Deployment of a hydrogen production and distribution infrastructure will be gradual, in particular via operational feedback from demonstration projects, which have been mounted in increasing numbers, over the past few years, especially in Europe. A framework of standards and regulations will need to be set up concurrently.

Challenges of a hydrogen **distribution infrastructure**

The connecting link of energy policy

The manner of hydrogen production and distribution infrastructure deployment – building up very gradually in any event – will reflect the place assigned to it by energy policy.


Air Liquide

Hydrogen delivery to a US customer by Air liquide Group.

Hydrogen, as a vehicule **fuel**, is the target of intense research activity. The first few dozen demonstration vehicles are now in operation, supplied by nascent grids: 21 **fuel-cell** powered vehicles are running in the Tokyo Bay area, in Japan, for instance, where, under the We-Net Program, a network of hydrogen filling stations has allowed these vehicles to travel freely. One should however bear in mind that hydrogen is not an energy source, but an **energy carrier**, and that its production (see the preceding section, *How is hydrogen to be produced?*) does require such sources, just as does generation of the other major energy carrier, electricity. As is the case for the latter, the benefit of using hydrogen as a fuel, as far as security of supply or **greenhouse gas** emissions are concerned, depends on the way it is generated. Should the energy source employed be coal, for instance, this makes for more secure supplies, but causes heavier **CO_2** emissions. If hydrogen is produced from non-**fossil** sources (nuclear energy, or renewable energies), then it makes a contribution both to greater security of supply, and lower CO_2 emissions. Which means that any assessment of the benefits accruing from a switch to hydrogen as a fuel for transportation purposes involves a number of assumptions as to the long-term evolution, presently somewhat uncertain, of energy policy.

A flexible link, acting as a buffer

As a future large-scale energy carrier, hydrogen offers the benefit (as does electricity) of allowing production to be carried out using any energy source, and (by contrast with electricity) of lending itself to storage over extended periods. As regards infrastructure, it brings the benefit of forming a flexible link, acting as a buffer, for a decentralized, nonfossil-fuel-based energy market.

Storage of adequate amounts of energy in a vehicle, while not as satisfactory with hydrogen as with liquid **hydrocarbon fuels**, is as of now far more efficient than is the case with electric **batteries**.

Obviously, hydrogen's potential benefits as a fuel can only be realized once hydrogen storage techniques and fuel cell technology have matured, and provided major investments are devoted to production and distribution facilities.

There is broad agreement that it will take several decades before hydrogen can see widespread commercial distribution as an automotive fuel, owing both to advances that yet need to be achieved with regard to fuel cells, and the gradual building up of a hydrogen infrastructure that has yet to attain sufficient deployment.

Currently, hydrogen utilization only accounts – in energy equivalent terms – for 1.5% of world primary energy production, and, for the major part, this hydrogen is in fact a byproduct from other processes being operated at the industrial sites involved (see Hydrogen from chemistry to energy) (see Figure). As yet, hydrogen serves as an energy carrier only for spacecraft propulsion, this only accounting for a tiny part of hydrogen utilization.

A new regulatory status

Industrial use of hydrogen is governed by an array of regulatory instruments (concerning production, distribution, and storage), which are still a reflection of hydrogen utilization as a chemical or process feedstock molecule. These regulations are in fact undergoing harmonization at European level. Taking on board the new "energy hydrogen" dimension will involve assigning a new status to hydrogen, accompanied by the requisite regulatory framework to guarantee the safety of users of this new carrier.

In this respect too, transition from the "fossil" economy to a hydrogen economy will be gradual, in keeping with the tempo of its emergence, initially for such niche applications as captive utility-vehicle fleets, public transport, and high-performance electric generators. Transition may then be effected through a multiplicity of demonstration operations (see Box), ensuring significant operational feedback.

Air Liquide

Figure.
Air liquide's 100-bar gaseous-hydrogen supply pipeline grid covering France, Benelux and Germany.

