SUPERGEN Wind

Wind Energy Technology

Session 8

Energy Storage in Power Systems

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Supergen Wind Training Seminar

University of Manchester 24th – 25th March 2011

Presentation Format

- Storage Applications in Electrical Power Systems
- Storage Technologies
- Storage Systems
- Supergen Wind
- Summary

Storage Applications

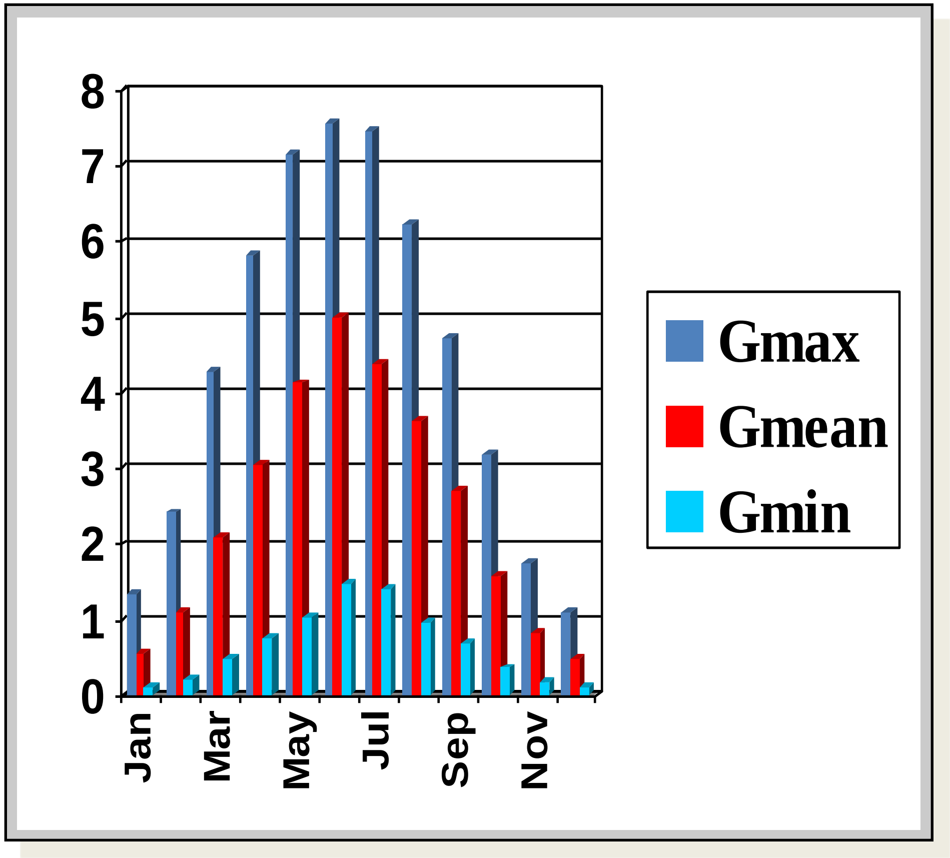
- Variability of renewable energy sources
- Application Categories
- Grid Networks
- Remote Power Systems

