Renewable Energy Technology

# Energy Storage

**Storage modes are determined by the particular end-use applications**

# Energy Storage

Part 1: Introduction

## Main Parameters

Energy density: The amount of energy that can be stored.

Recovery rate: The efficiency at which the energy can be recovered.

Hydrogen has for example has one of the highest storage densities (kWh/kg) of 38 as compared to that of lead acid batteries, 0.04.

The efficiency of work exchange processes:

$$\eta_{cycle} \equiv \frac{W_{recovered}}{W_{in}} = \eta_{in}\eta_{out}$$

# Generic Storage Systems

**Electrochemical systems**
batteries and flow cells

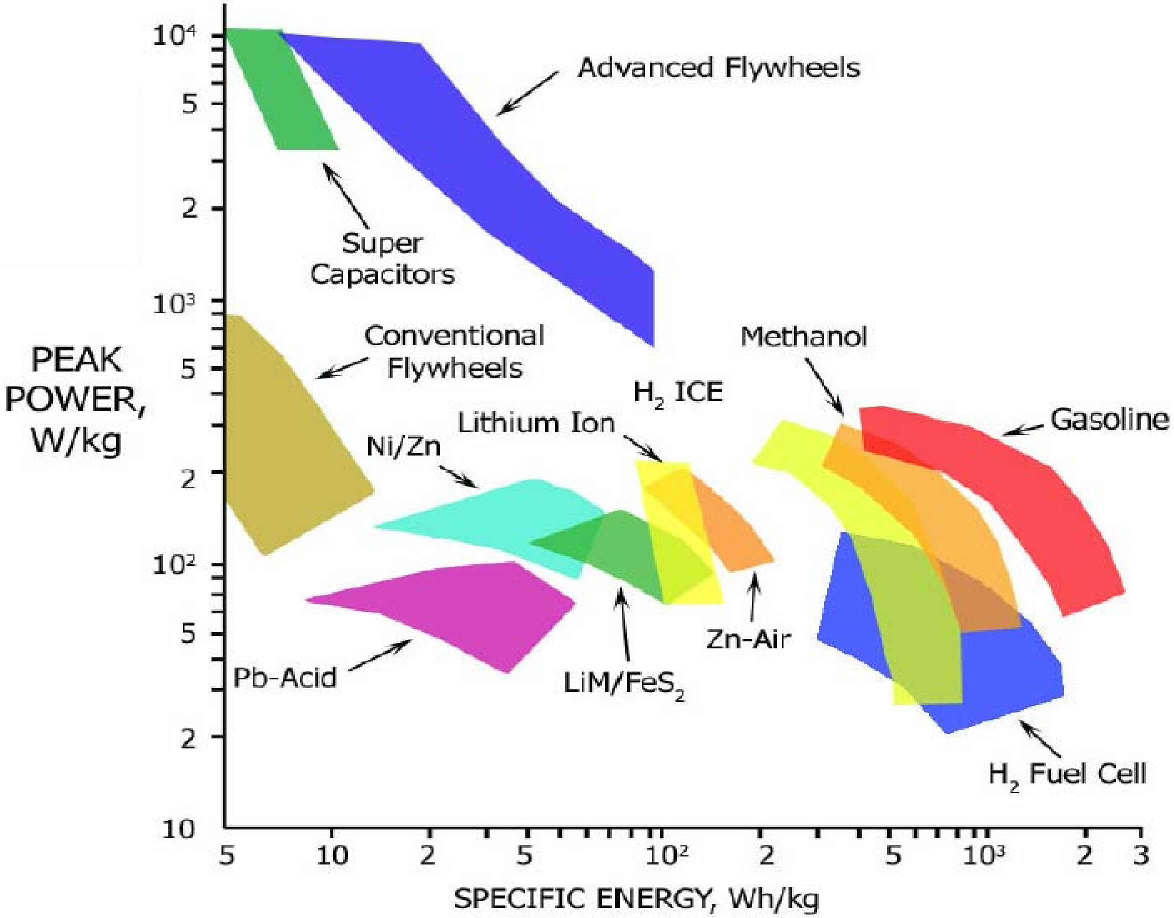
**Mechanical systems**
fly-wheels and compressed air energy storage (CAES)

**Electrical systems**
super-capacitors and super-conducting magnetic energy storage (SMES)

**Chemical systems**
hydrogen cycle (electrolysis -> storage -> power conversion)

**Thermal systems**
sensible heat (storage heaters) and phase change

# Ragone Plot




Source: Tester et. al. Sustainable energy, MIT Press

# Energy Density

| Method | kWh/kg |
|---|---|
| Gasoline | 14 |
| Lead Acid Batteries | 0.04 |
| Hydrostorage | 0.3/$m^3$ |
| Flywheel, Steel | 0.05 |
| Flywheel, Carbon Fiber | 0.2 |
| Flywheel, Fused Silica | 0.9 |
| Hydrogen | 38 ← |
| Compressed Air | 2/$m^3$ |

# Energy Storage

Part 2: Batteries

# Battery Storage

Designed for load leveling

Large number of batteries charged during low demand periods

One acre could store 400 MWh of energy, deliver 40 MW for 10 hours

Batteries require environmentally damaging chemicals

Typical installation: Southern California Edison

8000 lead acid battery modules to deliver up to 10 MW of power for four hours of continuous discahrge

# History of the Battery

## Second coming

Batteries have been around for over 200 years, and as early as 1900 they were already being used to power cars

1800 — Alessandro Volta invents the voltaic pile - the first battery

1832 — Robert Anderson invents the first electric carriage

1859 — French inventor Gaston Planté develops the first practical rechargeable lead-acid battery - the basis of today's conventional car battery

1897 — Regenerative braking first used in a car to recharge its battery, by P. A. Darracq in Paris

1899 — Waldmar Jungner invents the nickel-cadmium rechargeable battery. Almost 100 years will pass before it is used in hybrid cars

1900 — MORE ELECTRIC AND STEAM-POWERED CARS ON THE ROAD THAN THOSE POWERED BY THE INTERNAL COMBUSTION ENGINE

1908 — Henry Ford launches the Model-T

1912 — Electric car production peaks

1930s — Electric cars all but gone from the streets

1970s — M. S. Whittingham at Binghamton University, New York, proposes a design for lithium batteries

1975 — The nickel hydrogen battery patented - rapidly adopted for powering low Earth orbit satellites

1986 — The nickel-metal hydride battery (NiMH), a variation on nickel hydrogen, patented by entrepreneur and inventor Stanford Ovshinsky

1990 — Commercialisation of the NiMH battery

1991 — First commercial lithium-ion battery sold by Sony of Japan

1997 — Toyota Prius hybrid electric car launched, partly powered by NiMH batteries

2006 — Tesla Motors launches the world's first all-electric production car - the Tesla Roadster - powered by lithium-ion batteries

2009 — US government pledges to invest $2 billion in battery development

# Battery Characteristics

1. Energy Density
2. Rechargeable
3. Customizable
4. Nontoxic and nonvolatile
5. Earth abundant materials
6. affordability

# Performance Factors

1. Life time (maximum number of charge and discharge cycles)
2. Overall cycle efficiency
3. Depth of discharge per cycle (deep cycle - less instant energy but longer term energy delivery: e.g.: Golf cart battery)
4. Cost of unit of power or energy stored

# Rechargeable Battery Characteristics

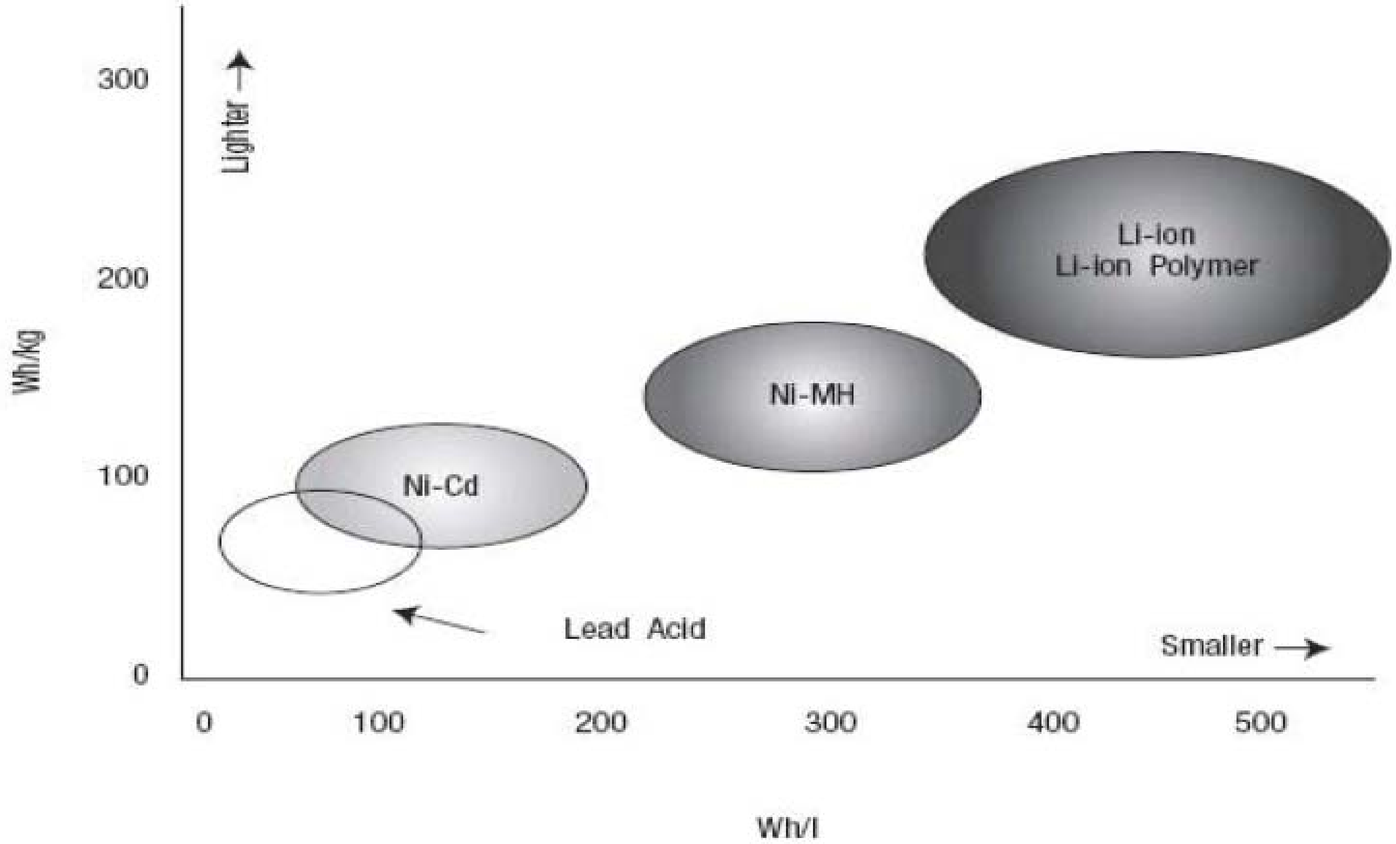
| Properties | Wh/kg | Wh/m$^3$ | Voltage | Cycle Life |
|---|---|---|---|---|
| Lead acid | 35 | 0.08 | 2 | 400 |
| Nickel Cadmium | 35 | 0.08 | 1.2 | >1000 |
| Nickel hydrogen | 55 | 0.06 | 1.2 | >10,000 |
| Lithium | 150 | 300 | >3.6 | >2,000 |

http://www.afrlhorizons.com/Briefs/Feb04/PR0306.html

# Rechargeable Battery Characteristics

| | Nickel-cadmium | Nickel-metal-hydride | Lead-acid sealed | Lithium-ion cobalt | Lithium-ion manganese | Lithium-ion phosphate |
|---|---|---|---|---|---|---|
| **Gravimetric Energy Density** (Wh/kg) | 45-80 | 60-120 | 30-50 | 150 - 190 | 100 - 135 | 90 - 120 |
| **Internal Resistance** in mΩ | 100 to 200[1] 6V pack | 200 to 300[1] 6V pack | <100[1] 12V pack | 150 - 300[1] pack 100 -130 per cell | 25 – 75[2] per cell | 25 – 50[2] per cell |
| **Cycle Life** (to 80% of initial capacity) | 1500[2] | 300 to 500[3,4] | 200 to 300[3] | 300 - 500[3] | Better than 300 – 500[4] | >1000 lab conditions |
| **Fast Charge Time** | 1h typical | 2 to 4h | 8 to 16h | 1.5 - 3h | 1h or less | 1h or less |
| **Overcharge Tolerance** | moderate | low | high | Low. Cannot tolerate trickle charge. | | |
| **Self-discharge / Month** (room temperature) | 20%[5] | 30%[5] | 5% | <10%[6] | | |
| **Cell Voltage** Nominal Average | 1.25V[7] | 1.25V[7] | 2V | 3.6V 3.7V[8] | Nominal 3.6V Average 3.8V[8] | 3.3V |
| **Load Current** peak best result | 20C 1C | 5C 0.5C or lower | 5C[9] 0.2C | <3C 1C or lower | >30C 10C or lower | >30C 10C or lower |
| **Operating Temperature**[10] (discharge only) | -40 to 60°C | -20 to 60°C | -20 to 60°C | -20 to 60°C | | |
| **Maintenance Requirement** | 30 to 60 days | 60 to 90 days | 3 to 6 months[11] | not required | | |
| **Safety** | Thermally stable, fuse recommended | Thermally stable, fuse recommended | Thermally stable | Protection circuit mandatory; stable to 150°C | Protection circuit recommended; stable to 250°C | Protection circuit recommended; stable to 250°C |
| **Commercial use since** | 1950 | 1990 | 1970 | 1991 | 1996 | 2006 |
| **Toxicity** | Highly toxic, harmful to environment | Relatively low toxicity, should be recycled | Toxic lead and acids, harmful to environment | Low toxicity, can be disposed in small quantities | | |

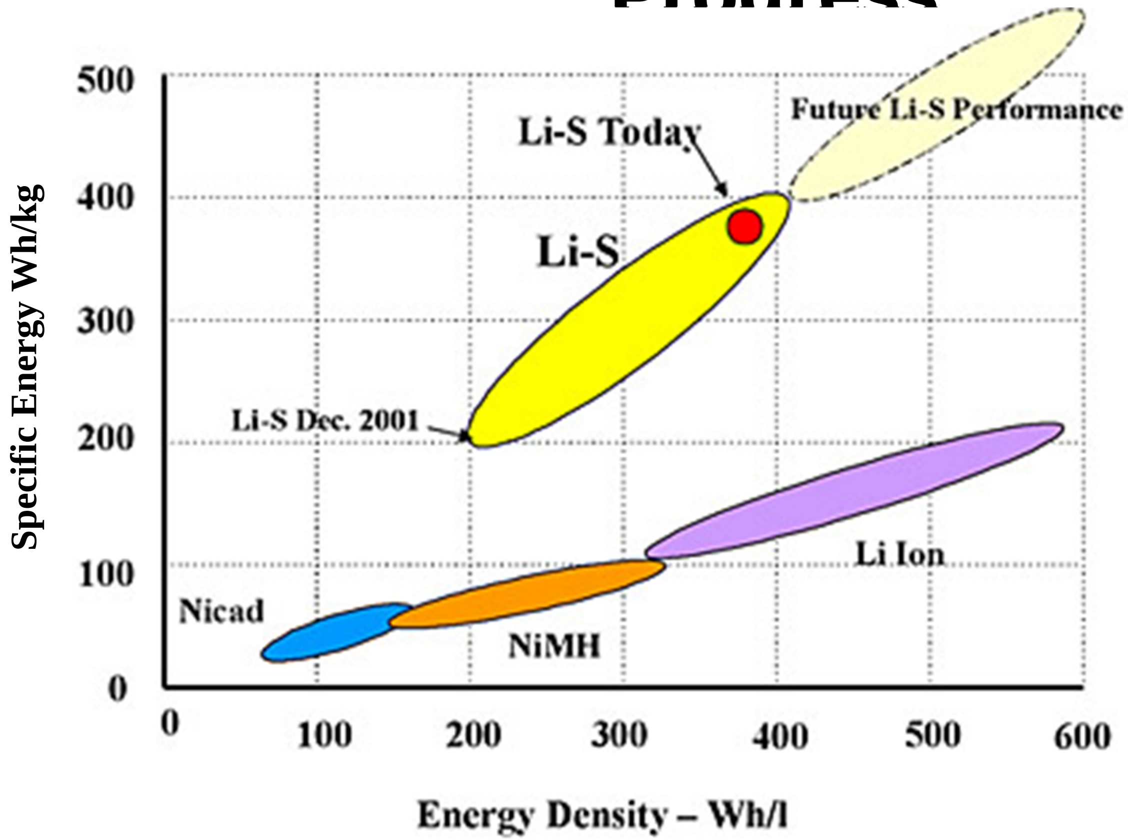
# 400 Wh/kg Goal




Li-Ion batteries operate at higher voltages than other rechargeables, typically about 3.7 volts for lithium-ion vs. 1.2 volts forNiMH or NiCd. This means a single cell can often be used rather than multiple NiMH or NiCd cells. Lithium-ion batteries also have a lower self discharge rate than other types of rechargeable batteries.

