Electrical Energy Storage

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***Abstract*—In today's trend to power generation from renewable sources it is necessary to store electricity. An overview is given for the different means from directly storing in the electric or magnetic field and indirect storage by chemical means, like accumulators, and mechanical like flywheel, pumped hydro and compressed air.**

An overwiew about the cost is finally given.

***Index Terms*—electricity storage, cost of electricity storage, battery technologies**

I. Introduction

This document is a model and instructions for LaTeX. Please observe the conference page limits.

II. Electricity storage

Several storage options are suitable for power supply:

1) direct electric storage
2) indirect storage
   a) chemical
   b) mechanical
   c) other

The following options apply to direct electric storage:

A. *In the electric field -> capacitor, SuperCAP*

$$W = \frac{1}{2} C \cdot V^2 \tag{1}$$

Technical specifications of a SuperCAP:

Rated capacitance	3500 F
Nominal voltage	2.5 V
Maximum voltage	2.7 V
Minimum Voktage	0 V (1.0 V for practical purposes)
Resistance HFR	< 0.5 mΩ (1 kHz or 2 s pulse)
ESR	< 1 mΩ (0.01 Hz)
Dimensions (diameter $*$ height)	$55 * 220$ mm
Volume	0.5 l
Weight	0.65 kg
Maximum current	1000 A (750 A repetitive)
Maximum specific power	3225 W/kg at 500 A
Operating temperature range	-40°C to +60°C
Transport and storage temperature	-40°C to +70°C

Price: approx. 65.- € per unit in 2011
The stored energy is

W = C $\cdot$V^2 = 3,500 $\cdot$ 2.5 ^{2} Ws = 0.003 kWh

This amounts to:

Price per kWh: approx. 300 $*$ 65.- € = 20,000 €/kWh

Weight per kWh: approx. 300 $*$ 0.65 kg = 200 kg/kWh

or: 5 Wh/kg

B. *In the magnetic field -> large (superconducting) coils*

These systems are referred to as
Superconducting Magnetic Energy Storage (SMES)

Stored energy:

$$W = \frac{1}{2} L \cdot I^2 \tag{2}$$

The first European SMES was developed by the Forschungszentrum Karlsruhe in cooperation with the University of Karlsruhe and installed in a saw mill in Fischweier/Albtal in the low voltage grid of the Badenwerk. It has a maximum storage capacity of 250 kJ and an output of 80 kVA. The SMES consists of 6 magnetic modules in a solenoid coil. Each magnetic module comprises 1,000 turns of the 1.3 mm thick NbTi superconductor and has a diameter of 36 cm. Thus, the overall design has an inductance of 4.37 H and only uses a current of 300 A to store the required energy.

The price is unknown; the stored energy of 250 kJ is 0.069 kWh!

This may be 23 times more than in a SuperCAP, but the expenses are also much higher, not to mention the issue of cooling.

The industrial-scale storage of electrical energy in either the electric or magnetic field will not be achieved in the near future.

III. Indirect storage of electrical energy as chemical energy

A. *Classic: Battery and rechargeable battery*

Comparison battery and SuperCAP

	Accumulators	SuperCAPs
Energy storage method	**Faradaic reactions** mass transfer between the electrodes	**mostly electrostatic interactions** ionic charge accumulation at the active material
discharge curve		
cycle life	depending on cycling profile	>> 1,000,000 (100%DoD)
energy level	60 Wh/kg (alkaline) 140 Wh/kg (Li-ion)	1 - 10 Wh/kg
power level	0.4 - 0.8 kW/kg (alkal.) 0.3 - 1.5 kW/kg (Li-ion)	1 - 6 kW/kg

Typical data of different battery types:

Type	Energy (1) Wh/kg	Output (2) W/kg
Lead-acid battery	50	200
Nickel-cadmium battery	53	160
Nickel-metal hydride battery	70	175
Sodium-sulfur battery battery	85	115
Lithium iron sulfide battery	95	104
Lithium polymer battery	130	140
Lithium iron phosphate battery	120	180
Zinc-bromine battery	75	45
Medium-term goals in the development of batteries	80-130	150-200

(1) 3 hours discharge cycle
(2) Peak power to a depth of discharge (DoD) of 80 %

B. *Some prices*

1) Lead-acid battery
   13.8 V /100 Ah approx. 60.- € (wholesale, 2015), that is 1.38 kWh.
   Problems in long-term use: number of cycles
2) Li-polymer battery
   22.2 V /20 Ah approx. 120.- € (wholesale, 2015), that is 0.44 kWh
   Same here: finite number of charge and discharge cycles as well as finite service life (typically about 500 cycles and 2-3 years, except batteries used in the field of space operations: here, up to 60,000 cycles with 20 % DOD for LEO or 18 years with 80 % DOD for GEO)

IV. Alternative: Fuel cell

The basic principle of storage is electrolysis: water is split into hydrogen and oxygen before the hydrogen is conventionally stored in tanks.