> Cyrille Millet
Air liquide
(Paris)

European demonstration programs

Since 1999, when the first hydrogen filling station was opened at Munich Airport (Argemuc Program), (1) a very limited number of demonstration programs have been initiated in Europe. Total, in partnership with the Berlin Public Transport Company (BVG: Berliner Verkehrsbetriebe-AG), showed the way, with the opening of the Berlin Hydrogen Competence Center in October 2002. (2) 2003 saw the coming into operation of the first buses and hydrogen filling stations of the European CUTE and ECTOS Program. (3) This program, with joint funding from the **European Commission**, will enable validation of operating conditions for three Citaro fuel-cell buses (built by Evobus), running in ten cities, i.e. a total of 30 buses: Madrid (where three buses have been running since summer 2003), Reykjavik, Amsterdam, Barcelona, Hamburg, London, Luxembourg, Porto, Stockholm, and Stuttgart.

This is the largest demonstration operation involving buses in the world. The fuel cells, supplied by Canadian manufacturer Ballard, are fuelled with gaseous hydrogen, stored in pressure tanks at 350 bars. A variety of fuel production and supply processes are being tested for the buses, as well as systems maintenance and operating conditions. Further, acceptance of these new technologies is also being tested with local users (see p. 103).

Total

Total's Hydrogen refuelling station in Berlin.

(1) http://www.hydrogen.org/h2muc
(2) http://www.total.com/ho/en/csr/environnement/p2_4_3_5.htm
(3) http://www.fuel-cell-bus-club.de/html/cute___ectos.html

Demonstration initiatives helping to set the technical and regulatory framework

"Fuel hydrogen" must yet pass many lilestones before product and distribution specifications can be set out, in an agreed regulation and standards framework, prioritizing safety, with regard to both persons and property.

In only ten countries or so is **hydrogen** considered as a **fuel**, eiher on an exceptional or derogatory basis, for the purposes of specific demonstrations, over limited periods. There are fewer than one hundred filling stations wolrdwide, nearly all of them being for private use only, and for the most part operated in highly sporadic fashion, far from the standards pertaining to a conventional fueling station, with its several hundred tank fills per pump per day.

The past few years have seen an unquestionable ramping up of work in this area, under the combined impulse of committed automotive manufacturers, developers of relevant technologies (**electrolysis** or **reforming**, compressors, storage…), and from the industries

A & M. Creaccion

Filling station supplied with hydrogen by Air liquide, run by Madrid bus operator EMT.

involved in the production, transport and distribution of hydrogen fuel. To go from the industrial gas stage to that of a commodity available to the public at large, "fuel hydrogen" has yet to pass numerous validation steps and milestones, starting with establishing the nature and quality of the hydrogen to be supplied (liquid or compressed, purity level). Then the key technologies must be identified, and developed (production – particularly onsite at the point of dispensing – transport and storage, fast filling methods, vehicle interfaces).

Further, common frameworks of standards and regulations must be set, and implemented, addressing first and foremost safety issues, with regard to both persons and property. Standardization of hydrogen technologies is being carried out, in particular, within an **ISO** technical committee (TC 197) which, along issues concerning safety, and hydrogen quality, production and storage, has specifically addressed, since the end of 2003, the topic of service stations. Bearing in mind it takes at least five years to introduce and approve new international standards, one may reasonably expect an initial standards framework to be ready by 2010, which is the date mooted by the more optimistic manufacturers, for introduction of their initial precommercial hydrogen vehicles. One of the prerequisites for the setting up of a hydrogen infrastructure will then have been met.

The coming years must be put to best use, for the assessment of the manifold aspects of the hydrogen pathway, bringing in all the protagonists involved. The aim indeed is to have in hand all of the required information (maturity levels for the various technologies, associated costs, environmental and societal benefits, acceptability) by the time decisions have to be taken, which may ultimately be irreversible. The **European Commission**, in response to the recommendations made by the High-Level Group set up in late 2002, has decided to prepare a hydrogen "roadmap," as has been done in Canada or the United States. This concerted approach should enable rigorous examination to be carried out, of the case of the hydrogen infrastructure, taking in all the specific features of the European context.