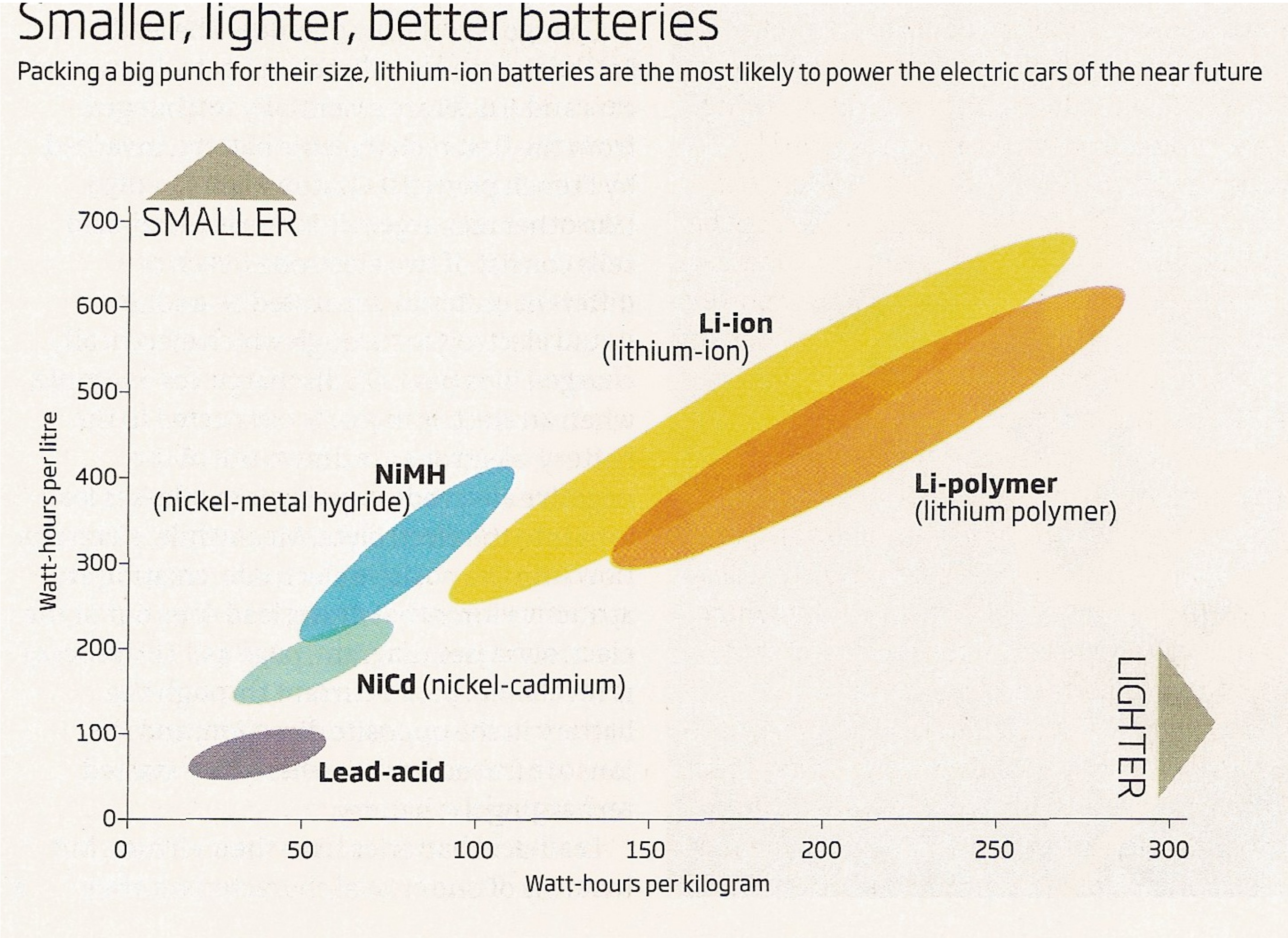
NiMH and NiCd batteries can lose anywhere from 1-5% of their charge per day, (depending on the storage temperature) even if they are not installed in a device. Lithium-ion batteries will retain most of their charge even after months of storage.

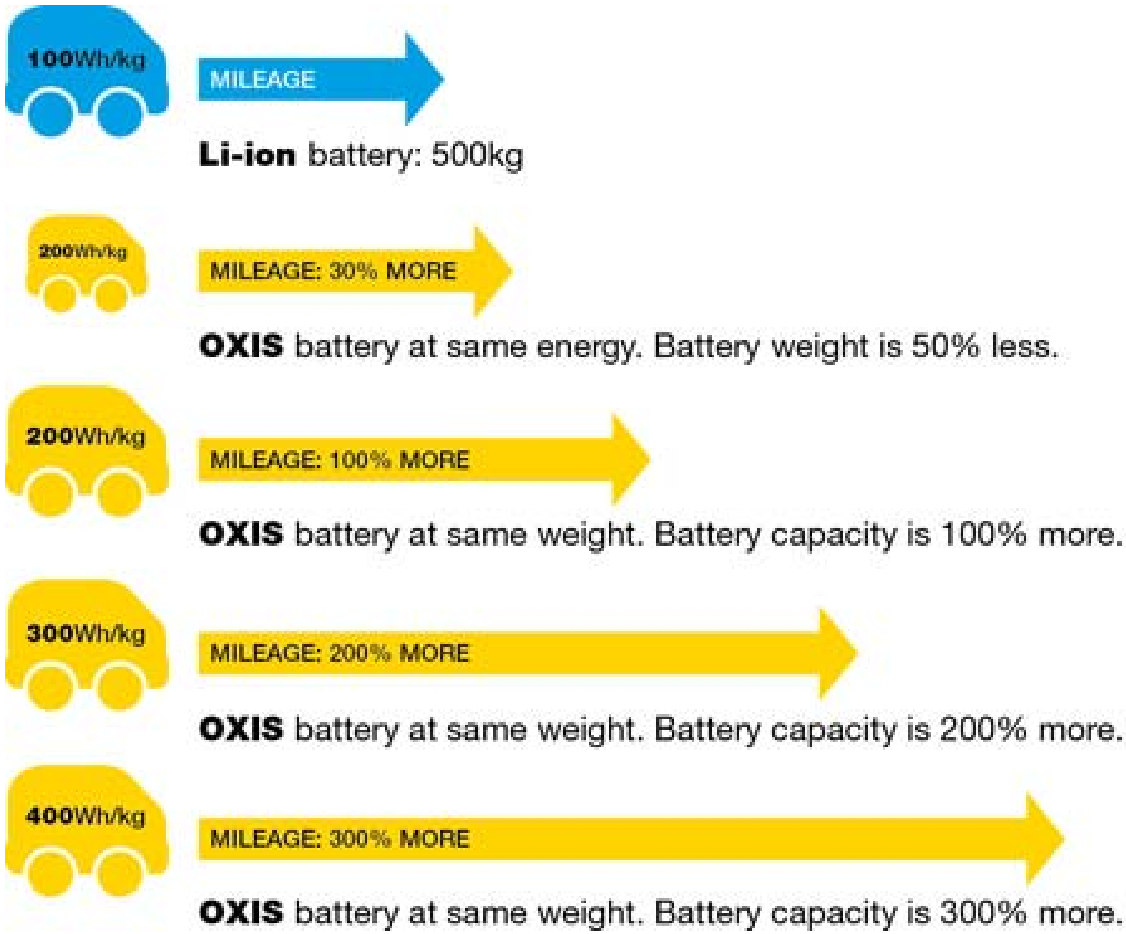
# Battery Technology Progress




http://www.sionpower.com/

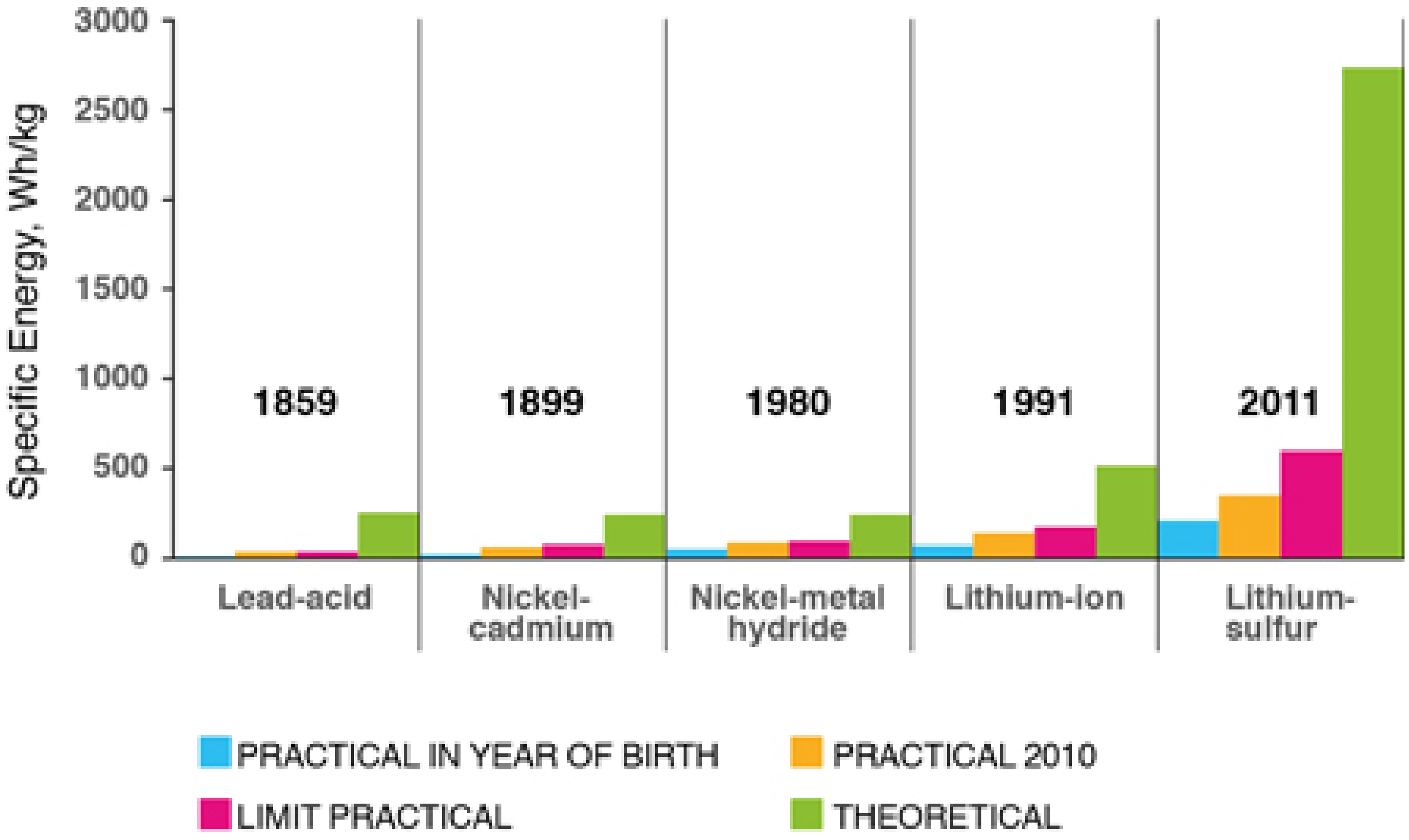
# Car Batteries



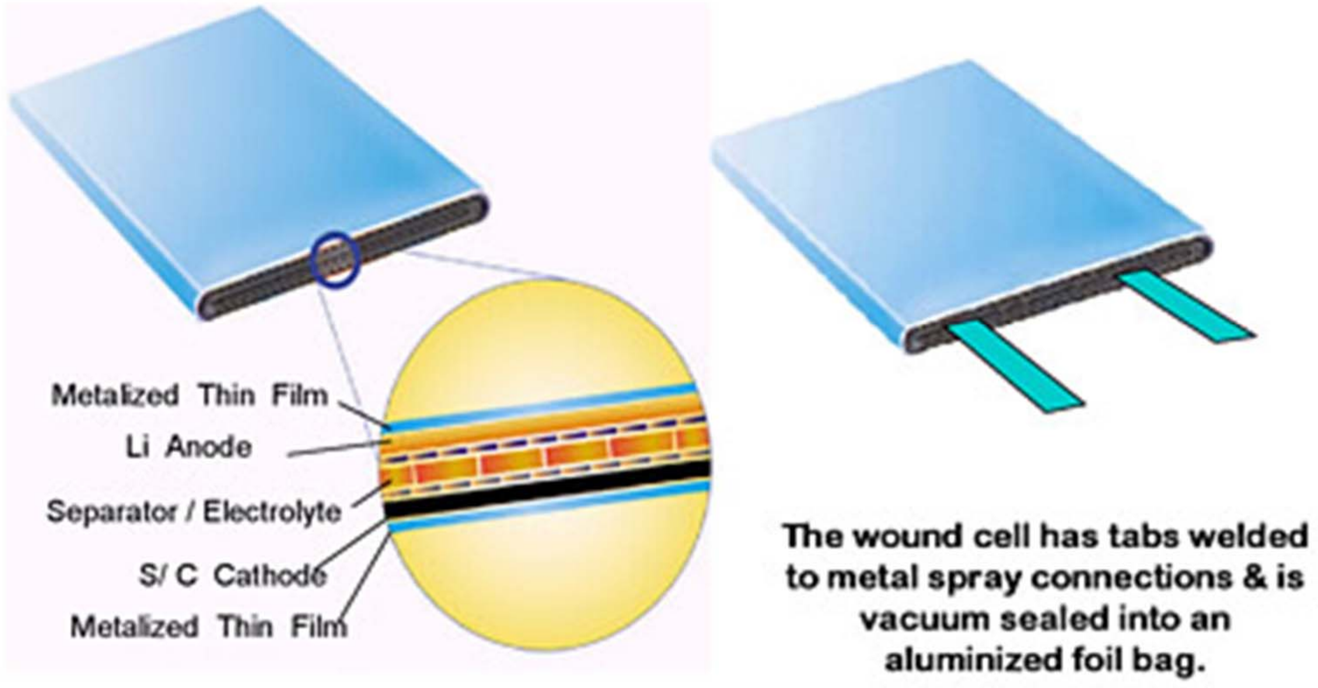


100Wh/kg
MILEAGE
Li-ion battery: 500kg
200Wh/kg
MILEAGE: 30% MORE
OXIS battery at same energy. Battery weight is 50% less.
200Wh/kg
MILEAGE: 100% MORE
OXIS battery at same weight. Battery capacity is 100% more.
300Wh/kg
MILEAGE: 200% MORE
OXIS battery at same weight. Battery capacity is 200% more.
400Wh/kg
MILEAGE: 300% MORE
OXIS battery at same weight. Battery capacity is 300% more.