The fuel cell then uses the hydrogen to generate electricity.

A. *Electrolysis*

Hydrogen has been produced with tried and tested methods for over 100 years. One of these methods is the alkaline water electrolysis. This versatile method has many applications, such as the supply of hydrogen to cool generators in power plants. The conventional alkaline electrolysis has further been developed, e.g. concentrating the electrode material and separator (diaphragm or membrane) on the anode and cathode side as well as its positioning towards the electrodes. These developments have improved the efficiency. Efficiency is currently from 50 - 60%.

There are systems with an output of 100 Nm^3/h (normal cubic meter per hour), equal to an output of about 90 MW.

Another method is the PEM electrolysis: Due to its less attractive price-performance ratio, it is only suitable for smaller systems of up to 50 kW. Efficiency currently varies from 55 - 70%.

Tanks are used for storage, an unproblematic and tried and tested method.

By the way, the hydrogen can also be used differently. For example, rotary piston engines (Wankel engines) can directly run on hydrogen due to their otherwise impractically low compression.

B. *Converting hydrogen into electricity using fuel cells*

Fuel cells (FC) use a source of fuel (usually hydrogen, but also methane etc.) and oxygen (air is often sufficient) to directly generate electricity.

The following applies if gas is used as fuel: Fuel cells reach conversion efficiencies of up to 60 % (with H_2) or 40 % (with CH_4) (that is, they are actually unacceptable as rechargeable batteries!)

Their good scalability is a further advantage: Fuel cells can be produced for various power classes, from a few milliwatts up to several megawatts.

If applicable, the waste heat (more than 40 %) can be used in cogeneration.

Of course, it can also be used to generate electricity with gas from other sources.

Hydrogen ions are carried through the central membrane, the electrons travel through an external circuit.

A fuel cell stack consists of several individual fuel cells. In PEM fuel cells (Proton Exchange Membrane), each cell has two lattice electrodes separated by a membrane. Hydrogen is on one side (image left), oxygen on the other. The external electricity is generated as hydrogen is split on the hydrogen side. Each hydrogen molecule is split into two electrons and two protons. The protons are conducted to the oxygen side through the membrane. The electrons travel there through the external circuit. The reason for this is the lack of electrons on the oxygen side. Here, water is produced from protons, electrons and oxygen. The main product of the fuel cell is electricity, but waste heat is also produced. This can be used in small cogeneration plants.

Which fuels can be used?

There is not just one fuel cell. In fact, five or six different types exist. All of them are modern interpretations of the idea formed by the English physicist Sir William Grove, who wrote about *cold combustion* as early as 1839. The following list provides an overview of the different types of fuel cells.

1) The PEM fuel cell:

PEMFC	Proton Exchange Membrane Fuel Cell		
Electrolyte	Polymer membrane	**Efficiency**	60 % (H_2) 40 % (CH_4)
Anode gases			
Hydrogen (Methanol)* (Methane)*			
Temperature	0-80 C		
Output	up to 250 kW	**Note**	CO sensitive

2) The Solid Oxide Fuel Cell:

SOFC	Solid Oxide Fuel Cell		
Electrolyte	$Zr(Y)O_2$	**Efficiency**	50-65 %
Anode gases			
Hydrogen Methane Coal gas			
Temperature	800-1,000 C		
Output	10-25 kW	**Note**	Reforming of fuel gases unnecessary

3) The alkaline fuel cell (AFC):

AFC	Alkaline Fuel Cell		
Electrolyte	Potassium hydroxide (KOH)	**Efficiency**	60 %
Anode gases			
ultrapure hydrogen			
Temperature	60-90 C		
Output	20 kW	**Note**	CO_2 sensitive

4) The molten carbonate fuel cell (MCFC):

MCFC	Molten Carbonate Fuel Cell		
Electrolyte	Molten alkali carbonate	**Efficiency**	48-60 %
Anode gases			
Hydrogen Methane Coal gas			
Temperature	650 C		
Output	2.2 MW	**Note**	CO_2 needs to be present in the cell cycle

5) The direct methanol fuel cell (DMFC):

