Storage of Electrical Energy

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The world is moving in the direction of using electricity derived from renewable sources

With the mass production of sources of renewable energy (wind, solar and tides), peak power capacity is competitive with that of deriving the electricity from fossil fuel

(While nuclear power is clean, the capital cost of plants, which must include that of decommissioning, makes the real cost of power more expensive than that obtained from renewables)

The problem is that the profile of power production does not match that of the requirements

(*The problem is not new, but more acute*)

Whence the increasing importance of **energy storage**

Electricity Grids

As long as there has been an electrical grid, companies have looked for ways to efficiently store energy so that power can be delivered on demand.

A wide range of technologies are employed and are being developed so that everyday needs can be met.

Energy storage is resource neutral, it allows us to use electricity from any power source more efficiently.

There are several ways to store energy. When applied to electrical energy, they must be chosen to take into account the ***location*** and ***cost*** of the storage, and its ***required duration***

- Potential energy — $m \cdot g \cdot h$
- Kinetic energy — $\frac{1}{2} m \cdot v^2$
- Magnetic energy — $\int_V (B^2/2\mu_0) d\tau = \frac{1}{2} L \cdot I^2$
- Capacitive energy — $\frac{1}{2} C \cdot V^2$
- Chemical energy — *reversible reaction*

Associated with each method there is the ***cycle efficiency***

Potential energy $m \cdot g \cdot h$

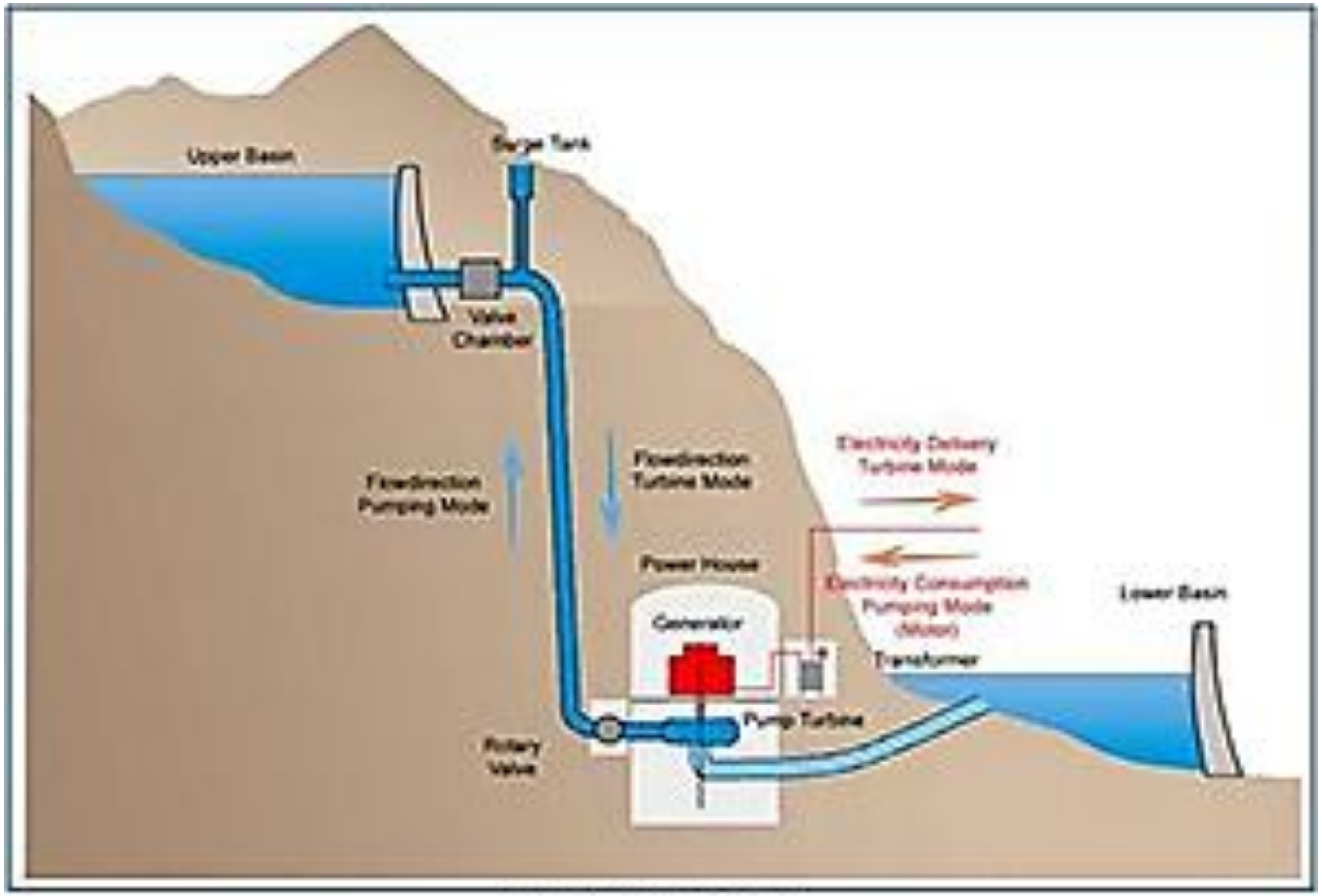
Pumped water is the traditional way of storing electrical energy, particularly in places where hydro-electric power is significant (e.g. the Alps). When power is cheap, pump water into the elevated lake. For example