Storage applications:
Variability of renewable energy sources

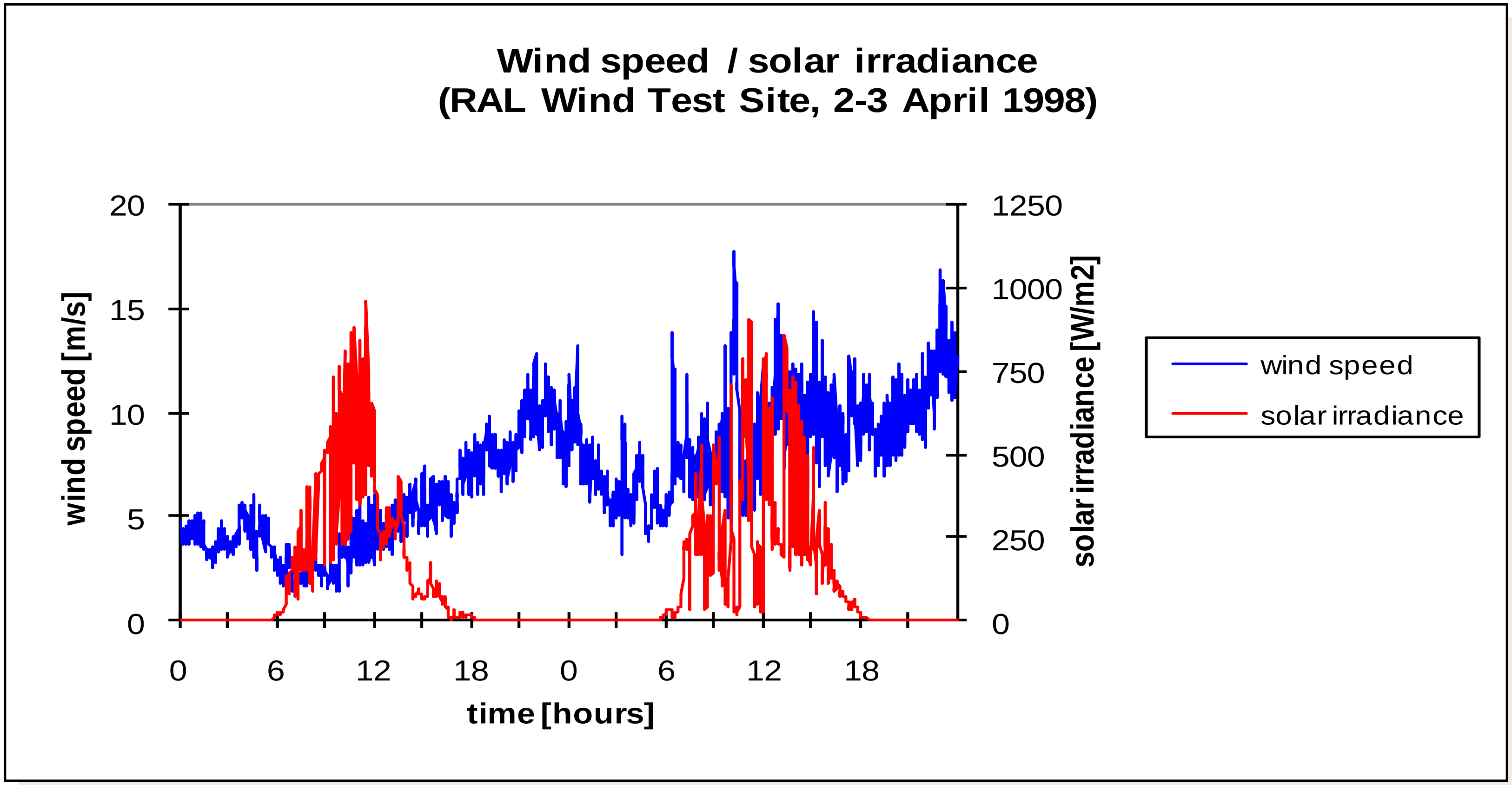
Solar (London, UK)

- seasonal and diurnal variation of daily global radiation [kWh/m²]
- seasonal variation e.g. 4.99 kWh/m² (Jun) to 0.47 kWh/m² (Dec)
- diurnal variation 1:10
- power can be subject to abrupt changes within theoretical envelope

(ref : European Solar Radiation Atlas)