# State of the Art – Battery Technology



# ┐Li-Sulphur Battery Configuration



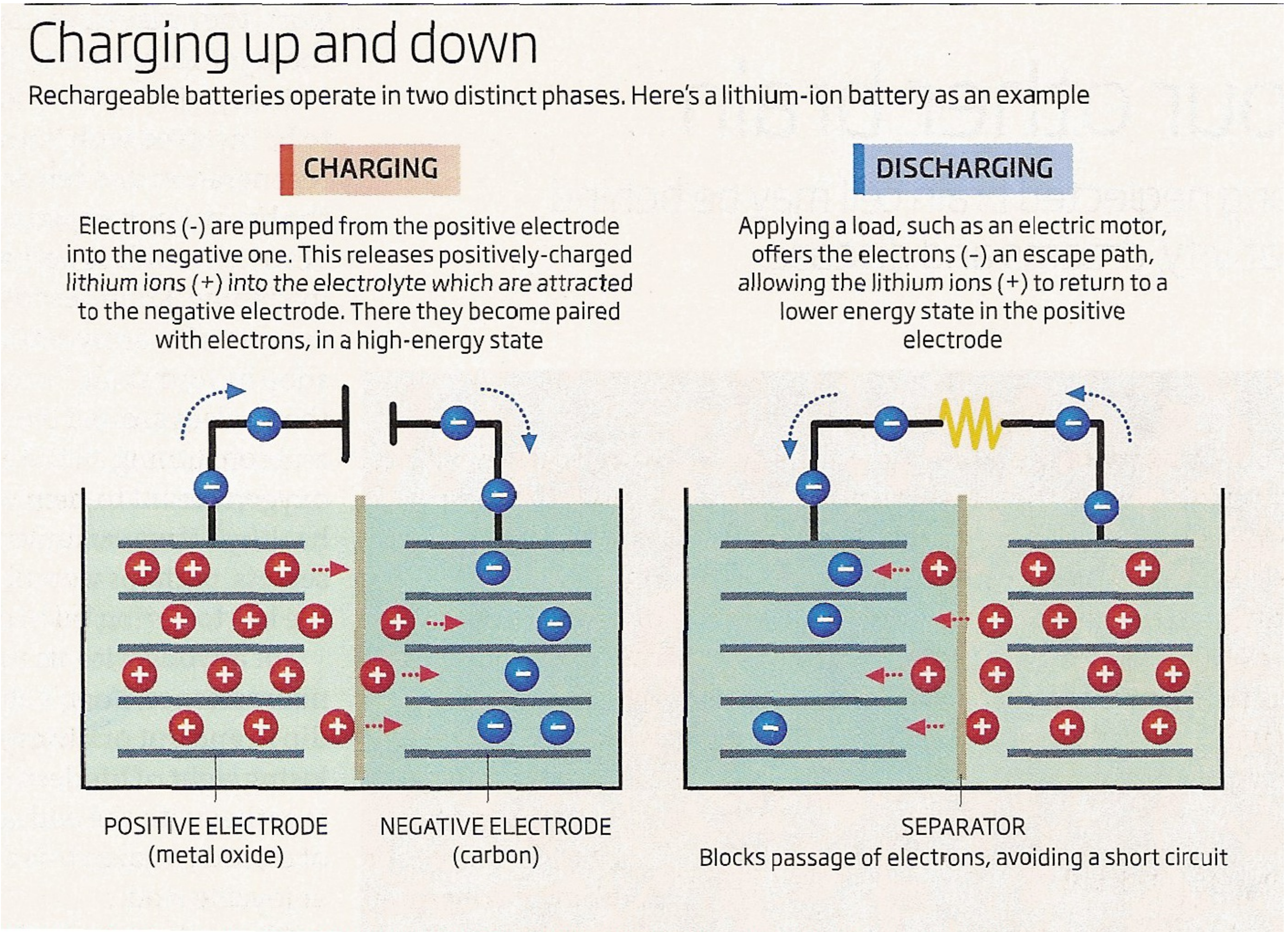

http://www.sionpower.com/

# Megawatt-class Large-capacity Energy Storage System


40ft-long container unit, which houses more than 2,000 units of lithium-ion rechargeable batteries. The system has the capacity to store 408 kWh (kilowatt hour) of power and is designed to have a system efficiency of 90%.

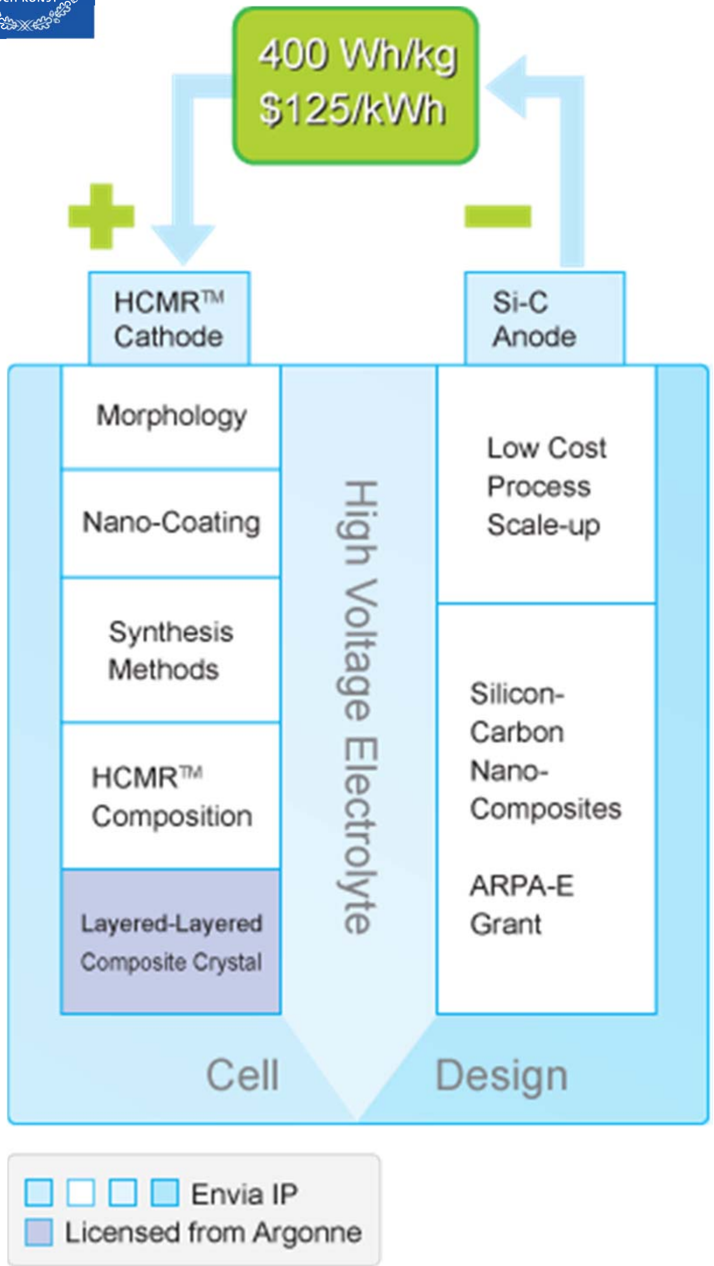
132 *wh/kg*; 284 *wh/liter*

# Li-Ion Battery Operation




In many Li-Ion batteries, the cathode is made from lithium cobalt oxide. Replacing cobalt with another metal, Chromium, for example has up to six active electrons compared with cobalt's maximum of three. This may result in 500 watt-hours per kg.

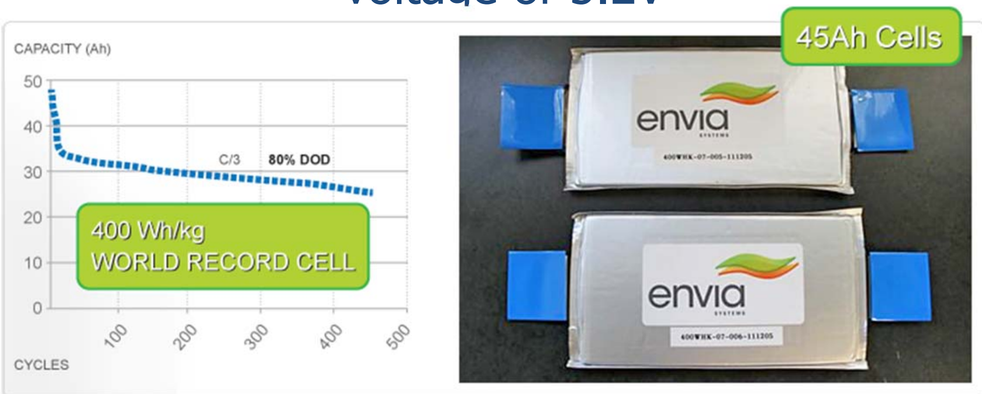
# Envia Li-Ion Battery




High Capacity Manganese Rich (HCMR™) cathode

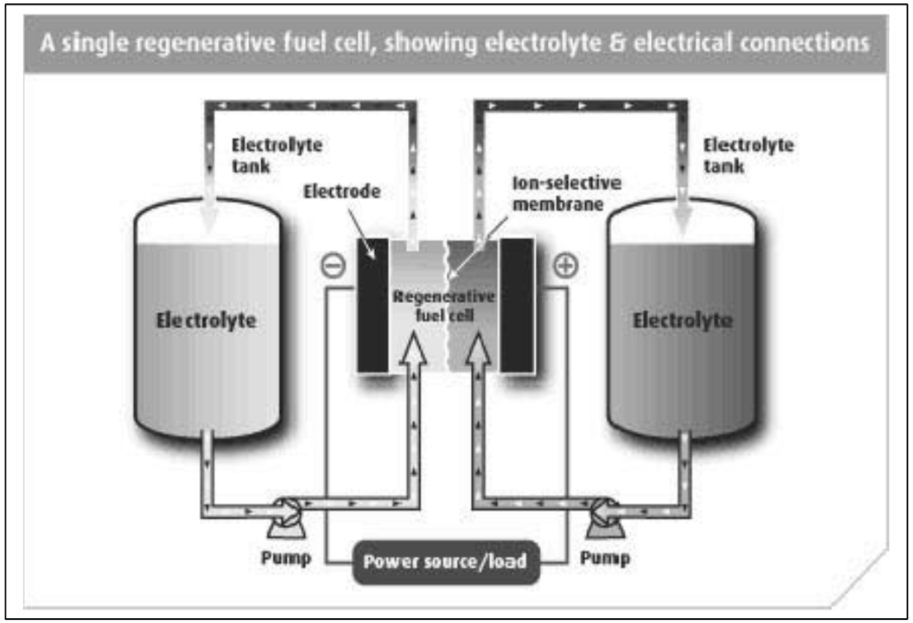
Silicon-carbon nanocomposite anode

Electrolyte that is stable up to a voltage of 5.2V




www.enviasystems.com

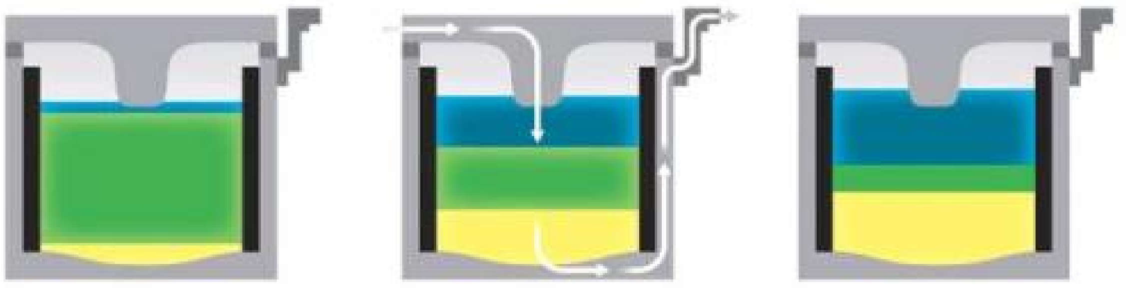
# Flow Batteries




Source: www.regensys.com

Flow batteries combine some the best features of fuel cells and batteries, yet avoid many of battery technologies' most significant problems. FBs use two salt solution electrolytes, which store or release electricity by means of reversible electrochemical reactions. The electrolytes are stored in independent reservoirs, and are pumped through separate manifolds into and out of half-cell compartments that are physically separated by an ion-selective membrane. The two electrolytes are transformed electrochemically inside each cell, without direct mixing. In actuality, some cross-contamination of electrolytes across the membrane may occur in some designs. Transfer of ions occur between the electrolytes and result in free electrons that are collected on the electrodes, generating electricity. The most significant difference between traditional batteries and flow batteries is that the electrodes are not directly involved in the electrochemical reactions, and thus do not degrade. Also, charged flow batteries do not suffer from leakage currents because the electrolytes are kept physically separated until a reaction is desired.

# MIT Liquid Battery



The all-liquid battery: discharged (left), charging (middle), and charged (right). Molten magnesium (blue) is the top electrode, in the middle is the electrolyte (green), and molten antimony (yellow) is the bottom electrode.

The battery consists of three layers of liquids: two electrode liquids on the top and bottom (electrodes are usually solid in conventional batteries), and an electrolyte liquid in the middle. In the researchers' first prototype, the electrodes were molten metals - magnesium on the top and antimony on the bottom - while the electrolyte was a molten salt such as sodium sulfide. In later prototypes, the researchers investigated using other materials for improved performance.Since each liquid has a different density, the liquids automatically form the three distinct layers. When charging, the solid container holding the liquids collects electrons from exterior solar panels or another power supply, and later, for discharging, the container carries the electrons away to the electrical grid to be used as electricity.

As electrons flow into the battery cell, magnesium ions in the electrolyte gain electrons and form magnesium metal, rising to form the upper molten magnesium electrode. At the same time, antimony ions in the electrolyte lose electrons, and sink to form the lower molten antimony electrode. At this point, the battery is fully charged, since the battery has thick electrode layers and a small layer of electrolyte. To discharge the electrical current, the process is reversed, and the metal atoms become ions again.