A mountain lake of 10 km^2 , 1000 m above another lake, will store 10^{14} J (= 10^5 GJ) per m of depth

1 MWh = 3.6 10^9 J $\Rightarrow$ 2.78 10^4 MWh

Allowing an efficiency of 75 % about 20 GWh

At this scale, the energy storage is clearly in the suppliers' hands…

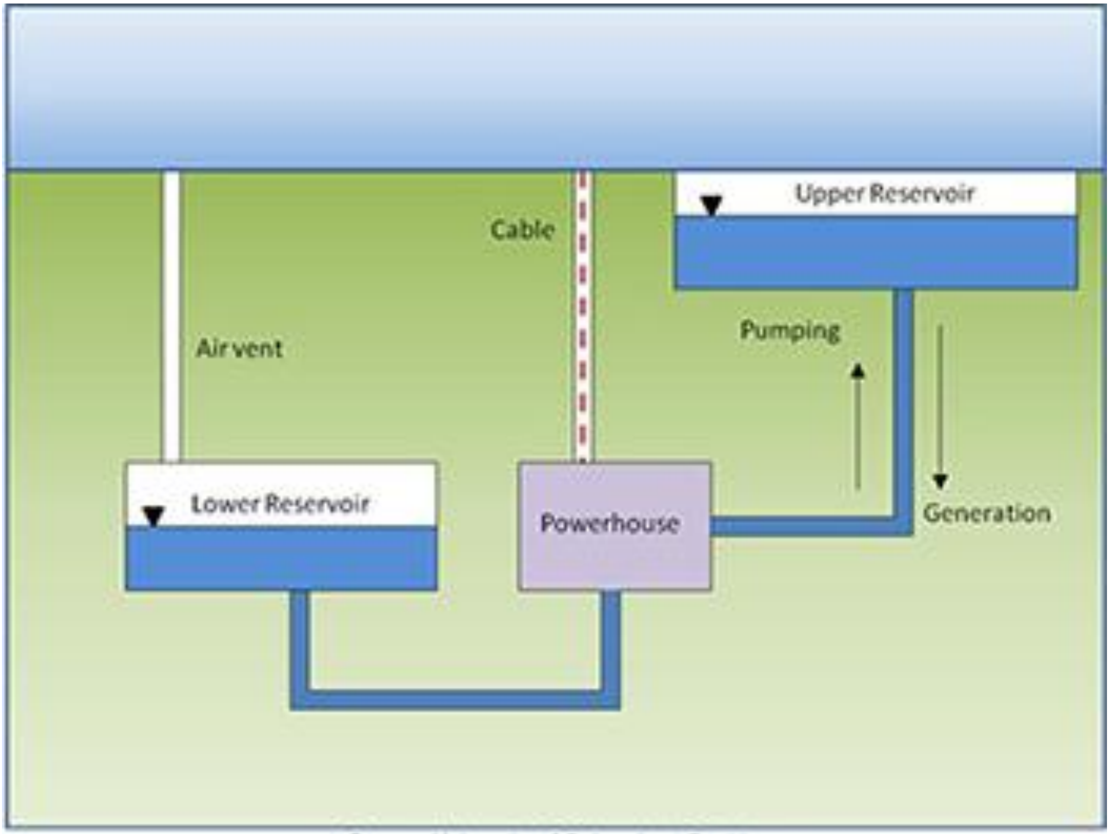


Source: Alstom Power

- In the world there is over 100 GW storage generating capacity
- Reported round-trip efficiency is up to 80%