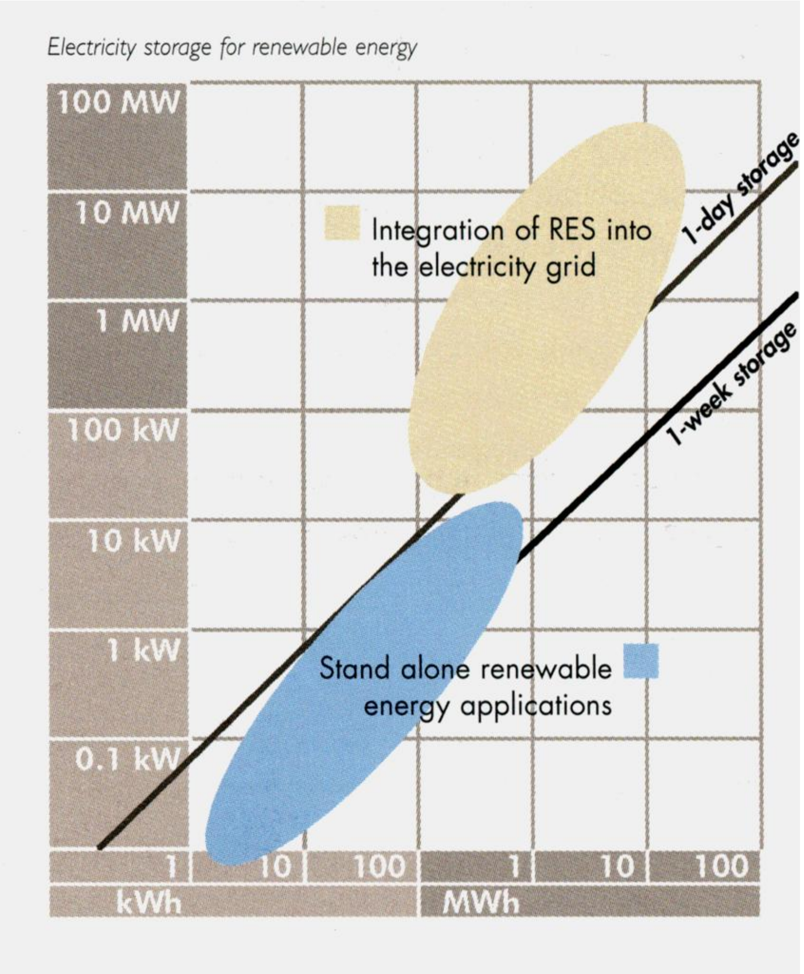
Variability of renewable energy sources



Storage Applications in Electrical Power Systems

- Variability of renewable energy sources
- Application Categories
- Grid Networks
- Remote Power Systems

Storage Application Categories:
- Electricity grid networks
- Remote Power Systems



- reproduced from:
- EC Publication EUR19978 2001
- Energy Storage *A key technology for decentralised power, power quality and clean transport*

Storage Applications

- Short-term energy storage
  - to compensate for rapid voltage fluctuations & flicker (continuous)
  - to compensate for voltage transients
  - possible technologies: flywheels, batteries, supercapacitors, SMES
- Long-term energy storage
  - to provide stability (high power cycling)
  - to provide grid reinforcement (peak lopping, distributed storage)
  - to provide firm power
  - possible technologies: redox-flow, electrolyser/hydrogen/fuel cell, pumped hydro, large compressed-air, batteries

Storage Applications in Electrical Power Systems

- Variability of renewable energy sources
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Grid networks

- Present power system:
  - Central Generation (economies of scale)
  - Pooling of Generation & Reserve capacity
  - Grid network for transmission from resource areas to load centres
  - Distribution
- Moving towards:
  - Integration of a high level of renewable generation
  - Decentralisation of power generation

Grid networks - evolving

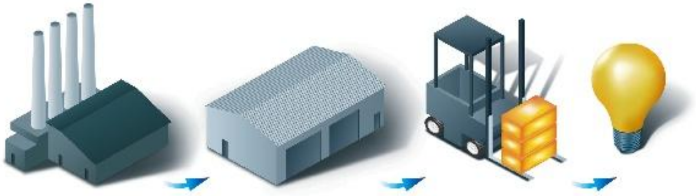
- UK Renewable Energy Strategy: 15% of energy (30% of electricity) from renewables by 2020 (around 120TWh pa)
  - means 30-45GW capacity (capacity factor 30-45%)
  - UK minimum loading in summer < 20GW
  - network stability, spinning reserve
  - curtailment of renewable generation
- In Denmark wind power already supplies over 20% of total electricity