Source: MIT, Technology Review, March/April 2009

# Battery Storage Requirement

Individual Americans use about 1.5 kWh of electricity every hour

Typical storage requirement: 15 kWh

Battery capacity: 400 Wh/kg

Batteries weight: 37.5 kg; Cost: $3000

Typical compact automobile power requirement: 50 KW

Typical driving distance: 500 km

Average speed: 100 km/hr

Required stored energy: 250 kWh

Battery capacity: 400 Wh/kg

Batteries weight: 625 kg; Cost: $50,000

# Energy Storage

## Part 3: Potential Energy Storage

# Potential Energy Storage

Pumped hydropower:

Use excess energy to pump water uphill from a lower reservoir to higher reservoir:

Energy recovery depends on total volume of water and its height above the turbine location

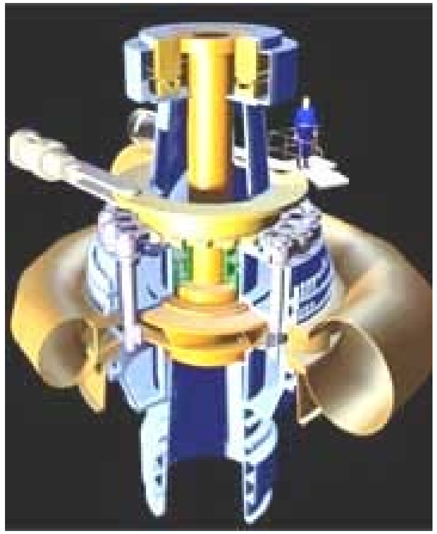
The efficiency of pumping: 80%

Net efficiency: 0.8 x 0.8 = 0.64

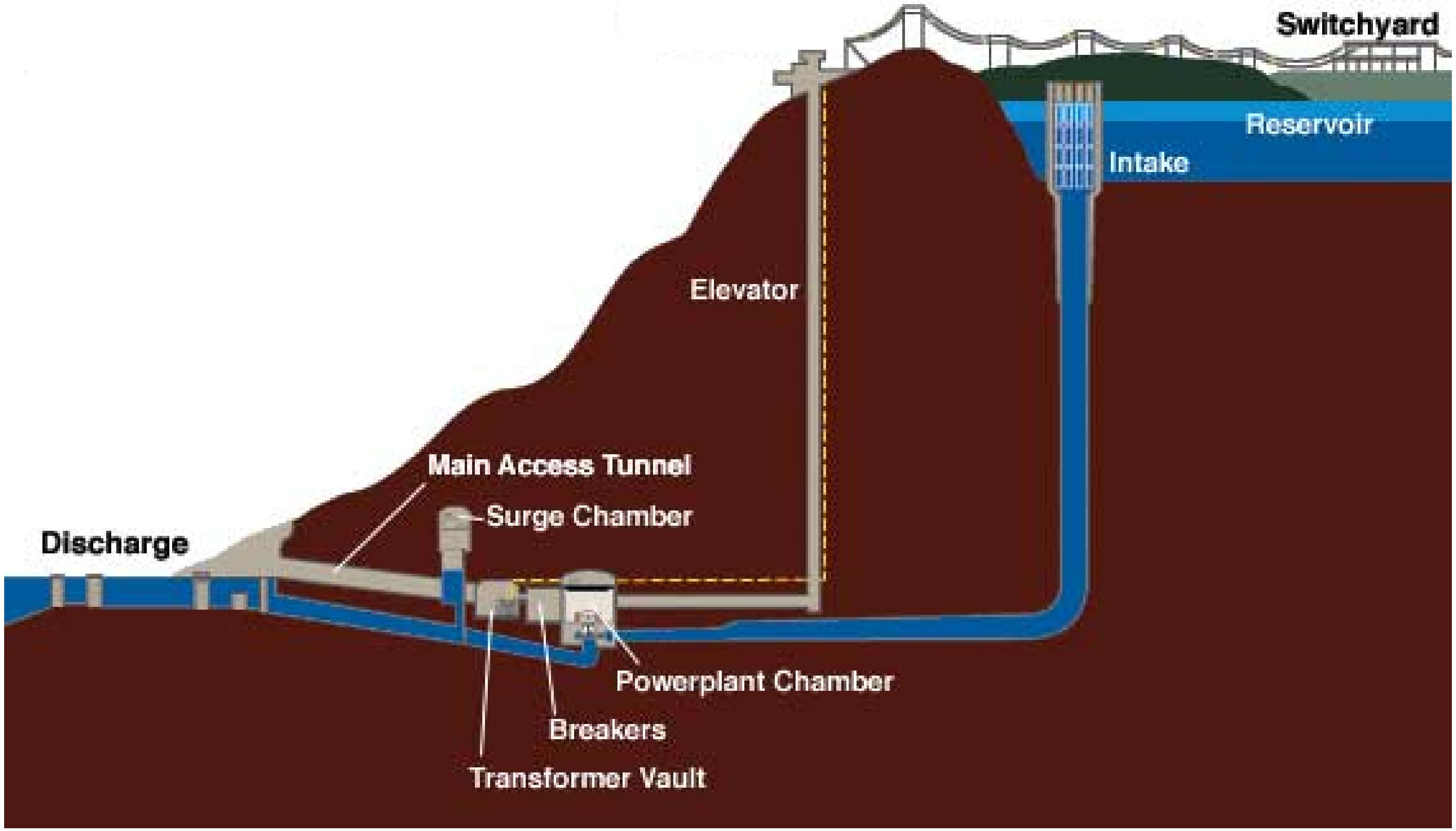
The typical coal power plant efficiency ~ 40%

The efficiency of the recovered energy =

0.64 x 0.4 ~ 0.25 (25%)



# Pumped-Storage Plant

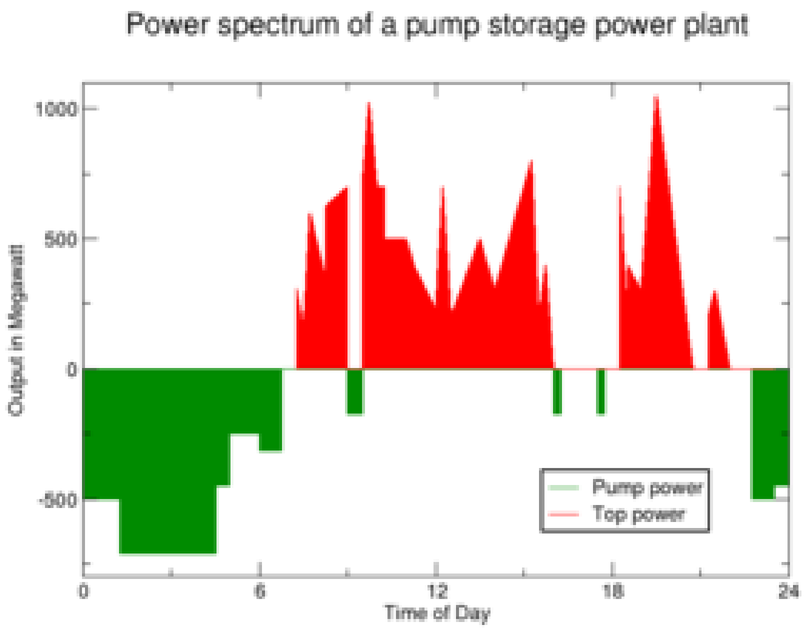



Source: NREL

# Hydropower Storage Facility

The world's largest hydro-storage facility al Ludington, Michigan, uses Lake Michigan as the lower reservoir and an artificial lake 100 m higher as the upper reservoir. This plant can deliver 2000 MW at full power and can store 15,000 MWh of energy

# Pumped Stored Energy




The relatively low energy density of pumped storage systems requires either a very large body of water or a large variation in height. For example, 1000 kg of water (1 cubic meter) at the top of a 100 meter tower has a potential energy of about 0.272 kWh.

Taking into account evaporation losses from the exposed water surface and conversion losses, approximately 70% to 85% of the electrical energy used to pump the water into the elevated reservoir can be regained. The technique is currently the most cost-effective means of storing large amounts of electrical energy on an operating basis, but capital costs and the presence of appropriate geography are critical decision factors.

# Pumped Stored Energy

Energy stored is predominantly Nuclear Power

The water head ranges widely: 25 - 600m

Large range in capacity: 4 MW - 2100 MW

USA storage capacity: 20 GW

Europe: 32 GW

Others: 34 GW

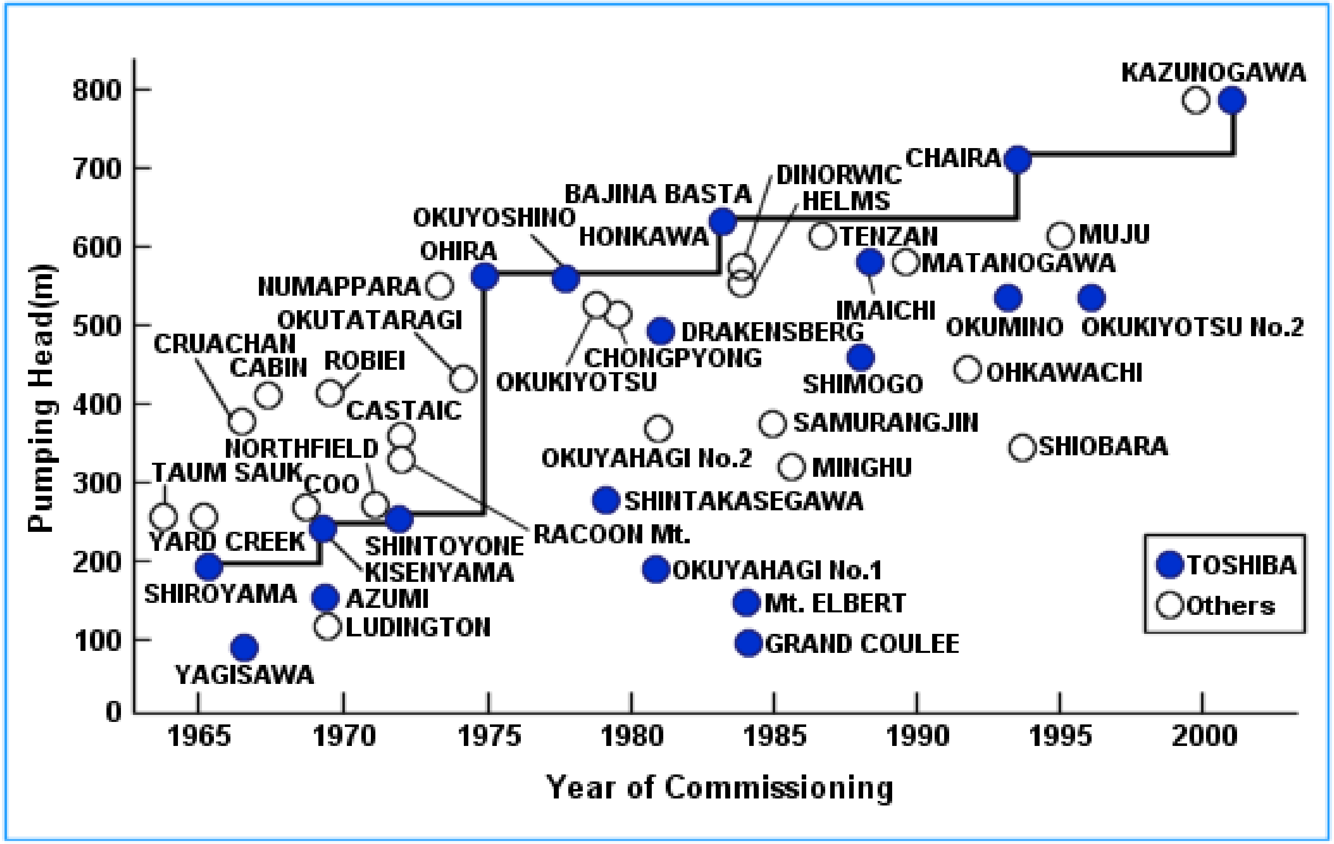
Opportunity to store renewable energy (especially wind) when it is produced and delivered when needed.

Ideally suited in mountainous regions.

Total hydro capacity: 420 GW

Typical pumping up cost: $14 ~ $21/MWh

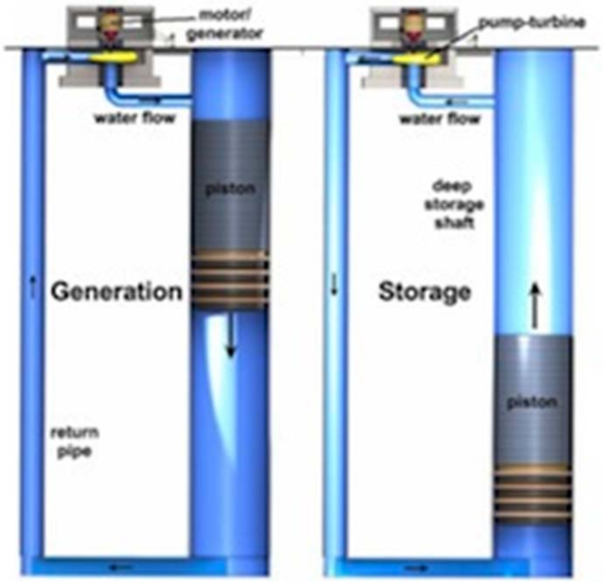
# Pump Turbine Progress




Source: Toshiba

http://www.dom.com/about/stations/hydro/bath_video/index.html

# Gravity Power Module

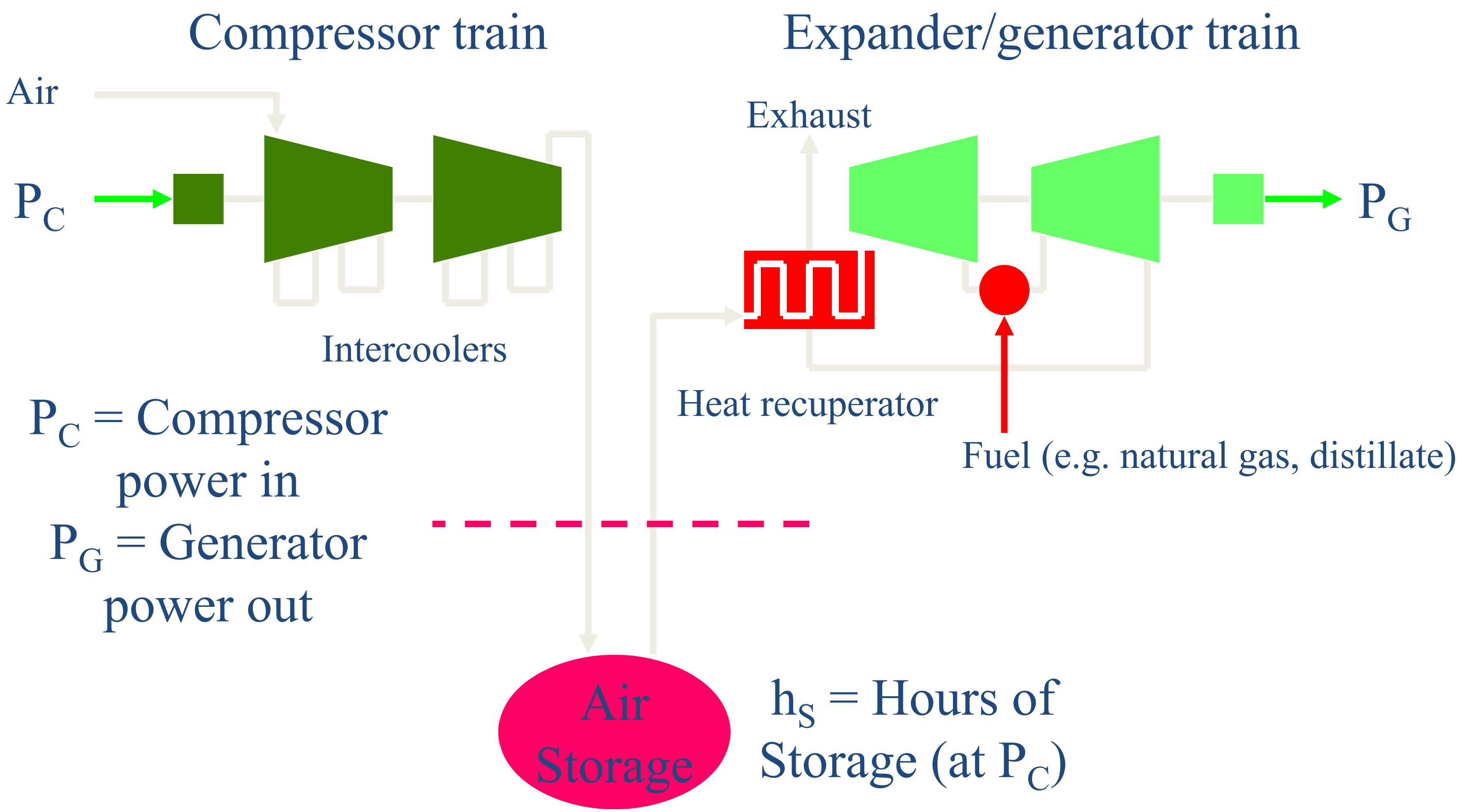



Each GPM employs two deep, water-filled shafts, one of which stores energy in heavy pistons that move vertically within this shaft. The smaller shaft of the two is a return pipe which connects each piston shaft to a ground level, Francis pump turbine. The system is filled once with clean water and sealed. As a piston falls, it forces water through the pump-turbine to generate electricity. In storage mode, grid electricity drives the pump-turbine, forcing the weight up the shaft.