> **Patrick Schnell** and **Philippe Mulard**
Total
Paris

The Utsira hydrogen–wind power program

Werner Juvik/Hydro

Scale model showing a simplified representation of the stand-alone wind–hydrogen electricity generation system used for the Utsira demonstration program.

At Utsira, an island off the Norwegian west coast, the world's first full scale stand-alone wind–hydrogen power generation unit is demonstrated.

The 240 inhabitants of Utsira are connected to the main grid in Norway by means of an 18-kilometer undersea cable. With the installed wind-hydrogen plant, they are now exporting power to the mainland, but 10-15 households get their entire power supply from renewable energy, whether the wind is blowing or not.

Utsira's prevailing weather conditions makes it a natural choice for wind power generation and the wind turbines here will generate a large power surplus in prime conditions. But like all renewable energy sources, the electricity supply is periodic – wind turbines stand still when there's not enough wind.

At Utsira, we get round this fundamental problem by storing surplus electricity as chemical energy – in the form of **hydrogen**. When the wind blows, **electrolysers** produce hydrogen for storage – and when it doesn't, a hydrogen motor and a **fuel cell** convert the stored hydrogen back into electricity.

What's unique about the Utsira project is, that it is supplying autonomous renewable power to 10 households. The islanders' need for energy varies – but the stored hydrogen ensures that there is always enough energy, even when demand peaks or production is low.


Pål Otto Eide/Hydro

The two wind turbines erected on the island of Utsira are the most visible element of the world's first stand-alone wind–hydrogen electricity generation system.

Hydrogen ensures stable power supply. It will be produced from water generated by one of two 600 **kilowatt** wind turbines and an electrolyser. Surplus energy from the turbines is sold on the market.

The island's consumption stands at around 3,500 **MWh**/year, peak winter demand being of the order of 900 kW. Decisive for the demonstration project is the peak demand in the uatnomous system serving the 10-15 households. The maximum load is some 50 kW. The longest zero-wind period is found to last about two days. The equipment has been designed on the basis of standard wind turbines and simulations carried out by means of a modeling code, based on Hydrogems and TRNSYS, using a measured load profile.

Environmental considerations

The major part of the population resides in the valley which traverses the island from north to south, and a few holiday homes are to be found. Maximum noise levels allowed for the nearest dwelling was set at 40 dBA by the Norwegian Pollution Control Authority (SFT: Statens forurensingstilsyn). During construction, a 10,000-year-old archaeological site was uncovered. Hydro decided to relocate the wind turbine to preserve this site. Final decision as to wind-turbine installation and positioning was made on the basis of an environmental impact assessment (EIA) study. The plant was inaugurated on July 1st 2004 and the demonstration program will extend over two years.

A joint project

The Utsira program had initially been launched by the Norwegian industrial group Hydro (1) with local support from the Utsira authorities as well as the population. Subsequently, the leading German wind-turbine manufacturer Enercon GmbH joined the collaboration. Hydro has been engaged in hydrogen production and utilization since 1927. Today, its wholly-owned subsidiary Hydro Electrolysers AS is one of the main manufacturers of electrolysers- hydrogen-production units based on water electrolysis. The company is also involved in a number of European Union programs, such as ECTOS, CUTE, the Clean Energy Partnership and RenewIslands, and has delivered complete hydrogen filling stations to refuelling sites in Reykjavik and Hamburg.

energy component	manufacturer	characteristics
wind turbine	Enercon	2 × 600 kW
flywheel		
master synchronous alternator	Enercon	100 kVA
electrolyzer	Hydro	10 Nm^3/h
hydrogen storage unit	Hydro	2400 Nm^3 (at 200 bars) = 12 m^3
fuel cell	IRD	10 kW
hydrogen-fueled generator	Continental	55 kW

Table. Main technical specifications for the Utsira wind–hydrogen program (source: Hydro ASA).