Grid networks - evolving

- Renewables & CHP integration:
  - Future high penetration of renewables (non-dispatchable)
  - Possible over generation or high levels of spinning reserve
- Curtail renewable generation or use storage?
- Economics of electricity trading - premium on predictability
- See ‘Review of NETA on smaller generators’ Ofgem 2001 http://www.ofgem.gov.uk/
  - energy trading via bilateral contracts encourages predictability
- matching variable renewable generation & loads
  - geographical distribution (N-S, embedded generation)
  - capacity factor (diurnal and seasonal)
- Match supply to demand (low cost, high security, high quality)

Grid Networks - evolving

- Generation mix (Nuclear, conventional thermal, gas turbine, spinning reserve); flexibility; control; scheduling
- Demand: demand-side management?
- Management of distributed networks? (micro-grids?)
- Change existing T&D network?
- **Is storage part of the solution?**
  - centralised or distributed?
  - Storage technologies?
  - Link with hydrogen economy?

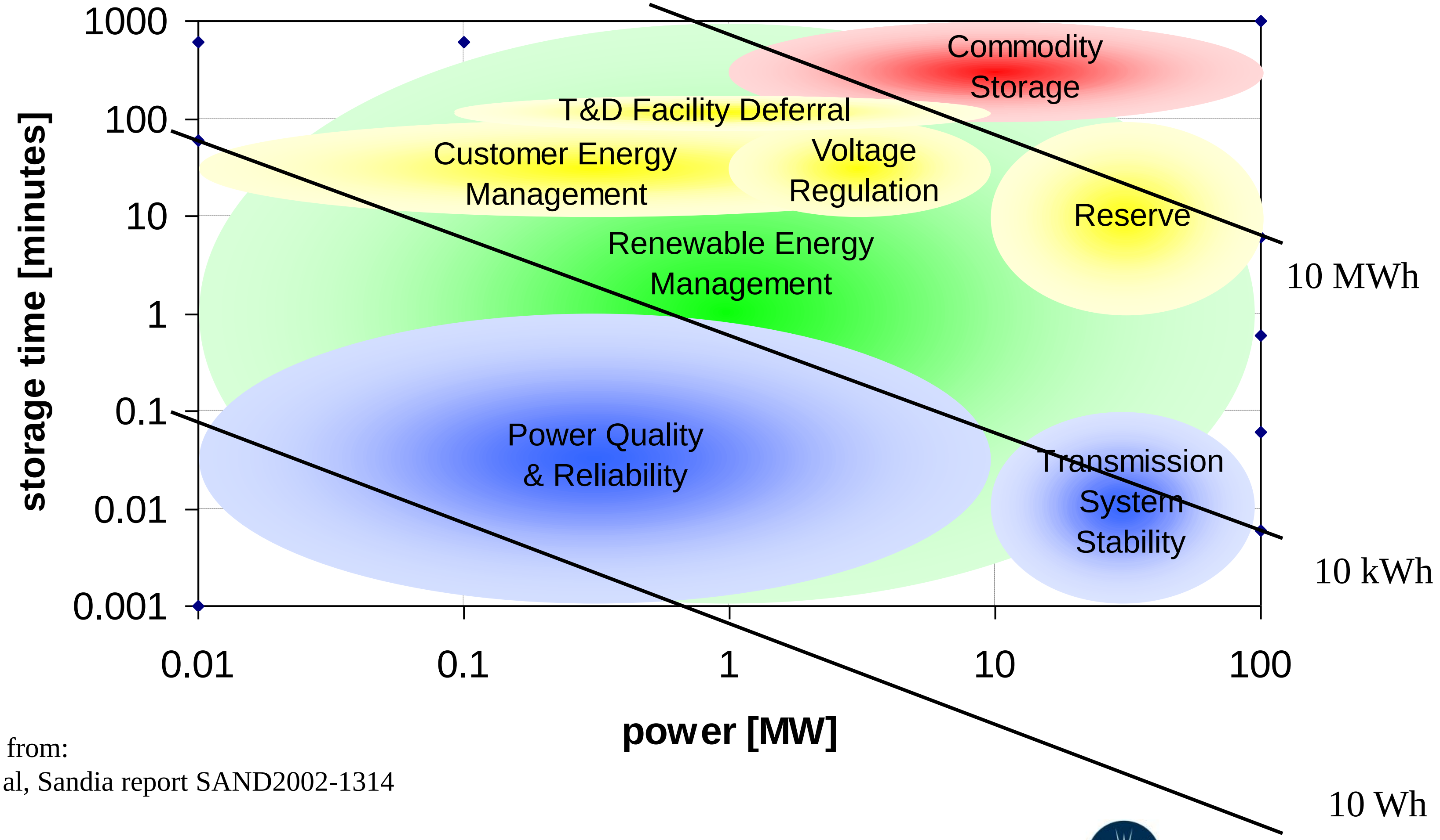


Electricity warehouse (Regenesys Technologies Limited)

Grid networks
Storage – early studies

- CEGB (1980) Large scale electricity storage
  - Review of potential for large-scale energy storage
- RAL (1984) A study of electricity storage and central electricity generation