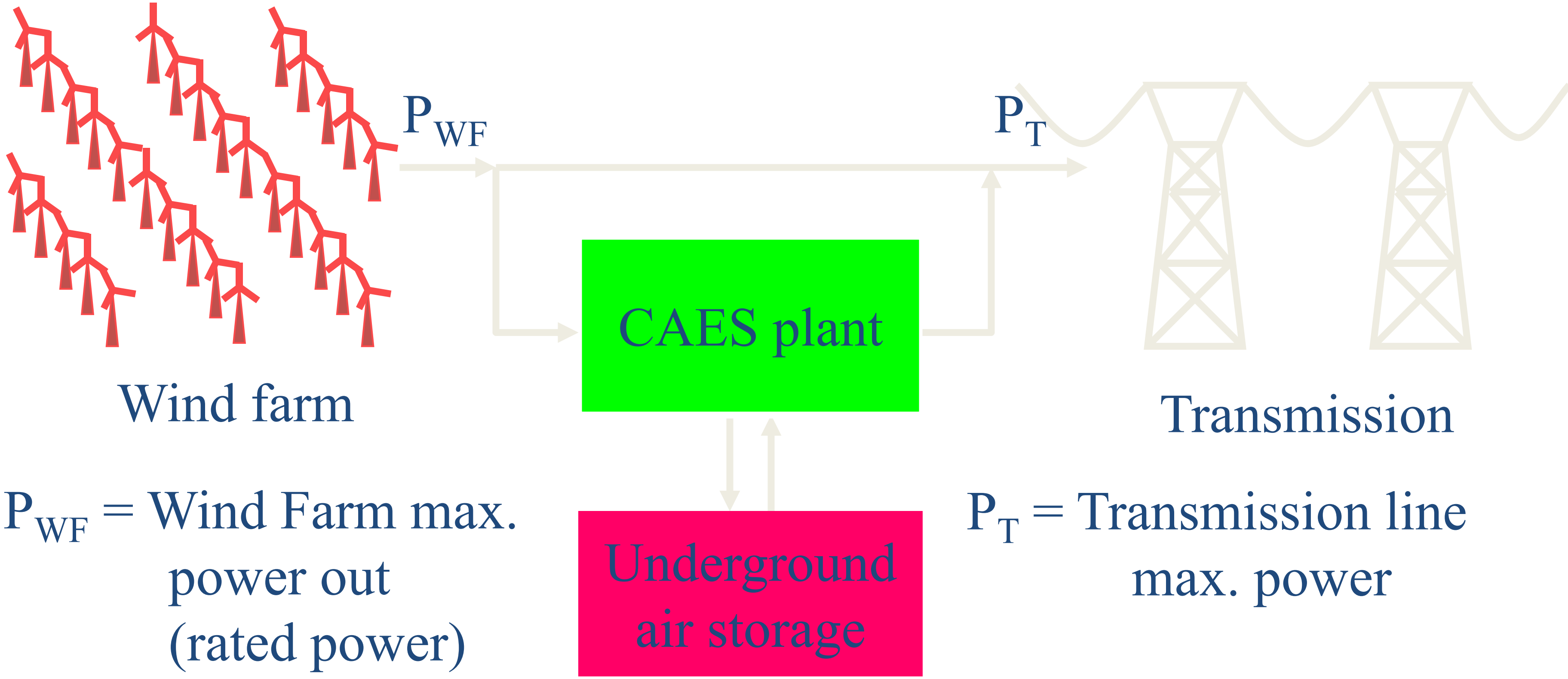
Source: http://www.gravitypower.net/

# Potential Energy Storage

## Compressed Air Energy Storage System



# Wind / CAES

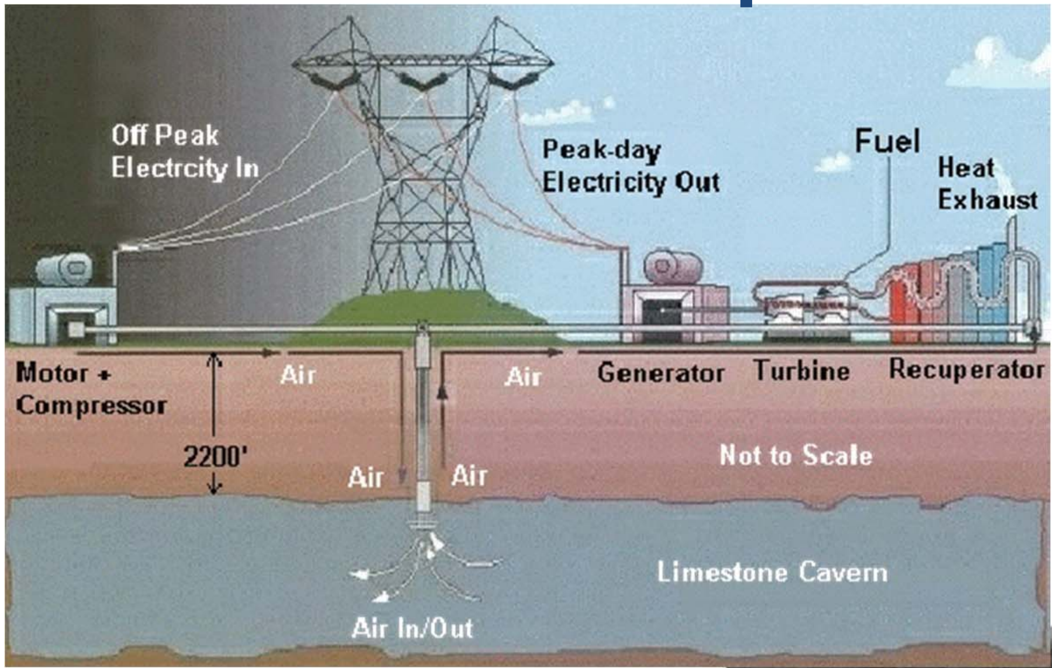



*Wind capacity factor can be significantly improved*

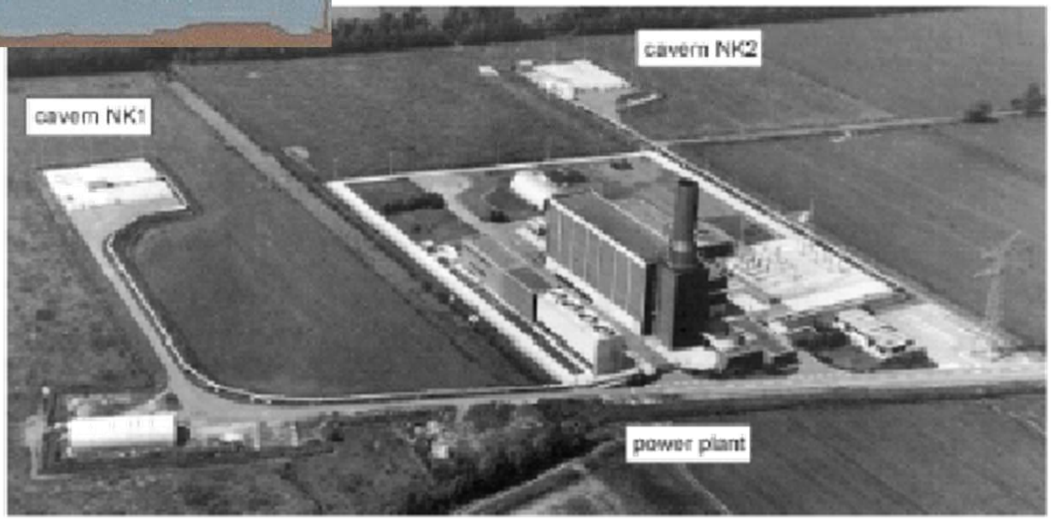
***Source: Toward optimization of a wind/ compressed air energy storage (CAES) power system***

**Jeffery B. Greenblatt, Samir Succar, David C. Denkenberger, Robert H. Williams, Princeton University**

# Compressed Air Energy Storage




Huntorf plant



# Compressed Air Energy Storage

| Basic design parameters of the Huntorf plant | |
|---|---|
| **Output** | |
| Turbine operation | 290 MW (< 3 hrs) |
| Compressor operation | 60 MW (< 12 hrs) |
| **Air flow rates** | |
| Turbine operation | 417 kg/s |
| Compressor operation | 108 kg/s |
| Air mass flow ratio in/out | 1/4 |
| Number of air caverns | 2 |
| **Cavern location** | |
| Top | 650 m |
| Bottom | 800 m |
| Maximum diameter | 60 m |
| Well spacing | 220 m |
| **Cavern pressures** | |
| Minimum permissible | 1 bar |
| Minimum operational (exceptional) | 20 bar |
| Minimum operational (regular) | 43 bar |
| Maximum permissible and operational | 70 bar |
| Maximum pressure reduction rate | 15 bar/h |

# Compressed Air Energy Storage

Energy needed to compress gases: the adiabatic compression work

$$W = \frac{\gamma}{\gamma - 1} p_o V_o \left[ \left( \frac{p_1}{p_o} \right)^{\frac{(\gamma-1)}{\gamma}} - 1 \right]$$

*W: specific compression work (J/kg); $p_o$: initial pressure; $p_1$: final pressure; $V_o$: initial specific volume ($m^3$/kg); $\gamma$: ratio of specific heats*

*Net work* = $W_{net} = W_{turbine} - W_{compressor}$

$$\eta_{overall} = \eta_{turbine} \eta_{compressor}$$

# Flywheels

A flywheel is a mechanical battery storing energy mechanically in the form of kinetic energy. It uses an electric motor to accelerate the rotor up to a high speed and return the electrical energy by using the same motor as a generator. The rotational energy is delivered until friction overcomes it.

Flywheel has a higher energy density over chemical energy storage. The rate at which energy can be exchanged into or out of the flywheel is limited only by the motor-generator design. Hence, it is possible to withdraw large amounts of energy in a far shorter time than with traditional chemical batteries. As such they are widely used in automobile applications.

Flywheels store energy very efficiently and can provide high specific power (kWh/kg) compared with batteries.

Flywheel purchase costs: \$100/kW - \$300/kW

Installation costs: \$20/kW - \$40/kW

# Flywheel Parameters

Stored energy:

$$KE = \frac{1}{2} I \omega^2 = \frac{1}{2} kmR^2 \omega^2$$

ω = rotational velocity

I = moment of inertia (ability of an object to resist changes in its rotational velocity)

= $kmR^2$

*k:* inertial constant depends on shape; m: mass; R: radius

Wheel loaded at rim (bike tire); k = 1: solid disk of uniform thickness; k = 1/2
solid sphere; k = 2/5; spherical shell; k = 2/3; thin rectangular rod; k = 1/2

# Flywheel Parameters

In order to optimize the energy-to-mass ratio, the flywheel needs to spin at the maximum possible speed.

Rapidly rotating objects are subject to centrifugal forces that can rip them apart.

Centrifugal force = $mR\omega^2$

While dense material can store more energy it is also subject to higher centrifugal force and thus fails at lower rotational speeds than low density material. Therefore the tensile strength is more important than the density of the material.

Efficiency ~ 80%

# Specific Energy Density

$$\textit{Specific energy density} = \frac{KE_{rotational,\max}}{m} = \frac{k\sigma_{\max}}{\rho_m}$$

$\sigma_{max}$= maximum allowable tensile stress of the material

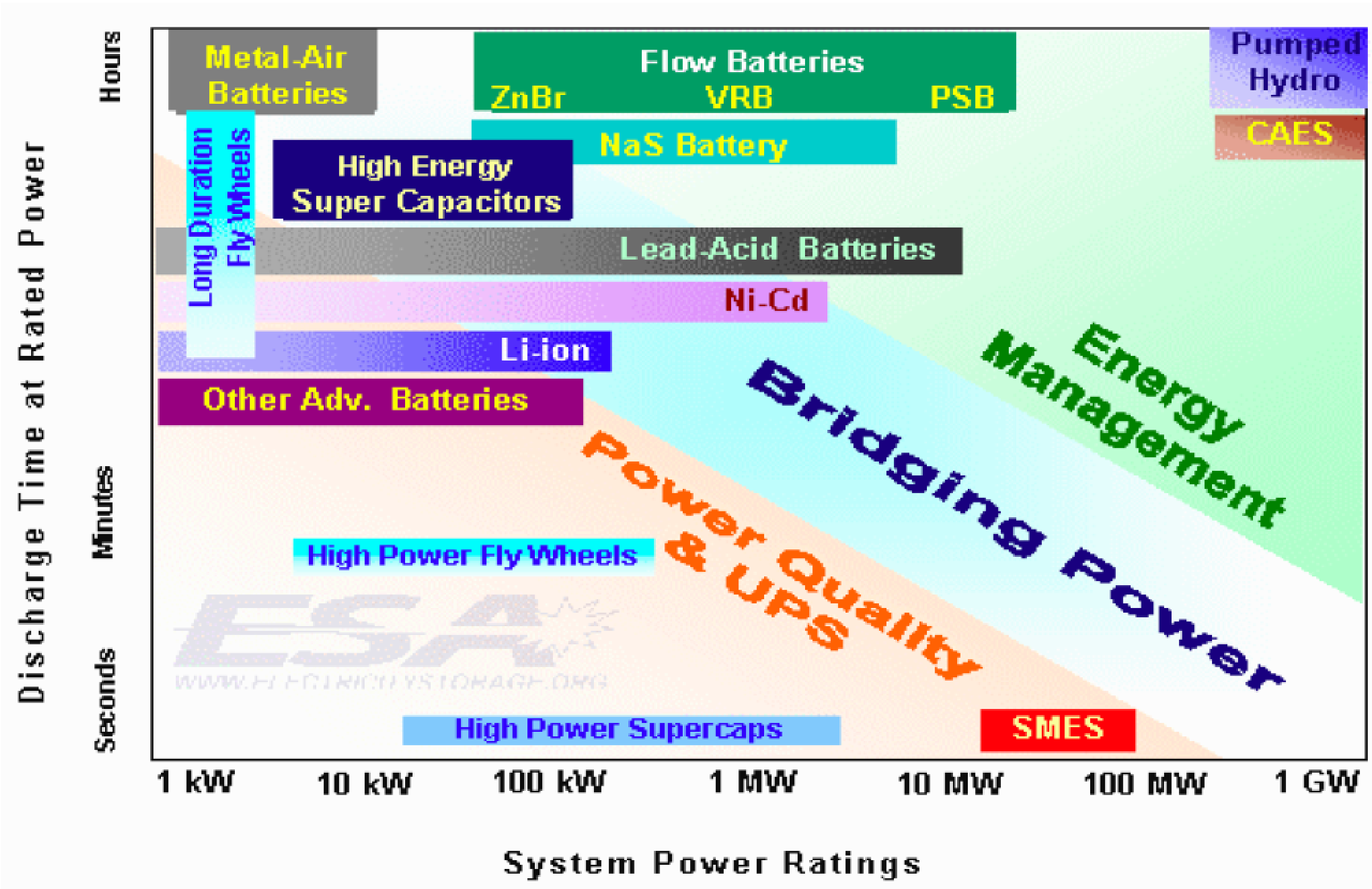
$\rho_m$ = volumetric mass density ($kg/m^3$)

Technical Challenges: Light weight high tensile strength rotors (e.g. Fused Silica or composite material rotors) , low density and reduced friction using evacuated housing with magnetic bearings

# Estimated Costs

| **Storage Type** | **US$/kW** | **US$/kWh** |
|---|---|---|
| Pumped Hydro | 800 | 12 |
| Li-Ion | 300 | 200 |
| Flywheels | 350 | 500 |
| CAES | 750 | 12 |
| SMES | 650 | 1500- |
| Ultracapacitors | 300 | 3600- |

# Alternative Ragone Plot



# Supercapacitors

Electrical energy storage in the form of confined electrostatic charges in a device consisting of conductive plates separated by dielectric medium.