<u>Sub-surface energy storage</u>

Old mines are sometimes used for pumped energy storage (PHS)



Source: University of Colorado at Boulder

Even in places without high mountains and large dams, this method is quite popular for storing electrical energy (on a smaller scale) by utilities, but is less appropriate for private use. One could consider pumping water from a well to a container at the surface, and returning the water to the well via turbines. This could be appropriate in remote locations, but care would have to be taken to avoid contaminating the water table…

For private use, it has also been suggested to use surplus power to raise a mass of say 20 t to a height of say 15 m, with appropriate gearing to a generator, but the result is not very attractive except perhaps where space is abundant

$20 \times 10^3 \times 9.81 \times 15 \approx 3$ MJ $\qquad 3000 \times 0.8 \div 3600 \approx 0.7$ kWh

i.e. about the energy stored in 2 car batteries! Hardly appealing, except that maintenance would be minimal…

Other forms of potential energy include

- Compressed air (or nitrogen)
- Liquified gas (air, N_2, H_2)
- Heat

Compressed air (CAES)

First used in the 1870s

Utility scale installations: 290 MW (1970)

Method: stores energy used to compress the gas
- Air heats up to 150^{o}C during compression
- Standard storage pressure: 70 bar

Applications
- Diabatic - use cycle for efficient liquefaction of LNG
- Adiabatic - heat of compression recovered and used to reheat compressed air during turbine expansion

(up to 70% efficiency, but requires possibility to store the heat)

Very large (due to low storage density) $\Rightarrow$ ***use salt caverns***
Either cool before compression or store in hot flow batteries

Isothermal CAES

Ideas:

Store heat in oil (up to 600 K)

Use wind turbines to compress with a mechanical link

Store in inflatable underwater bags…

RWE (D) is planning to use this storage method.

Thermal 1

Pumped heat electrical storage (PHES)

Uses two large steel tanks filled with mineral particulates (gravel)

1. **Charging the system**
   Argon at ambient temp is compressed to 12 bar, heats to 500^{o}C, storing the energy used to power the motor generator *(A monatomic gas (e.g. argon) is used as the working gas: it heat/cools more than air for the same pressure change, reducing storage cost)*
2. **Energy Storage**
   Ar injected at top of tank 1, slowly descends, exits at bottom at RT, at ~ 12 bar $\Rightarrow$ expander -160^{o}C $\Rightarrow$ tank 2 bottom - exits top at RT
3. **Power Recovery**
   Reverse process. Cool Ar to -160^{o}C in tank 2 $\Rightarrow$ compress to 12 bar, RT $\Rightarrow$ heat in tank 1; expand hot gas in turbine to generate power

Round trip efficiency: 75 to 80%

Thermal 2

Liquid air energy storage (LAES) [or *Cryogenic energy storage (CES)*]

1. **Charging the system**
   The charging system is an air (or N_2) liquefier, using electrical energy (700 litres of ambient air become 1 litre of liquid air).
2. **Energy Storage**
   The liquid air is stored in an insulated tank at low pressure, which functions as the energy store. Such equipment is used globally for bulk storage of liquid N_2, O_2 and LNG can hold GWh of energy.
3. **Power Recovery**
   When power is required, liquid air is drawn from the tank(s) and pumped to high pressure. The air is evaporated and superheated to ambient temperature. The warm high-pressure gas drives a turbine. The cold can be captured by a proprietary high-grade cold store, to be used later during the liquefaction process to enhance efficiency.