Commercial opportunities

The energy challenges faced by Utsira are typical of those experienced by many other islands and remote, isolated locations in Europe, as in other regions of the world: the wish to own a stand-alone renewable-energy system, and the requirement for energy storage, to even out variations in demand according to the time of year. While Utsira has higher energy requirements in wintertime, many islands more to the south exhibit higher consumption over the summer, with the arrival of tourists. Islands operating renewable-energy systems will thus present added attractiveness, especially for the growing numbers of "green" tourists.

The wind–hydrogen system presents a number of advantages over diesel: zero pollutant emissions, relevance to sustainable development, and a positive image. Price is equally an important issue, since diesel fuel transport and storage costs may be high for many of these locations.

Wind power is a growth sector in Europe, as in other world regions. Currently, Germany is the country having the largest installed capacity in the world (12,000 MW). The European countries with the best potential resources in this respect, however, are Ireland, Spain, France, Italy, the United Kingdom, and Norway.

> Elisabet Fjermestad Hagen
Hydro Oil and Energy, Markets
Oslo (Norway)

---

(1) For further information: www.hydro.com and www.hydroelectrolysers.com

A The many states of energy

“Nothing lost, nothing created,” as Lavoisier, the father of modern chemistry, wrote in his day. This motto, true as it is of chemical species, applies equally to energy. Indeed, energy is a multifarious entity, which may transform into highly diverse aspects. However, the primary energies that may be directly accessed in nature are limited in number: such are fossil energies (coal, oil, natural gas), **nuclear energy**, and renewable energies (hydro energy, biomass energy, solar energy, wind energy, geothermal energy, tidal energy). These primary energies are the constituents of what is known as the ***primary energy mix*** (see Figure 1).

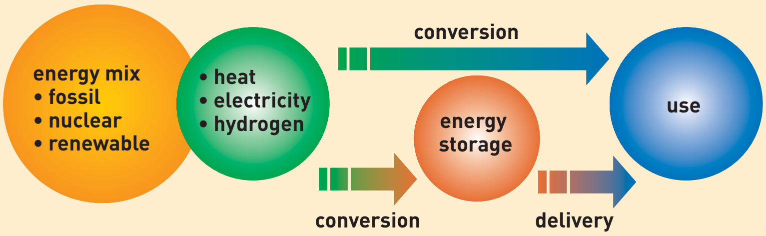


Figure 1.
The energy scheme.

For most applications, energy must be **converted** to make it compatible with the use under consideration. Of course, nature, highly ingenious as it is, devised the very first energy converters, namely living beings. Plants, through photosynthesis, effect the conversion of radiant light energy into chemical energy. The human body itself allows, in particular, the conversion of chemical energy into mechanical energy, by way of the muscular system. Subsequently, humans went on to invent large numbers of converters (see Figure 2). The first such converter, chronologically, is quite simply fire, converting chemical energy (combustion) into light, and heat. Of more recent origin, a television set carries out conversion of electricity into light energy (pictures) and mechanical energy (sounds). In fact, many energy systems involve a combination of a number of converters, as e.g. a nuclear power station, effecting as it does the conversion of nuclear energy into thermal energy (reactor), then into mechanical energy (turbine), finally through to electric energy (alternator). Unfortunately, the second principle of thermodynamics tells us that any energy transformation carries a cost: a more or less extensive portion of the energy involved is dissipated in the form of unusable heat (through friction in a mechanical system, for instance). In the case of a present-generation nuclear power station, the electric energy generated only amounts to one third of the nuclear energy initially contained in the fuel.

Of course, matters would be altogether too simple, however, if energy could be consumed as and when it is generated, on the very site where it is produced. In very many cases, energy-consuming sites may be far removed from the production site, production and concomitant demand, moreover, not always being matched (as with photovoltaic electricity in nighttime, for instance). Sound energy management thus requires deployment both of an **energy distribution network**, and of **energy storage** capabilities.

Energy transport is effected by means of an energy carrier. Currently, the two main such carriers are **electricity**, and **heat**. Tomorrow, however, a new carrier may become dominant: hydrogen, this being converted into electricity and heat by means of fuel cells.