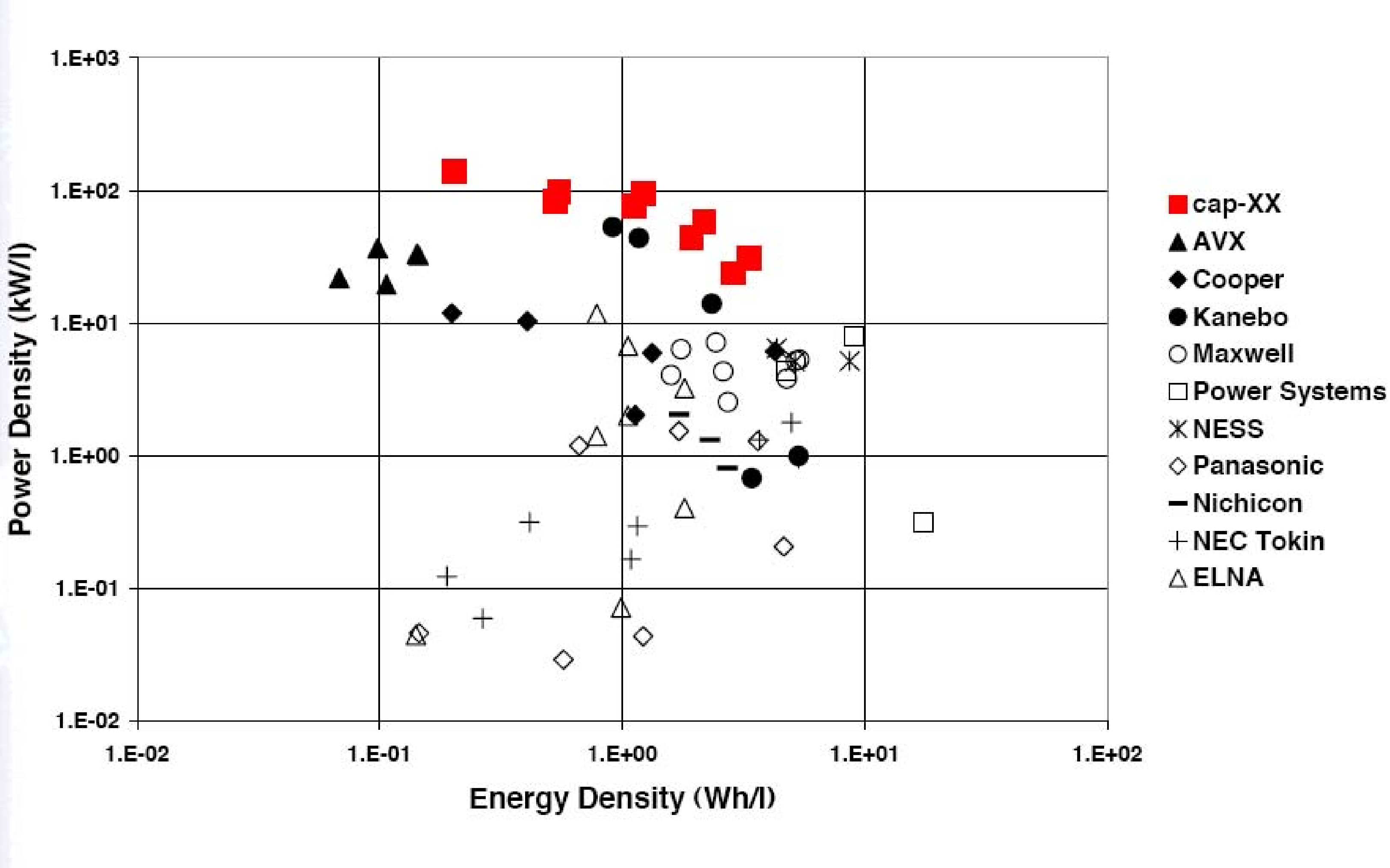
Power Density = $\dfrac{0.5V^2}{RA^2}$

V: applied voltage; R: total effective resistance of the capacitor, A: nominal surface area of the conducting plate or electrode

Very high surface area activated carbon (nanopores) electrodes and charge separation distances in nanometers.

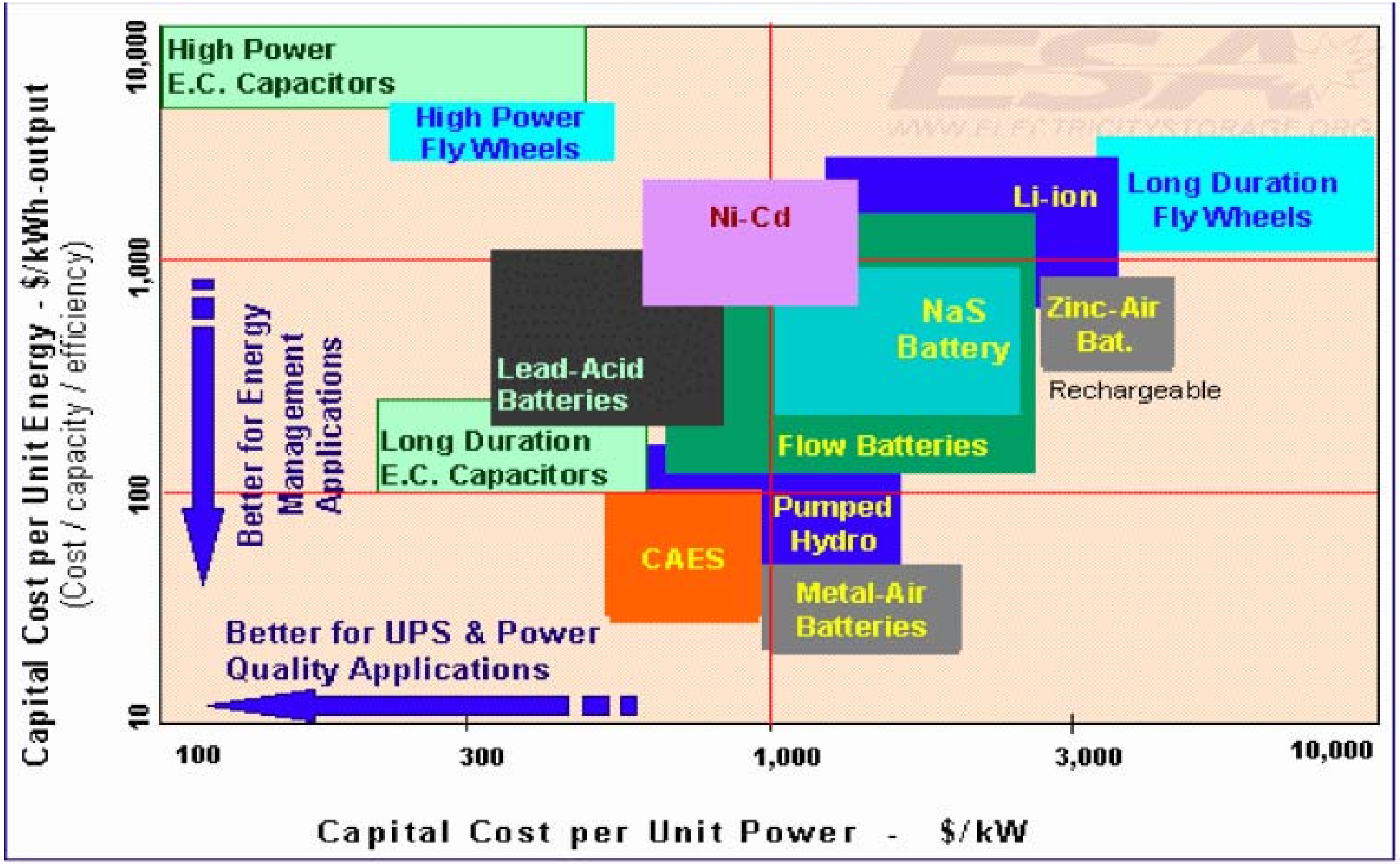
Attractive for Regenerative breaking and other power needs in electric and hybrid vehicles.