Example: Highview 2.5 MWh installation in UK (2011)

Kinetic energy $\frac{1}{2}\, m \cdot v^2$

Flywheels are a confirmed method to store significant quantities of energy for a limited time, e.g. for use during deceleration of a vehicle (instead of dissipating it in the brakes), for re-utilization afterwards to provide additional acceleration, or for providing pulsed power for particle accelerators. *(They have been used to power buses (using mechanical gearing rather than electricity)*

Modern composite materials are ideal for flywheels that spin at very high revolution frequencies (tens of thousands of rpm) in a partial vacuum enclosure (to reduce drag), and supported via magnetic bearings. These devices are used to avoid transmitting pulsed energy to the electrical grid, and for optimizing the power factor.

Moving parts – maintenance is important (can be critical)

Such Kinetic Energy Storage Systems (KESS) are based on an electrical machine joined to a flywheel. To store energy, the machine works as a motor and the flywheel is accelerated until it stores the nominal energy. When the system provides energy, the electrical machine works as a generator and the flywheel decelerates.

The aim is to store electrical energy when it the load is light and to provide devices with additional electrical power when they need it, without having to draw excessive power from the network. These systems provide ride-through power and voltage stabilization for power quality and power recycling applications. Typical commercial products (ELYTT) are:

100 kW / 5 MJ and 400 kW / 200 MJ

On board flywheel

Example of a commercial flywheel system for use in trains

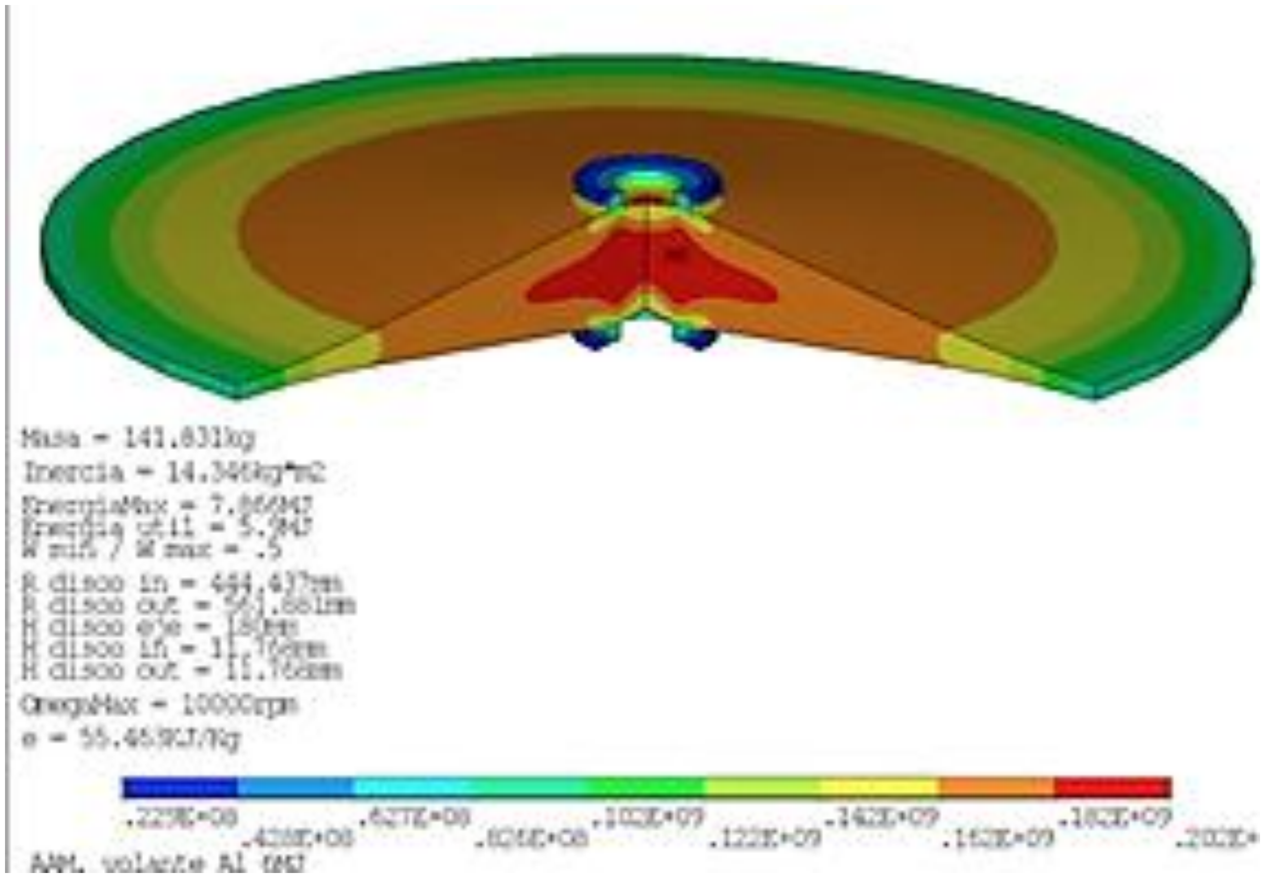
Energy	10 MJ
Power	310 kW
Operation Voltage	1100 V
Current max	365 A
Number of phases	3
Rotating speed	10000 r.p.m.
Flywheel diameter	376 mm
Rotating mass weight	350 kg
Total weight	1.500 kg
Guiding system	Standard Bearings with magnetic levitation
Operation conditions inside	Partial vacuum