Finally, if energy is to be available at all times, it is essential that there should be the ability to store it: to “get it in a can,” so to speak. Such **storage** may take a variety of forms. Energy may be stored in **mechanical** form (*potential energy*, in the case of the water reservoir of a hydroelectric dam, or *kinetic energy*, in the case of a flywheel), or in **thermal** (hot-water tank), **chemical** (gasoline tank, primary and storage batteries), or even magnetic (superconducting coil) form.

Energy management is thus a complex, involved craft, combining production, transformation, transport, and storage. In the current context of energy debate, it is becoming increasingly apparent that, tomorrow, energy networks will grow in size and number, in accordance with a multimodal approach (concurrent management of a number of networks combining diversified energy sources). **New energy technologies** are thus bound to play an essential part in these developments.

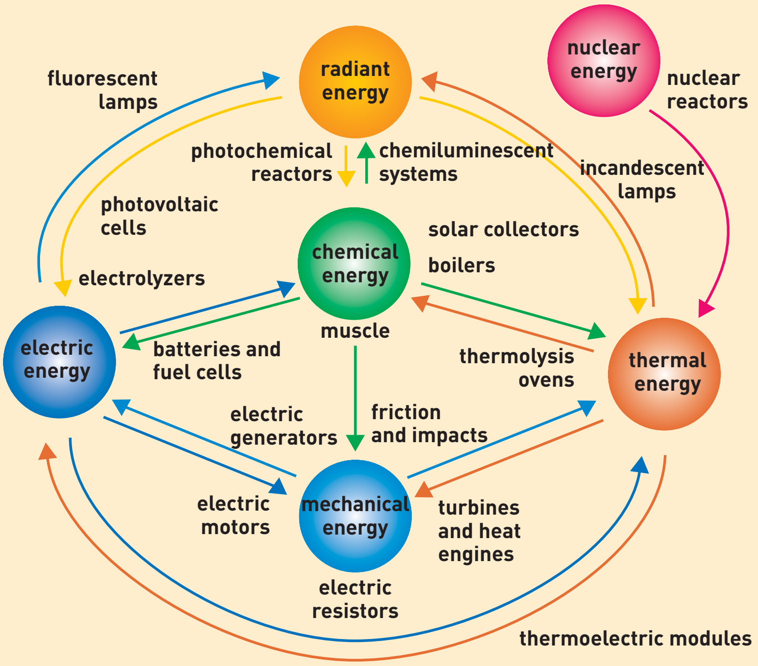
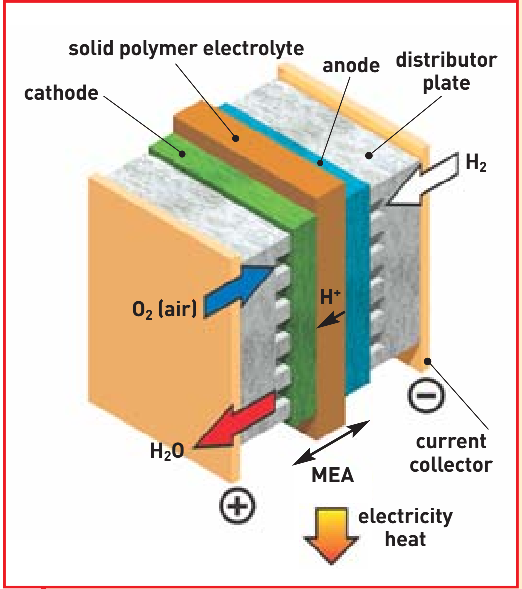


Figure 2.
Conversions of the six main forms of energy, with a few examples of energy converters.

C

How does a fuel cell work?



Operating principle of the fuel cell: the example of the proton-exchange membrane fuel cell. MEA stands for membrane-electrode assembly.

