr discharge



ANNEX 1.

Table 3: Different battery systems used in applications today.

System	Electrolyte	Type	Storage capacity [Wh/kg] [a]	Application
Lead-acid	aqueous electrolyte (sulfuric acid), mostly immobilized	often sealed (valve-regulated), works at low temperatures, rechargeable	20-50	starter battery for cars, batteries for fork-lifts, electric vehicles, submarine, and ships (also unsealed non-maintenance-free)
Nickel-hydroxide cadmium	aqueous electrolyte, mostly immobilized	sealed (valve-regulated) rechargeable	20-55	battery system mostly for small equipment and some for propulsion, on-board electronics, and on-site applications
Nickel-hydroxide hydrogen gas	aqueous electrolyte, immobilized	Sealed, pressurized, rechargeable	50-60	battery system for many satellites
Nickel-hydroxide metal hydrides [c]	aqueous electrolyte immobilized	sealed (valve-regulated), rel. high load capacity, rechargeable	50-80	can replace nickel cadmium batteries
Sodium sulfur [d]	solid electrolyte (β-alumina) at temperatures of 300-400 °C	high temperature system, rechargeable	90-120	Electric vehicles, trams, buses
Sodium nickel-chloride [d]	solid electrolyte (β-alumina) at temperatures of 300-400 °C	high temperature system, rechargeable	90-100	Electric vehicles, trams, buses
Lithium-ion polymer, lithium cobalt oxide, lithium manganese oxide iron - or aluminum disulfide	organic electrolyte at room temperature	rel. high voltage (4V), rel. high load capacity, rechargeable	ca. 100	battery system for small applications, tests for some electric vehicles
Zinc bromine[b]	aqueous electrolyte	rechargeable	65-70	tests for some electric vehicles
Zinc air (oxygen from air) [b]	alkaline or neutral electrolyte	mechanically rechargeable, i.e. exchange of zinc electrode after a few cycles	ca. 170	tests for some electric vehicles

[a] when applied
[b] different battery system architecture, i.e. reactive substrates stored outside cell
[c] some nickel alkaline electrolyte batteries also work at low temperatures
[d] sodium-sulfur and sodium nickel chloride have been abandoned for traction applications

Source: Kiehne, H. A., Berndt, D., Fischer, W., Franke, H., König, W., Köthe, K. H., Preuss, P., Sassmannshausen, G., Stahl, U.-C., Wehrle, E., Will, G., and Willmes, H. (2000). *Batterien: Grundlagen und Theorie aktueller technischer Stand und Entwicklungstendenzen*, Expert Verlag, Renningen (with permission; adapted including additional applications).