Electrical data
Power: 310 kW
Stored energy: 2.77 kWh
Energy at full power: 1.87 kWh
Time at full power: 34 seconds
Output voltage: from 400 V to 1100 V
Input voltage: from 450 V to 1100 V

Courtesy: ELYTT Energy

Mechanical Data
Speed: 5028 to 10067 rpm
Weight: 1500 kg
Dimensions (machine)
Height: 750 mm
Diameter (Footprint): 934 mm
Dimensions (electronics)
Height: 750mm
Width: 1600 mm
Depth: 2104 mm

Environmental Data
Operating temperature:
from -20°C to 40°C
Humidity: 95 %
Noise: 70 dB to 1mf



Magnetic energy $\int_V (B^2/2\mu_0)d\tau = ½ L \cdot I^2$

To put things into perspective, a field of 2 T in a volume of 1 m^3 (of air or vacuum) stores an energy of $(40/8\pi)10^6$ J $\approx$ 1.6 MJ, i.e. about the quantity of energy stored in a car battery.

This would therefore be an application for higher field (i.e. using superconducting magnets). If in the above example the field is pushed form 2 T to 10 T the stored energy is 40 MJ, and one can envisage larger volume magnets (toroidal or solenoidal). ***The CMS magnet at the CERN LHC stores 2.6 GJ***.

For high fields we need cryogenics – an additional headache. Demonstrator helium-free HTS coils, cooled using cryocoolers have been made for storing a few MJ.

Cost is also problem. For 10 MJ think at least 1 M$...

The Japanese have been quite active in studying the use of superconducting magnetic energy storage (**SMES**), and the corresponding design of suitable magnets, with regard to

- Use in conjunction with medical accelerators (10 MJ scale)
- Use in conjunction with large accelerators (100 MJ scale)

General use of this technique will have to pass through the stage of a practical demonstration. A major difficulty is the lack of off-the-shelf industrial components, which means that the cost is high. Potential users are of a conservative nature…

This will be further discussed in the second lecture.

- **Capacitive energy** $\frac{1}{2} C \cdot V^2$

This is a dynamic sector, due to the development of self-healing components for moderately high voltage applications

The public is becoming aware of the possibilities thanks to the incorporation in "stop-start" in cars, where it reduces the peak demand on the battery when starting the engine.

Attractive due to its passive nature (no moving parts, no cryogenics), and the mass production of components.
But the energy density is low (compared with some batteries), so one needs space... And the components may be delicate...

Sometimes assimilated in the category of batteries

Will also be further discussed in the second lecture.

If it fails, a capacitor will fail in one of three modes

1. Capacitor short-circuit

The capacitor gets short circuited with very high loss factor. It occurs when the dielectric breaks down completely and film melts. This is severe case.

2. Capacitor open-circuit

The capacitance value drops by more than 30% . There is no visible damage to the film metallization. This failure is due to poor metal spraying, or to defective welding of terminals.