DMFC	Direct Methanol Fuel Cell		
Electrolyte	Polymer membrane	**Efficiency**	40 %
Anode gases			
Methanol			
Temperature	60-130 C		
Output	up to 250 kW	**Note**	promising since there is no H_2 production required

6) The phosphoric acid fuel cell (PAFC):

PAFC	Phosphoric Acid Fuel Cell		
Electrolyte	concentrated H_3PO_4	**Efficiency**	40 %
Anode gases			
Hydrogen (Methane)*			
Temperature	130-220 C		
Output	11 MW	**Note**	weak CO sensitive

* Hydrogen is produced via reforming

Each principle has specific advantages and disadvantages. Not only are fuel cells still very expensive, their actual service life is also often too short. And there is one essential problem: Where does the fuel used in fuel cells come from? As long as fossil energy sources such as natural gas are used, there is nothing to gain. The reason for the popularity of the fuel cell is the fact that it works well with hydrogen, which can be produced from renewable energies.

V. Alternative Supply with Hydrogen?

When it comes to the future of the fuel cell, hydrogen economy is often talked about, such as the production of hydrogen in giant solar farms in the desert. From there, the hydrogen produced via electrolysis is supposed to be transported to Central Europe in large tankers or through pipelines. Apart from the fact that conversion and transport would generate major losses, there are other reasons why this is still a long way off. Today, industrial-scale fuel cells are powered with two other fuels: Methanol or methane gas (natural gas). Depending on the type of fuel cell, these fuels can be processed directly or via a so-called reformer. Reformers separate hydrogen from methane or methanol, which can then be used for the actual fuel cell.

Another concept is a *hybrid* hydrogen economy. Hydrogen produced via electrolysis (e.g. 5 %) is added to regular natural gas. In this way, the giant natural gas storage facilities that already exist can be utilized and this mixture of gases can be used as before. Natural gas consists of 85 - 98% methane, 4 - 1% alkanes and 11 - 1% inert gases.

The former town gas consisted of 51% hydrogen, 21% methane and 15% nitrogen plus 9% carbon monoxide.

VI. Redox Flow Battery

Advantages:

- Highest number of full cycles of all battery systems (> 10,000), proven without capacity and efficiency loss
- 100% chargeable and dischargeable without disadvantages on the lifetime (Li ions only approx. 80%, lead only approx. 50%)
- Can be configured as required: power and capacity can be configured separately
- Ideal for longer storage periods: From approx. 3 hours on, the most economical battery technology for very high energies/performances
- Storage of high capacities is comparatively simple, since only a few subsystems are required. In contrast, a 100kWh Li-Ion system already consists of thousands of single batteries, which all have to be constantly monitored and adjusted to each other regarding the charge state.
- Very low self-discharge with battery switched off, approx. 2% per year
- Safe: No fire hazard due to design principle

Disadvantages:

- Efficiency AC/AC 65-75% (LiIon 85%, Pb 80%)
- Maintenance of process engineering necessary (pumps, valves,...)
- Limited use in water protection areas
- Costs reasonable only with larger systems up from approx. 100 kWh
- For applications with a low number of cycles and/or a short storage period, it is not feasible
- only suitable for stationary applications

VII. Mechanical storage

Type	State of development	Potential output	Actual output
Compressed air	Comm.	50 - 300 MW	100 - 300 MW
Pumped storage plant	Comm.	250 - 2,000 MW	5 - 2,100 MW
Flywheel	Demos	1 - 1,000 MW	< 1 MW (1 kW for 2 hours in a telecom application)

All three versions have an efficiency of about 80%

VIII. Compressed Air Energy Storage (CAES) in salt domes

IX. Pumped storage plants

Kopswerk II in Vorarlberg/Austria built 2004-2008 – 175 MW

X. Flywheel energy storage

XI. Comparative cost estimation of industrial-scale plants

Cost of construction €/kW		Ditto €/ kWh	Storage time in h	Total €/kW if h = 6)
Compressed air storage (100 MW)	390	1	6	396
Pumped storage plant (1,000 MW)	110	10	6	170
Battery (100 MW)	120	170	6	1,140
SMES (1,000 MW)	120	300	6	1,920
Flywheel energy storage (100 MW)	150	300	6	1,950

XII. Cost example of the low-power sector:

An electrolyzer with an equivalent power of 2 kW, a storage device with an equivalent capacity of 10 kWh and a fuel cell of 1.5 kW 130,000 € (actual price 2012).

In 2015, the prices of fuel cells went down and remained stable in the case of electrolyzers. In contrast, tanks have become more expensive:

Current prices SOFC fuel cell 1.5 kW 29,000 € net, electrolyzer 1 kW 27,000 €