  - Central generation - increased storage justified by economic analysis
  - Distributed storage - potential reduction of T&D losses. High storage efficiencies are required.
- US DOE Energy Storage Systems Program: Energy Storage Opportunities Analysis (Phase I-1984, Phase II-2002)
  - Group of industry experts
  - Identified 10 applications with high value
  - Covering Generation, T&D, Customer service
  - Results published in 2 Sandia reports

Grid networks – storage applications (US DOE study)



Using data from:
P.Butler et al, Sandia report SAND2002-1314

Grid networks – Storage applications

- Applications range from:
  - load levelling, peak shaving and arbitrage
    - ‘energy’ storage (timescale: hours)
  - spinning reserve grid stability and generation scheduling
    - Timescale: minutes
  - power quality and reliability
    - ‘power’ storage (timescale: seconds)

Electricity Storage Association

Grid networks
Storage time vs applications

- Wide range of power (10 kW to 100 MW)energy (Wh to MWh), and storage times (energy / power):

Power/Energy [hour $^{-1}$]	**Storage time**	**Applications**
< 1 (high energy)	> 1 hour	• Load levelling • Peak shaving
60 to 1	1 minute to 1 hour	• Spinning reserve • Frequency and voltage regulation
> 60 (high power)	< 1 minute	• Power quality improvement • Transmission grid stability