# Supercapacitors - State of the Art




Source: CAP-XX Pty Ltd, Australia, 2005

# Storage Technology Costs

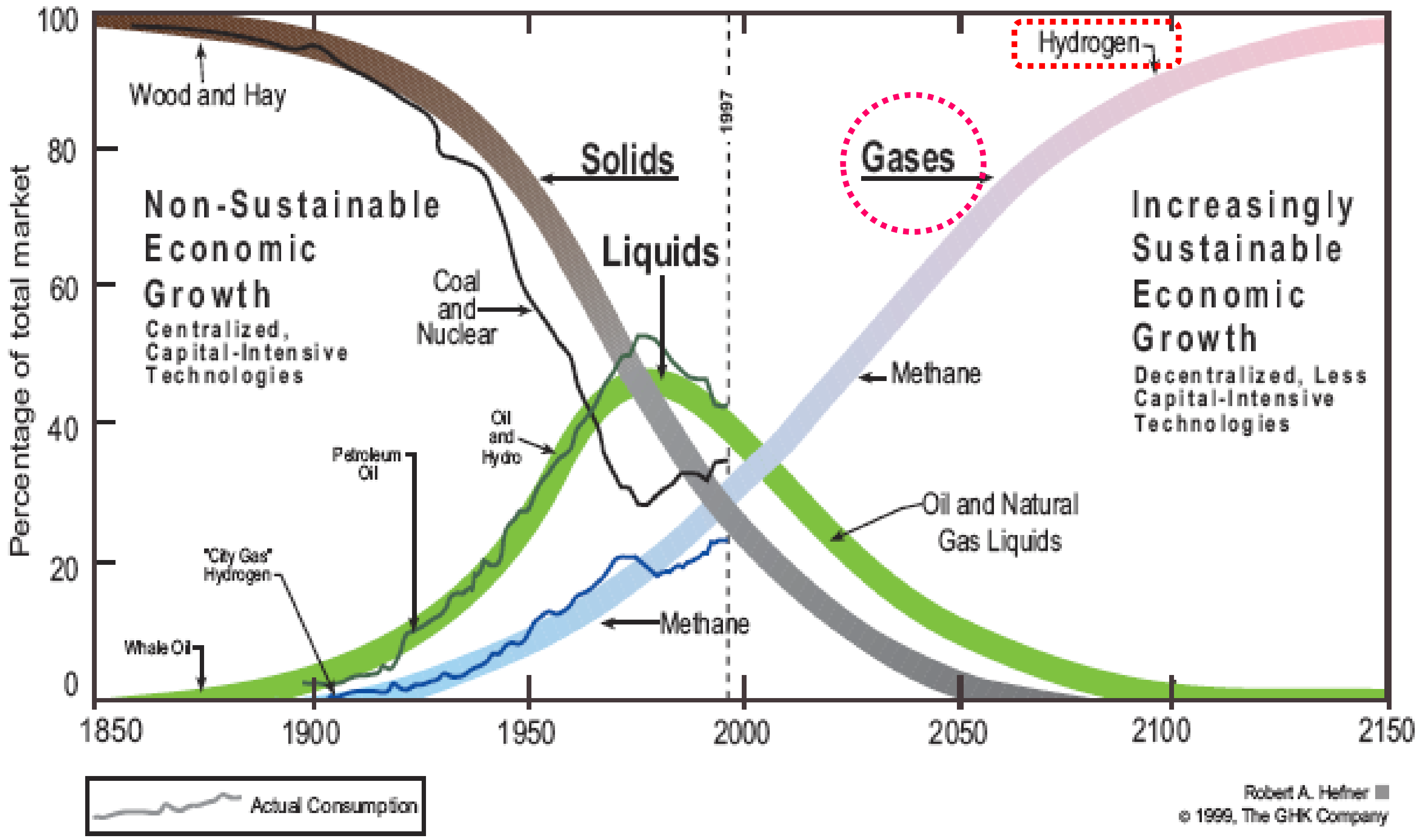



Source: iti Scotland Ltd, 2005

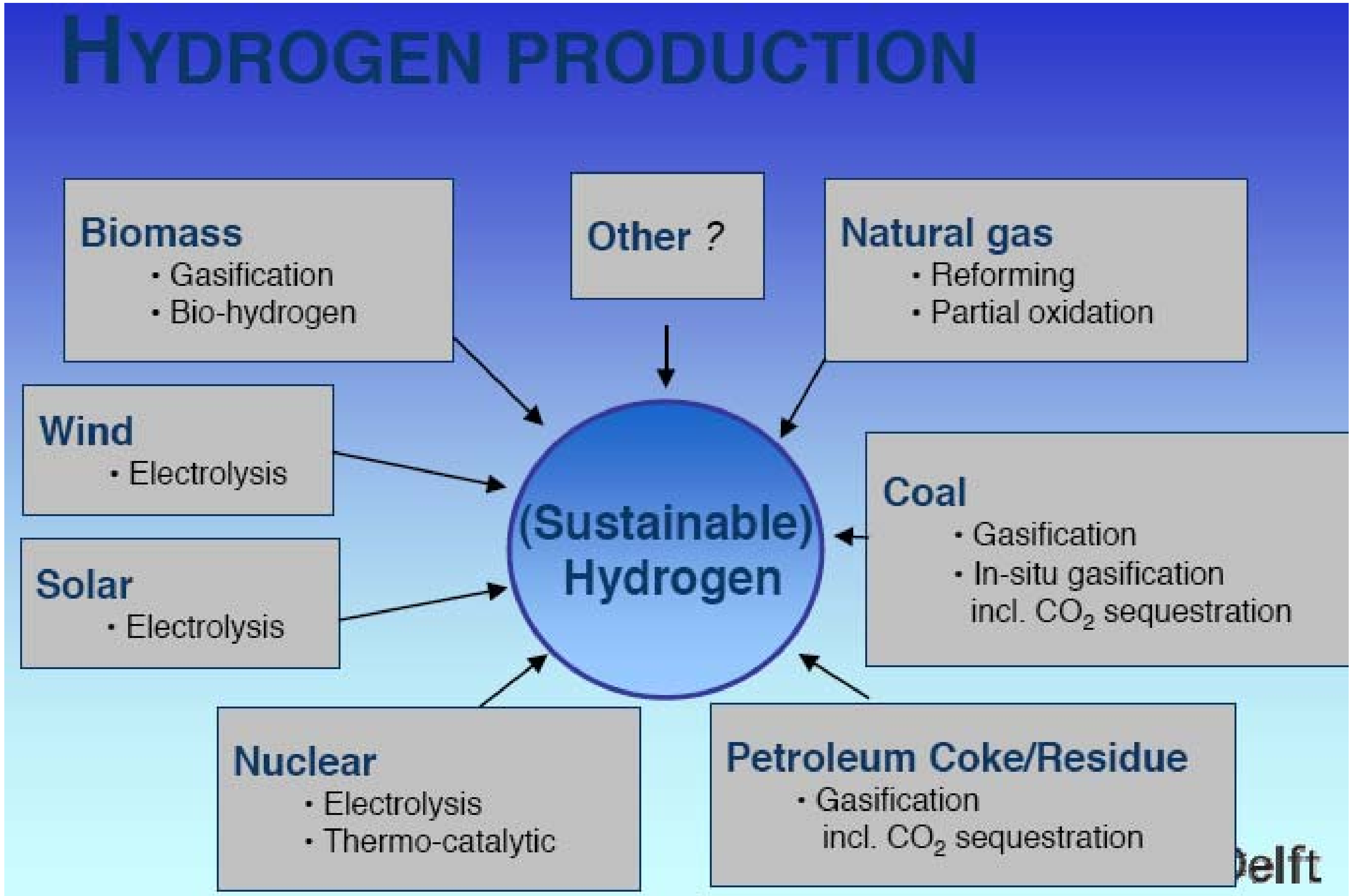
# Energy Storage

Part 4: Hydrogen

# Global Energy Systems Transition

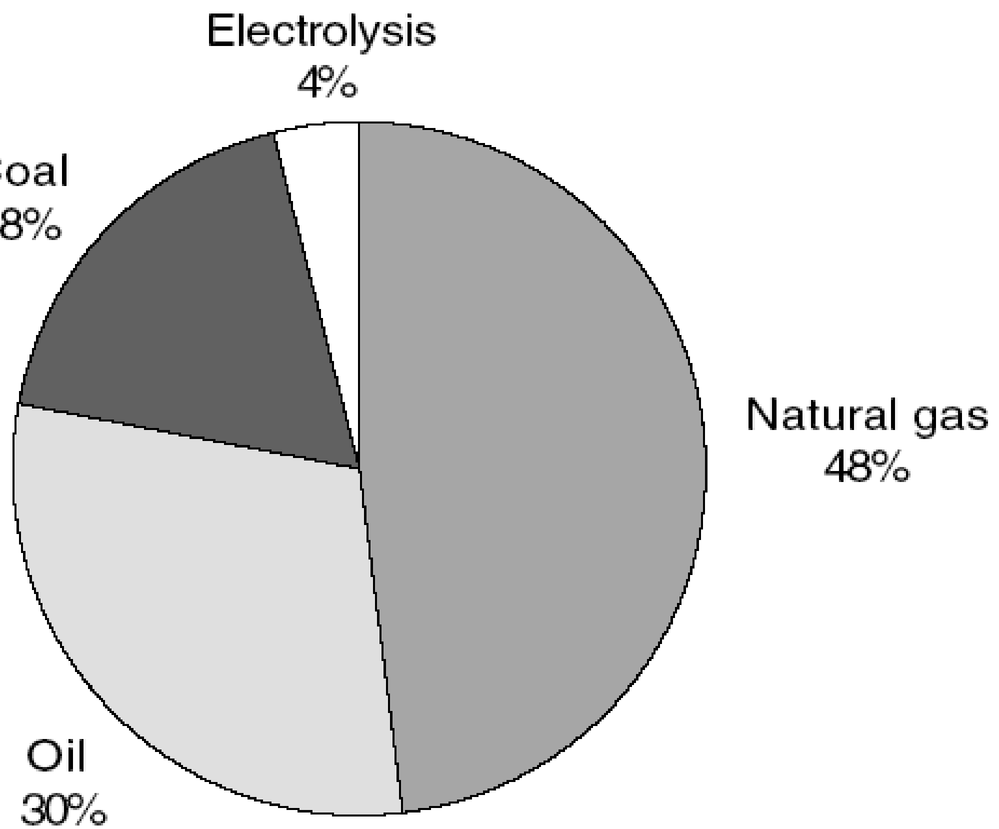


# Hydrogen Production




Source: Prof.Dr. J. Schoonman, Delft Institute for Sustainable Energy

# Feedstocks Usage in Hydrogen Production

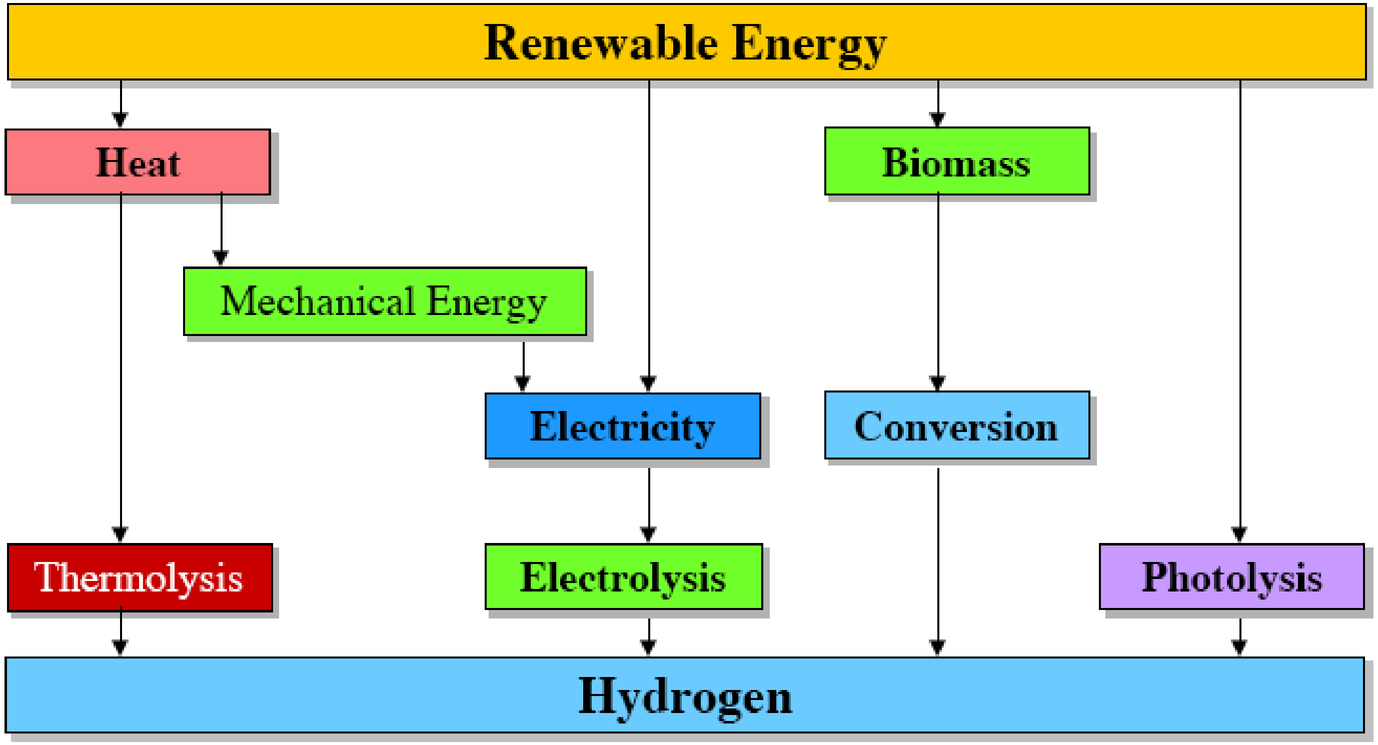



Source: NAS Study, 2004

THE HYDROGEN ECONOMY

Opportunities, Costs, Barriers, and R&D Needs

# Sustainable Paths to Hydrogen




Source:
D. Brent MacQueen
Brent.macqueen@sri.com
SRI International, Menlo Park CA

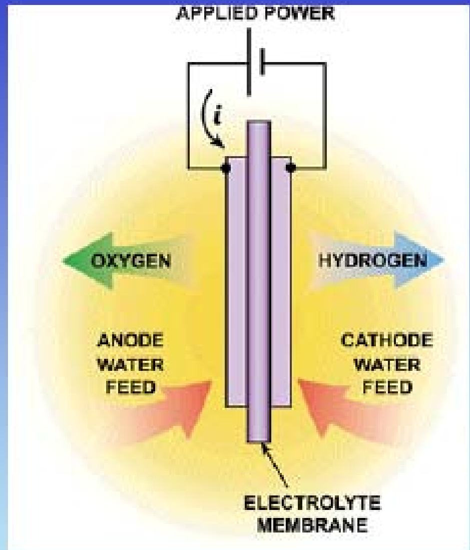
# Hydrogen Production Methods

Most methods of producing hydrogen involve splitting water ($H_2O$) into its component parts of hydrogen ($H_2$) and oxygen (O). The most common method involves steam reforming of methane (from natural gas), although there are several other methods.

- Steam reforming converts methane (and other hydrocarbons in natural gas) into hydrogen and carbon monoxide by reaction with steam over a nickel catalyst
- Electrolysis uses electrical current to split water into hydrogen at the cathode (+) and oxygen at the anode (-)
- Steam electrolysis (a variation on conventional electrolysis) uses heat, instead of electricity, to provide some of the energy needed to split water, making the process more energy efficient
- Thermochemical water splitting uses chemicals and heat in multiple steps to split water into its component parts
- Photoelectrochemical systems use semi-conducting materials (like photovoltaics) to split water using only sunlight
- Photobiological systems use microorganisms to split water using sunlight
- Biological systems use microbes to break down a variety of biomass feed stocks into hydrogen
- Thermal water splitting uses a very high temperature (approximately 1000° C) to split water
- Gasification uses heat to break down biomass or coal into a gas from which pure hydrogen can be generated

# Electrolysis

$$\text{Anode}: 4\,OH^- \longrightarrow O_2 + 2\,H_2O + 4\,e^-$$
$$\text{Cathode}: 4\,H_2O + 4\,e^- \longrightarrow 2\,H_2 + 4\,OH^-$$
$$\text{Overall}: 2\,H_2O \longrightarrow 2\,H_2 + O_2$$




Electrolyte composition:

Pure water ($\sigma < 5\ \mu S/cm$) + 30% KOH

TU Delft
Delft University of Technology

# Electrolysis

Requirements for electrolysis:

- High-purity water
- Electricity

Efficiency: 85-90%

$H_2$ Purity: >99.9%

# Electrolysis of Water

## System work:

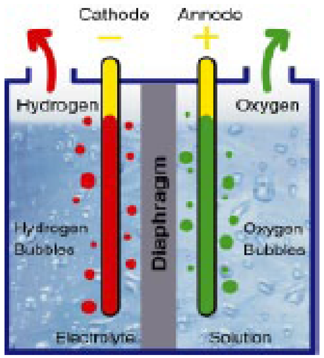
| Quanitity | $H_2O$ | $H_2$ | $0.5O_2$ | Change |
| --- | --- | --- | --- | --- |
| Enthalpy | -285.83kJ | 0 | 0 | $\Delta H$ = -285.83kJ |
| Entropy | 69.91 J/K | 130.68J/K | 0.5x205.14J/K | $T\Delta S$ = 48.7 kJ |

$W = P\Delta V = (101.3\ \text{kPa})(1.5\ \text{moles})(22.4\text{x}10^{-3}\text{m}^3/\text{mol})(298\text{K}/273\text{K}) = 3715\ \text{J}$

$\Delta U = \Delta H\text{-}P\ \Delta V = 285.83\text{kJ}-3.72\ \text{kJ} = 282.1\ \text{kJ}$

$\Delta G = \Delta H\text{-}T\ \Delta S = 285.83\ \text{kJ}-48.7\ \text{kJ} = 237.1\ \text{kJ}$

# Efficiency




- Energy efficiency of electrolysis =

$$\frac{\text{Chemical potential}}{\text{Electrolysis potential}} = \frac{1.23}{1.9} = 65\%$$

Systems that claim 85 %

- Coupling to a 12% PV array gives a solar-to-hydrogen efficiency of:

$$.12^{*}.65 = 7.8\%$$

Improved electrolysis efficiency can bring the PV-hydrogen efficiency to about 15%

# WATER AVAILABILITY

Reaction:

$$H_2\,(g) + O_2\,(g) \leftrightarrow H_2O\,(l) + 286\ \text{kJ/mole}$$

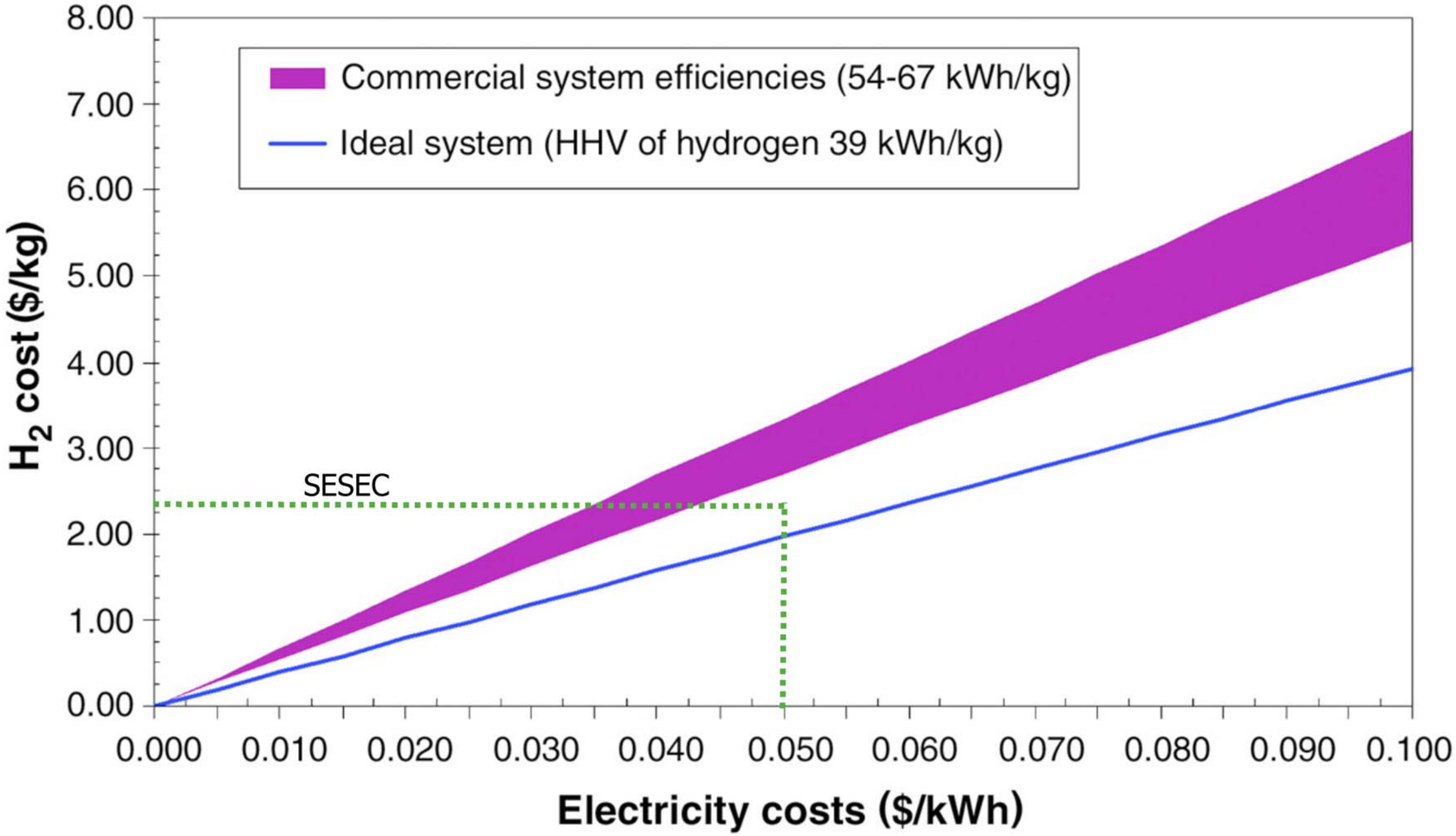
Global energy demand: $4 \times 10^{20}$ J/year

$H_2$ from water: 1 GJ per 90 liters $H_2O$

| | |
|---|---|
| Water needed: | $3.6 \times 10^{13}$ liters |
| Oceans: | $1.45 \times 10^{21}$ liters |
| Annual rainfall: | $3.62 \times 10^{17}$ liters |

There is enough water to sustain hydrogen!