3. Degradation of capacitance

There can be two reasons for this

- Excessive concentration of self-healing at the weak spots of the dielectric, leaving other areas unaffected
- Metal oxidation

$\Rightarrow$ ***Importance of very strict quality control***

- **Chemical energy** *reversible reaction* *i.e.* **batteries**

There is an immense effort put into improving batteries for large scale energy storage, in particular for powering cars and for domestic use (in combination with photovoltaic (PV) power production, this serves to reduce reliance on networks).

As was the case for PV, mass production and competition are driving down costs, opening the market to more users and enhancing the effect. Power utilities in certain cases are even getting interested (note the deal between TESLA and an Australian producer).

Problems due to volatility of material cost should be temporary

Batteries are in the news

Economie & Finance

Emplois américains
Pour ce mois de juin favorable aux jobs d'été, l'économie américaine a créé 222 000 emplois. Toutefois, le taux de chômage est remonté d'un dixième de point pour atteindre 4,4%.

MARIYA GABRIEL
Commissaire européenne chargée des Services numériques
L'eurodéputée bulgare occupera les fonctions de commissaire à l'Economie et à la société numériques. Sa nomination a été avalisée vendredi.

3%
EMPLOI Le taux de chômage en Suisse, un des plus bas du monde, a continué de refluer en juin pour s'établir à 3%, contre 3,1% le mois précédent, a annoncé vendredi le Secrétariat d'Etat à l'économie. Fin juin, 133 603 personnes étaient inscrites au chômage.

SMI 8883,27 -0.04%	↓	Dollar/franc	0,9639	↑
		Euro/franc	1,0987	↓
Euro Stoxx 50 3463,84 +0,05%	↑	Euro/dollar	1,1408	↓
		Livre st./franc	1,2480	↓
FTSE 100 7350,92 +0,19%	↑	Baril Brent/dollar	46,66	↓
		Once d'or/dollar	1211,62	↓

Une course aux batteries géantes débute

ÉNERGIE Confrontée à des pénuries d'électricité, l'Australie a demandé à Tesla de l'aider à la stocker. L'augmentation des énergies renouvelables dope la demande pour les batteries, marché sur lequel la société d'Elon Musk n'est de loin pas la seule

ANOUCH SEYDTAGHIA
@Anouch

L'Australie vit un paradoxe énergétique. C'est le premier exportateur mondial de charbon, qui lui permet aussi de produire plus de 60% de son électricité. Mais c'est aussi un pays dont le réseau électrique est fragile et qui s'est montré plusieurs fois incapable de satisfaire la demande lors de pics

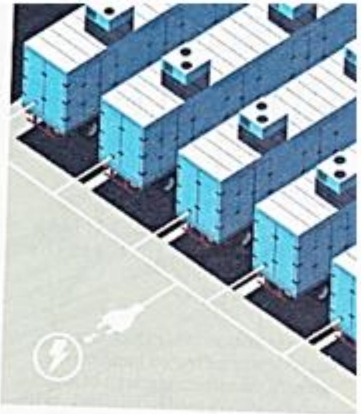
«Tesla a besoin de décrocher de gros contrats comme tête de pont, donc la société va être agressive sur les prix»
MICHAEL BARNARD,

30 000
Les batteries installées en Australie auront une capacité de stockage de 100 mégawatts, de quoi approvisionner 30 000 ménages.

1000
Ces batteries correspondent à environ 1000 batteries de Tesla.

100 jours, sans communiquer de prix. Si ce délai ne devait pas être respecté, le système ne serait pas facturé.

Selon un analyste de Bloomberg New Energy Finance, «ce sera le plus grand système de batteries lithium-ion au monde. Mais la concurrence pour être numéro un est serrée, puisque des projets de taille similaire sont prévus en Australie, au Canada et au Japon.» Récemment, un analyste indépendant, Michael Barnard, affirmait sur le site Quora que cette installation «allait résoudre les problèmes de l'Australie pour l'année prochaine [...]. Tesla a besoin de décrocher de gros contrats comme tête de pont, la société va donc être agressive sur les prix.» Selon le spécialiste, des batteries d'une capacité totale de 100 mégawatts correspondent à peu près à des batteries pour 1000 voitures Tesla.