The fuel cell is based on a principle discovered quite some time ago, since it was in 1839 that Sir William Grove constructed the first electrochemical cell working with hydrogen as its fuel, thus demonstrating the ability to generate electric current through direct conversion of the fuel's chemical energy. Since the fuel cell has the special characteristic of using two gases - hydrogen H_2 and oxygen O_2 - as its electrochemical couple, the oxidation-reduction reactions occurring inside the fuel cell are particularly simple.
The reaction takes place inside a structure (the basic electrochemical cell), consisting essentially in two electrodes (the anode and cathode), separated by an electrolyte, i.e. a material that lets ions through. The electrodes employ catalysts, to activate, on the one side, the hydrogen oxidation reaction, and, on the other, the oxygen reduction reaction.
In the case of an acid-electrolyte cell (or proton exchange membrane fuel cell), the hydrogen at the anode is dissociated into protons (or hydrogen ions H^+) and electrons, in accordance with the oxidation reaction: $H_2 \rightarrow 2\ H^+ + 2\ e^-$. At the cathode, the oxygen, the electrons and the protons recombine to yield water: $2\ H^+ + 1/2\ O_2 + 2\ e^- \rightarrow H_2O$. The principle of the fuel cell is thus the converse of that of water electrolysis. The thermodynamic potential for such an electrochemical cell, consequently, stands at around 1.23 volt (V). However, in practice, the cell exhibits a voltage of about 0.6 V for current densities of 0.6-0.8 A/cm^2. The efficiency of such a fuel cell is thus equal to about 50%, the energy dissipated naturally being so dissipated in the form of heat.

E Storage batteries, cells and batteries: constantly improving performance

Storage batteries – also known as accumulators, or secondary batteries – and batteries – so-called primary batteries – are electrochemical systems used to store energy. They deliver, in the form of electric energy, expressed in watt-hours (Wh), the chemical energy generated by electrochemical reactions. These reactions are set in train inside a basic cell, between two electrodes plunged in an electrolyte, when a load, an electric motor, for instance, is connected to its terminals. Storage batteries are based on reversible electrochemical systems. They are rechargeable, by contrast to (primary) batteries, which are not. The term "battery" may further be used more specifically to denote an assembly of basic cells (whether rechargeable or not).

A storage battery, whichever technology is implemented, is essentially defined by three quantities. Its gravimetric (or volumetric) energy density, expressed in watt-hours per kilogram (Wh/kg) (or in watt-hours per liter [Wh/l]), corresponds to the amount of energy stored per unit mass (or per unit volume) of battery. Its gravimetric power density, expressed in watts per kilogram (W/kg), measures the amount of power (electric energy delivered per unit time) a unit mass of battery can deliver. Its cyclability, expressed as a number of cycles, (1) characterizes storage battery life, i.e. the number of times the battery can deliver an energy level higher than 80% of its nominal energy; this quantity is the one most frequently considered for portable applications.

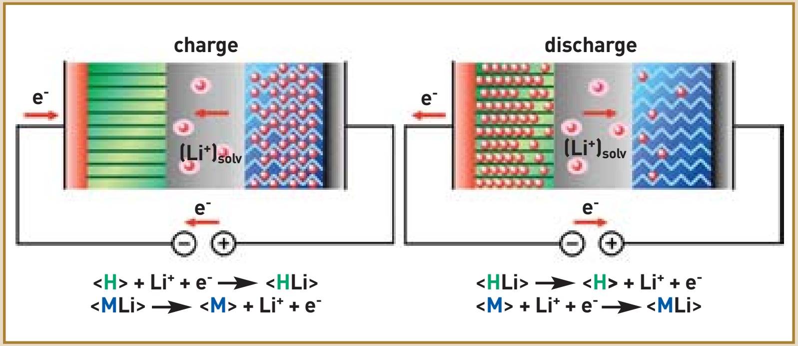
Up to the late 1980s, the two main technologies prevalent on the market were lead–acid storage batteries (for vehicle start-up, backup power for telephone exchanges...), and nickel–cadmium storage batteries (portable tools, toys, emergency lighting...). Lead–acid technology, more widely referred to as lead–acid batteries, or lead batteries, is also denoted as lead–acid systems. Indeed, the chemical reactions employed involve lead oxide, forming the positive electrode (improperly termed the cathode), and lead from the negative electrode (anode), both plunged in a sulfuric acid solution forming the electrolyte. These reactions tend to convert the lead and lead oxide into lead sulfate, further yielding water. To recharge the battery, these reactions must be reversed, through circulation of a forced current. The disadvantages found with lead–acid technology (weight, fragility, use of a corrosive liquid) resulted in the development of alkaline storage batteries, of higher capacity (amount of energy delivered during discharge), yielding however a lower electromotive force (potential difference between the system's terminals, under open circuit conditions). Electrodes for these systems are either based on nickel and cadmium (nickel–cadmium storage batteries), or nickel oxide and zinc (nickel–zinc storage batteries), or silver oxide coupled to zinc, cadmium, or iron (silver-oxide storage batteries). All these technologies use a potassium hydroxide solution as electrolyte. Lead–acid technologies, as indeed alkaline batteries, are characterized by high reliability, however gravimetric energy densities remain low (30 Wh/kg for lead–acid, 50 Wh/kg for nickel–cadmium).