# Hydrogen-Electricity



# Electrolyzers

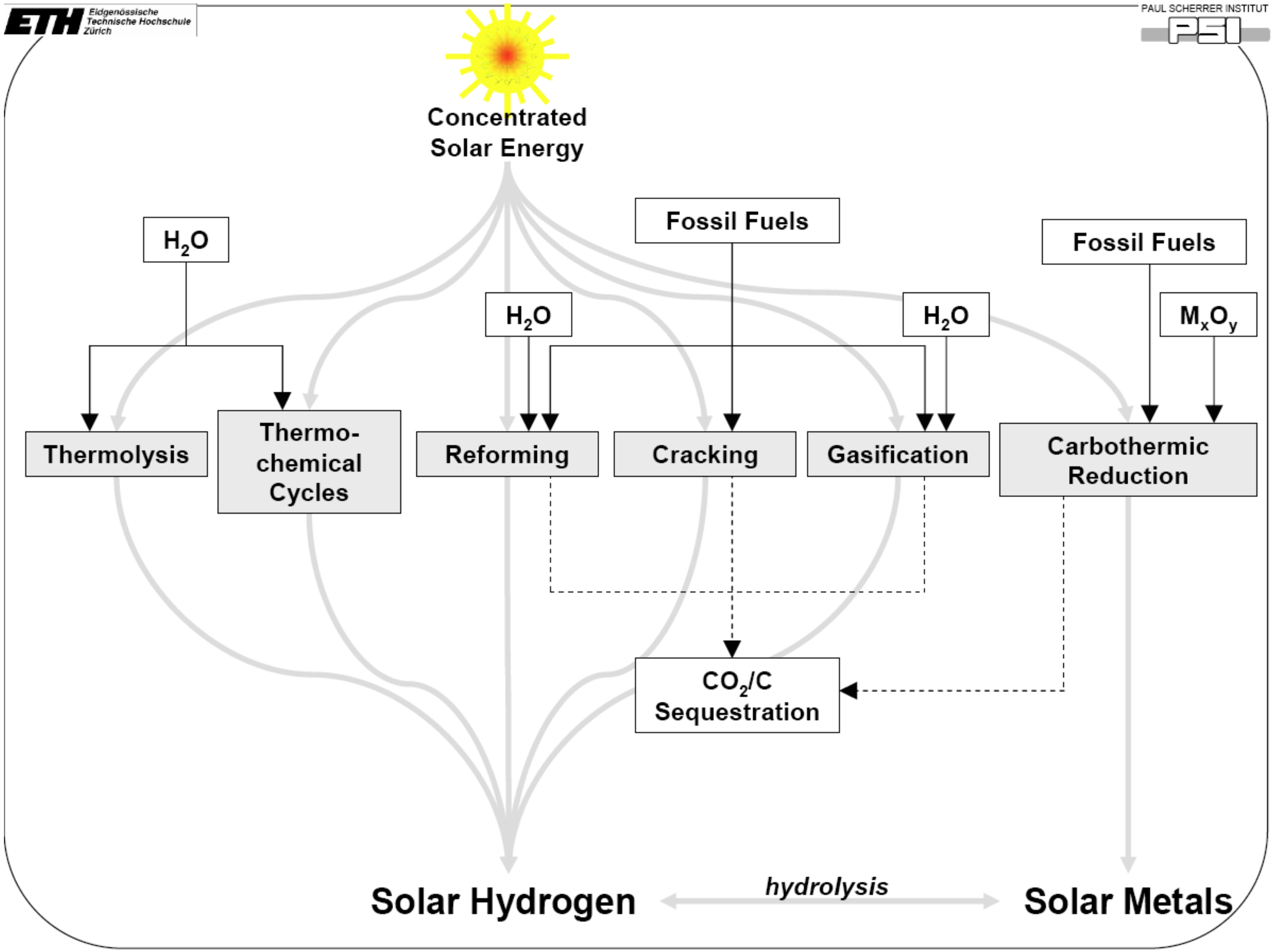
> 50 $Nm^3$ $H_2$/h

5-50 $Nm^3$ $H_2$/h

< 5 $Nm^3$ $H_2$/h

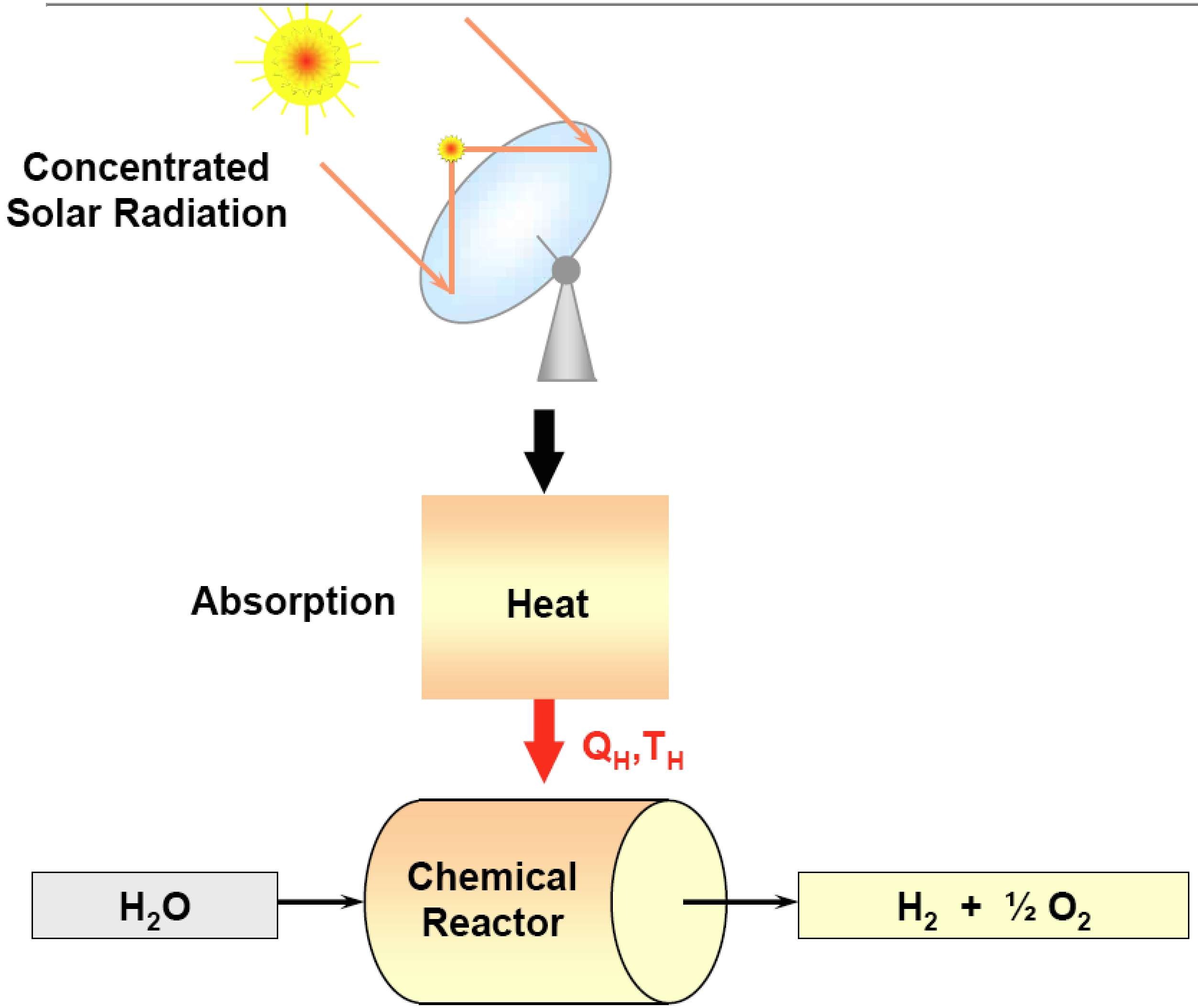
# Large scale Electrolyzers

# Solar Thermochemical Production

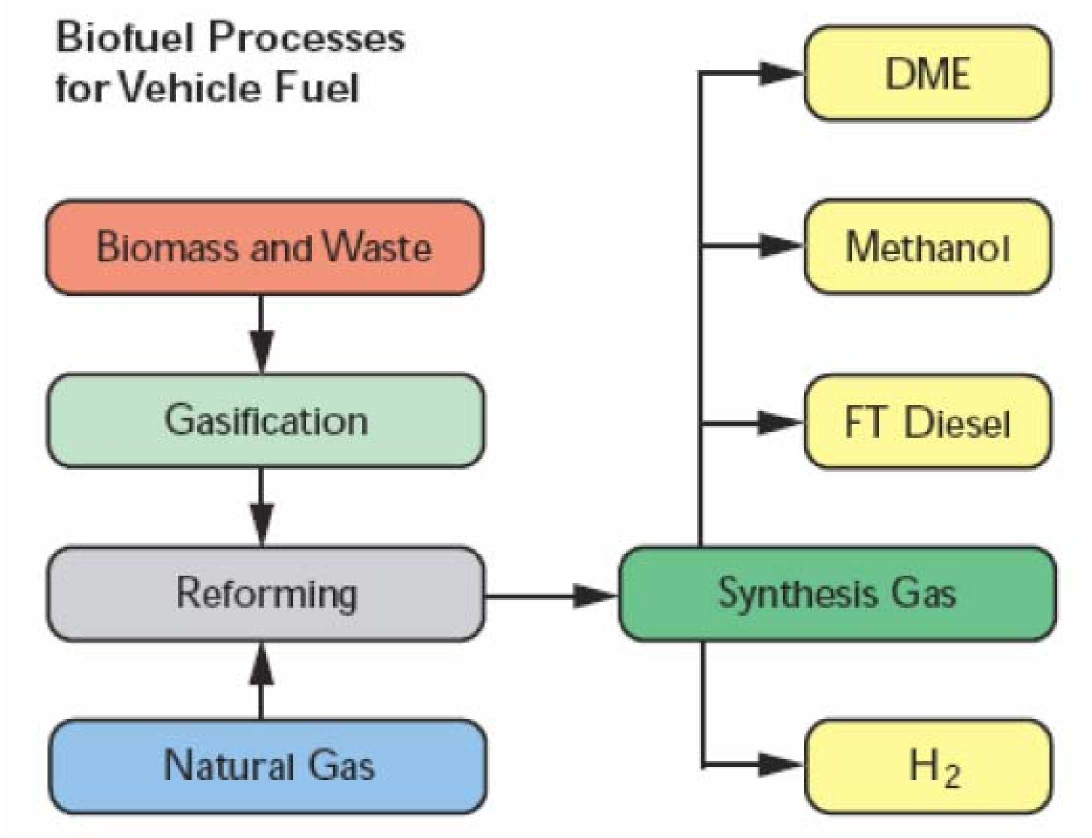



Source: Aldo Steinfeld

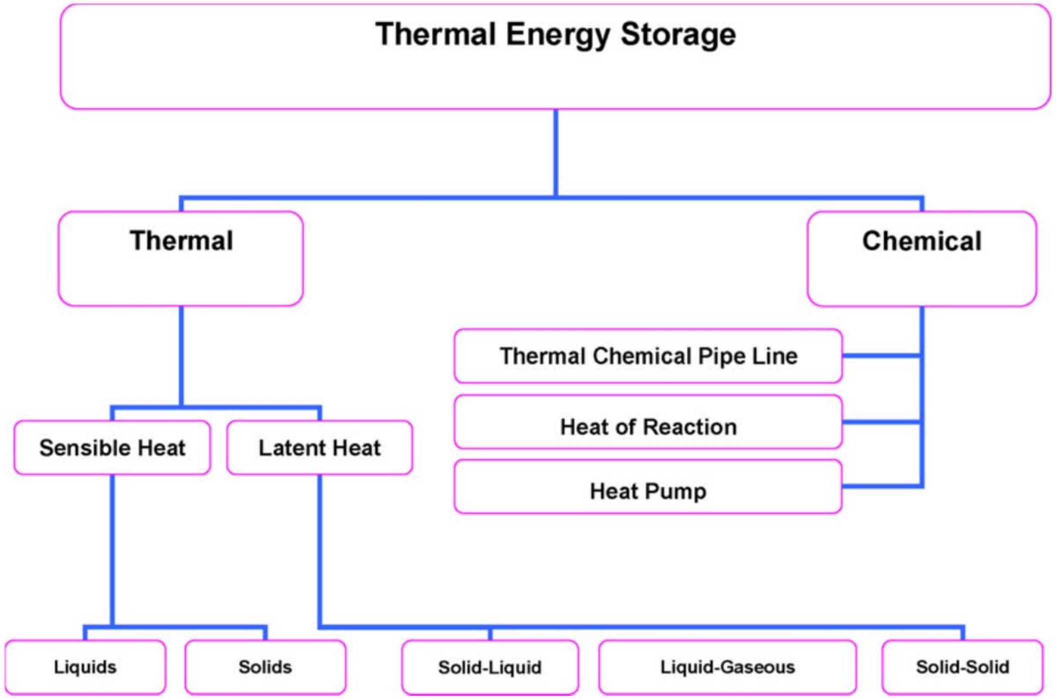
# Solar Thermochemical Production



# Biomass to Hydrogen



# Thermal Energy Storage




- Heating a liquid or solid which does not melt or otherwise change state during heating. (This is called “sensible-heat” storage, and the amount of energy stored is proportional to the system’ s temperature. )
- Heating a material which melts, vaporizes, or undergoes some other change of state at a constant temperature. (This is called “latent-heat” storage. )
- Using heat to produce a chemical reaction which will then release this heat when the reaction is reversed.