Better batteries

A SIMPLE SOLUTION THAT COULD TRANSFORM CLEAN POWER

In an otherwise empty lot near San Diego, two dozen trailers jammed with 400,000 batteries are part of an experiment that could revolutionize clean energy. If it works, the batteries would solve a key problem with wind and solar power—namely, that one works only on blustery days and the other when the sun is out. Developers say the batteries will store excess energy for later use, allowing power providers to rely less on fossil fuels as a backup.

Energy experts are optimistic, as are the many investors with a stake in the sector. "Networks care about reliability," says Logan Goldie-Scot, an energy-storage analyst at Bloomberg New Energy Finance. "Energy storage is being viewed by network operators as a potential tool in their toolbox, and that hasn't been the case up until now."

This kind of energy storage would be a game changer for the growing list of cities that have pledged to source all their electricity from wind and solar in the coming decades. Until now, that goal was considered not only lofty but also practically unattainable.

Now all eyes are on San Diego's pilot program, the most expansive one to date. It's operated by San Diego Gas & Electric, which already gets more than one-third of the electricity it provides from renewable sources like wind and solar. The batteries store enough electricity to power 20,000 homes for four hours. If all goes according to plan, the program will show utilities that going 100% renewable can be more than a pipe dream. —*Justin Worland*

Battery

A device that converts chemical energy into electrical energy

- Positive terminal – **anode**
- Negative terminal – **cathode**
- An **electrolyte** allow ions to move the electrodes $\Rightarrow$ **current**

First battery (1800) Alessandro Volta

Advances in technology

- improved **output** and **reliability** of battery systems
- **economies of scale** $\Rightarrow$ **cost reduction** $\Rightarrow$ more applications

“Wet” devices

The “Workhorse” has been (and is) the lead-acid battery

Pros

- Mature technology
- Mass produced
- Lead can be recycled

Cons

- Heavy
- Relatively short life (5 years)
- Poor storage density

Solid state batteries 1

Lithium Ion (Li-Ion) batteries (*1991, Sony and Asahi Kasei*)

Advantage w.r.t. lead-acid batteries

- Better energy density
- Low weight (no lead)
- No acid
- No H_2 during charging

Synergy with emergence of **electrically powered vehicles** (EV)

Li-Ion refers to an array of chemistries, characterized by the transfer of Li ions between electrodes during charge/discharge

Chemistry is chosen to satisfy system requirements regarding

energy density ***safety*** ***power capability*** ***cost***

Price of lithium has increased from $3 to $10 a kilo…

La soif de lithium déclenche une ruée vers «l'or blanc»

MATIÈRES PREMIÈRES

Le prix du lithium a triplé en cinq ans, se situant désormais aux alentours de 10000 dollars la tonne. La croissance du marché des véhicules électriques est une cause directe de cette envolée des prix

La course des constructeurs automobiles vers le «tout électrique» entraîne dans son sillage l'ensemble de la chaîne d'extraction et de production du lithium, principal composant des batteries des téléphones portables, des ordinateurs… et des voitures électriques. Tesla confirmait récemment son objectif de produire 500000 véhicules en 2018 et d'atteindre le million d'unités en 2020, ce qui représenterait une demande en lithium supérieure à la production totale annuelle actuelle.

Selon l'organisme chargé du développement de l'activité économique du Chili, la demande mondiale de lithium devrait atteindre les 190000 tonnes en 2017. Plusieurs prévisions évoquent un chiffre supérieur à 500000 tonnes dès 2025. Goldman Sachs a évalué dans un rapport datant de décembre 2015 qu'une croissance de 1% sur le marché des voitures électriques ferait grimper les besoins annuels en lithium de 70000 tonnes.

Depuis 2011, le prix de la matière première a explosé. Dans certains contrats, la tonne s'échangeait à près de 4300 dollars en 2011, contre plus de 12000 dollars en début d'année. L'an dernier, le prix de «l'or blanc» a augmenté de 60%. Le principal indicateur de prix du lithium, qui n'est pas coté en bourse, se limite au cours boursier des entreprises d'extraction, telles que la société chilienne SQM ou la société américaine Albemarle. Sur les dix-huit derniers mois, le cours des deux entreprises a connu une croissance de respectivement 74 et 88%.