In the early 1990s, with the growth in the portable device market, two new technological pathways emerged: nickel–metal hydride storage batteries, and lithium storage batteries (see Box on *Operating principle of a lithium storage battery*). The first-mentioned pathway, involving a nickel-based positive electrode and a negative electrode – made of a hydrogen-absorbing alloy – plunged in a concentrated potassium hydroxide solution, allowed gravimetric energy densities of 70–80 Wh/kg to be achieved. The second pathway had already been targeted by research around the late 1970s, with a view to finding electrochemical couples exhibiting better performance than the lead–acid or nickel–cadmium storage batteries used up to that point. Initial models were thus designed around a metallic-lithium-based negative electrode (lithium-metal pathway). However, that technology was faced with issues arising from poor reconstitution of the lithium negative electrode, over successive charging operations. As a result, around the early 1990s, research was initiated on a new, carbon-based type of negative electrode, this serving as a lithium-insertion compound. The lithium-ion pathway was born. Japanese manufacturers soon made their mark as leaders in the field. Already in business as portable device manufacturers, they saw the energy source as numbering among the strategic components for such devices. Thus it was that Sony, not initially involved in battery manufacture, decided, in the 1980s, to devote considerable resources to advance the technology, and make it suitable for industrialization. In February 1992, Sony announced, to general stupefaction, the immediate launching of industrial production of lithium-ion storage batteries. These early storage batteries exhibited limited performance (90 Wh/kg). Since then, these batteries have seen notable improvement (from 160 Wh/kg to over 180 Wh/kg in 2004), owing, on the one hand, to the technological advances made (reduction in the unproductive fraction of battery weight and volume), and, on the other, to optimization of materials performance. Gravimetric energy densities of over 200 Wh/kg are expected around 2005.

(1) One cycle includes one charge and one discharge.

Operating principle of a lithium storage battery

1



During use, hence during discharge of the storage battery, lithium released by the negative electrode (<H>: host intercalation material) in ion form (Li^+) migrates through the ion-conducting electrolyte to intercalate into the positive electrode active material (<MLi>: lithium-insertion compound of the metal oxide type). Every Li^+ ion passing through the storage battery's internal circuit is exactly compensated for by an electron passing through its external circuit, thus generating a current. The gravimetric energy density yielded by these reactions is proportional both to the difference in potential between the two electrodes, and the quantity of lithium intercalating into the insertion material. It is further inversely proportional to system total mass. Now lithium is at the same time the lightest (molar atomic mass: 6.94 g), and the most highly reducing of metals: electrochemical systems using it may thus achieve voltages of 4 V, as against 1.5 V for other systems. This allows lithium batteries to deliver the highest gravimetric and volumetric energy densities (typically over 160 Wh/kg, and 400 Wh/l), 50% greater, on average, than those of conventional batteries. The operating principle of a lithium storage battery remains the same, whether a lithium-metal or carbon-based negative electrode is employed. In the latter case, the technological pathway is identified as lithium-ion, since lithium is never present in metal form in the battery, rather passing back and forth between the two lithium-insertion compounds contained in the positive and negative electrodes, at every charge or discharge of the battery.