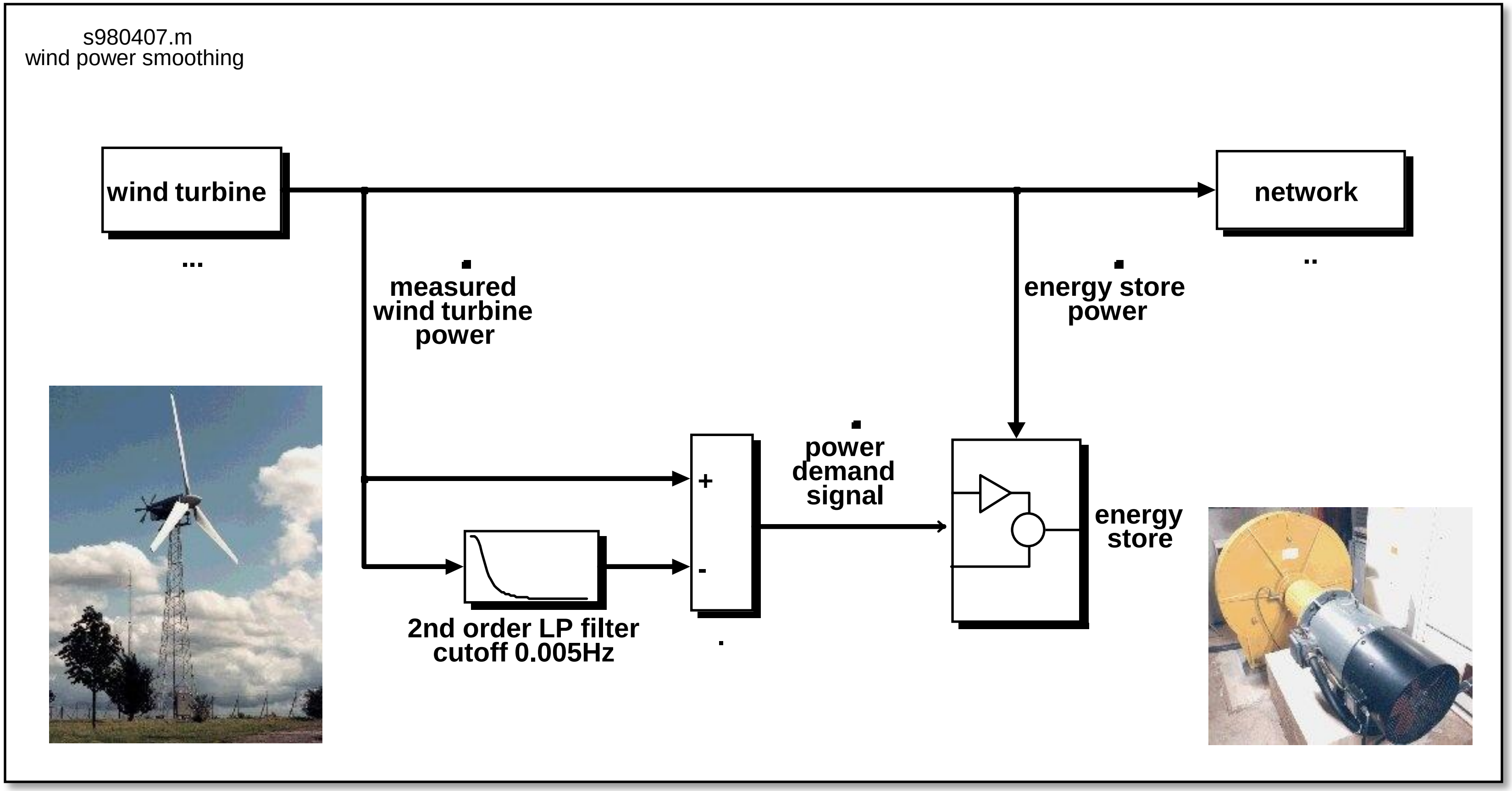
Applications of Storage in Electrical Power Systems

- Variability of renewable energy sources
- Application Categories
- Grid networks
- Remote Power Systems