Le Chili dispose actuellement de plus de la moitié des réserves mondiales déjà exploitées

Le «triangle du lithium»

L'Amérique du Sud abrite les plus grands gisements de lithium au monde, au cœur des *salars* (déserts de sel) des hauts plateaux d'Argentine, du Chili et de Bolivie. Cette région, surnommée le «triangle du lithium», représente 70% des réserves mondiales. Selon l'Institut d'études géologiques des Etats-Unis (USGS), le Chili dispose actuellement de plus de la moitié des réserves mondiales déjà exploitées (53%), devant la Chine (22%), l'Argentine (14%) et l'Australie (11%).

Aujourd'hui, le Chili semble être le mieux placé dans la course au lithium. Les conditions d'extraction en plein cœur du désert de sel d'Atacama sont optimales et permettent aux Chiliens de fournir la matière première la moins chère du marché.

L'Argentine et la Bolivie sont en retrait. Depuis décembre 2015, le nouveau président argentin, Mauricio Macri, tente de faciliter les investissements dans son pays. En Bolivie, le *salar* d'Uyuni abrite le plus important gisement du monde. Le pays disposerait de plus de 9 millions de tonnes de matière première, selon l'USGS.

La Bolivie en retard

La nationalisation de l'ensemble des ressources naturelles du pays n'a pas profité à la Bolivie, qui accuse désormais du retard sur ses voisins argentin et chilien. Le président bolivien, Evo Morales, a freiné l'ouverture des frontières aux entreprises privées étrangères, pourtant plus qualifiées, et ainsi limité considérablement l'exploitation du sol. La politique du gouvernement de Morales et le manque d'infrastructures adaptées ont pour l'instant découragé les exploitants miniers. Seules quelques tonnes de lithium ont été vendues à la Chine en 2016, la production restant minoritaire au niveau mondial. Le parlement bolivien pourrait créer dans les prochaines semaines une entreprise publique spéciale, à même de négocier et signer des contrats avec des entreprises privées nationales ou étrangères. — THIBAUD BULLIER

Solid state batteries 2

Nickel-cadmium (Ni-Cd) batteries (*in production since 1910*)

Advantage w.r.t. lead-acid batteries

- Longer life
- Near maintenance-free operation
- Low but acceptable energy density

Advantage w.r.t. Li-Ion

- Cost (due to long manufacturing experience)

Have been used in energy storage systems

Solid state batteries 3

Sodium-sulphur (Na/S) batteries (*1960, Ford; now NGK, Japan*)

Operate at 300 to 350 °C - *not likely to appear in homes!*
Remarkable round-trip efficiency (up to 90%)

Anode is molten sulphur, cathode is molten sodium
Separation(electrolyte) is sodium alumina

Largely used for energy storage in Japan (190 sites)
Largest installation: 245 MWh, 34 MW

Nickel metal hydride (NiMH)

This is the battery that Toyota has been using for its hybrid cars. The traction battery is a sealed 28 module pack storing 1.31 kWh (201.6 V, 5.6 Ah) made by Panasonic.

Energy density 46 Wh/kg; maximum output power is 1.3 kW/kg. Over 2 million Priuses have been sold. Batteries last 10 years.

This type of battery is proposed for domestic use too, as it is cheaper than Li-ion devices (but heavier and taking more space)

Flow batteries

A rechargeable battery where energy is provided by 2 chemical components, dissolved in liquids, separated by a membrane

Similar to a fuel cell

Immediate recharge possible by replacing electrolyte

It is nice to know that the technology exists –
Who knows when a killer application will appear?
Like many other ideas, it may have to wait a while…

Summary

From the very beginning, the electrical grid system designers have been aware of the importance of finding ways to store the energy

Electrical power from renewable sources (Wind, PV) fluctuates widely, focusing on the importance of storage

Electrical power and electronic engineering has advanced to make DC-DC, AC-DC and DC-AC conversion highly efficient, and components are readily available, opening up new possibilities

The public is increasingly aware of the importance of the subject and open to initiatives involving local projects to store energy – and to better understand the importance of reducing waste