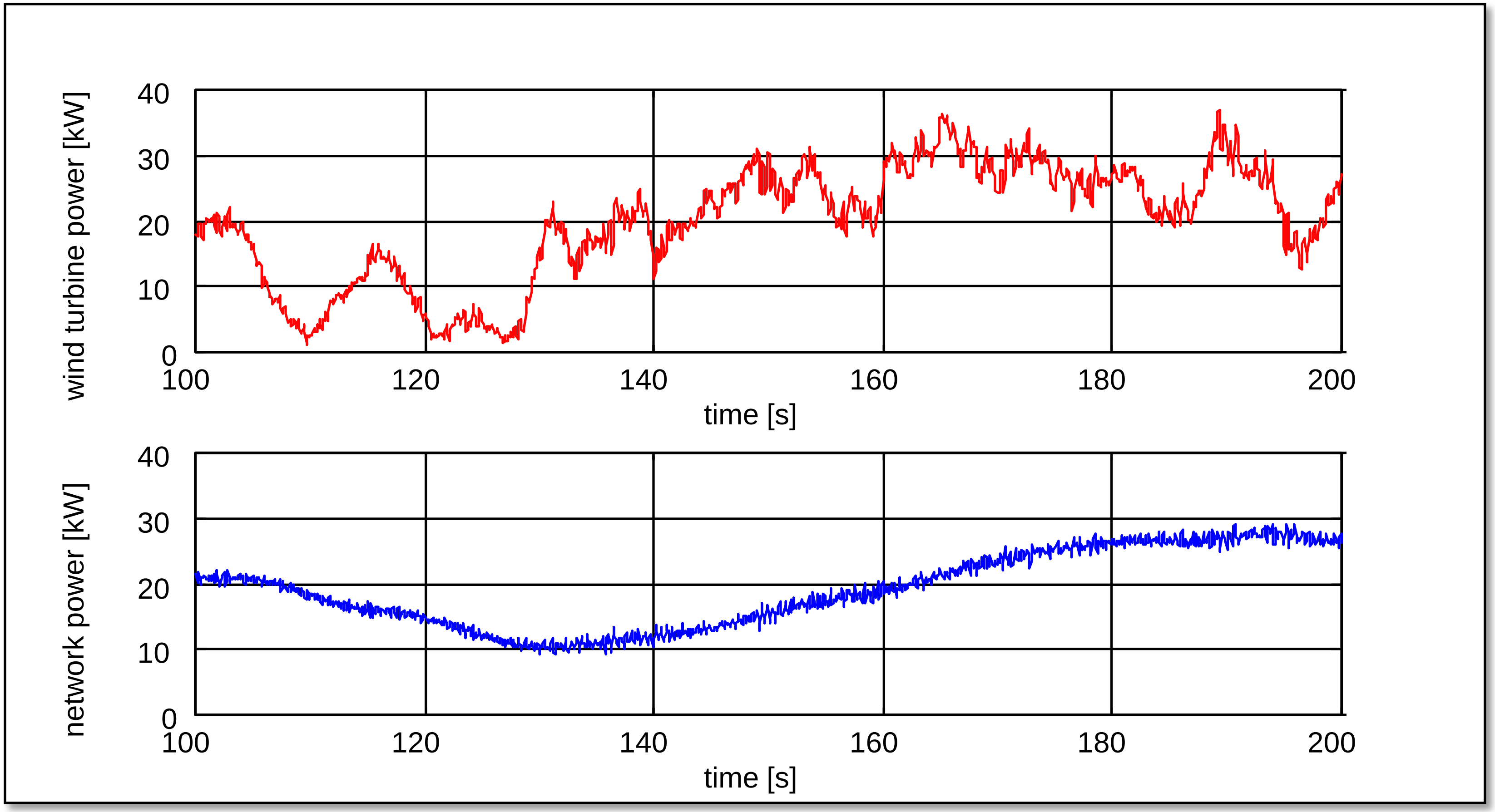
Rural & Remote Power Systems

- rural electrification (mains power)
  - isolated communities, islands, villages
  - grid extension or reinforcement may not be economic
  - energy: 1000 - 8000 kWh/capita per annum
- remote area power supplies (low voltage d.c.)
  - navigational aids, telecommunications, monitoring, cathodic protection, lighting
  - grid connection usually not possible or economic
  - low energy requirements, up to 1kWh per day
- **energy storage is required**

Wind Power Smoothing: short term storage



Wind Power Smoothing: short term storage



Science & Technology
Facilities Council

Storage Technologies

- General requirements
- Investire (2003) Storage technology reports, Technical criteria and specifications, Existing data, Economic analysis, Environmental issues, RTD strategies
- Current status of deployment
- Technologies

Storage Technologies:
- General requirements

- low capital cost, low O&M costs, throughput costs
  - e.g. needs to be < 0.01 £/kWh throughput
- long lifetime (standby and cycling)
- high availability and reliability
- high in/out efficiency, low standing losses
- fast response
- capacity and rated power independently specified
- commercially available
- size of storage modules
  - e.g. 1MW – 100MW, 4 hour storage

Storage Technologies

- General requirements
- Investire (2003) Storage technology reports, Technical criteria and specifications, Existing data, Economic analysis, Environmental issues, RTD strategies
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- Technologies overview

Storage technologies
EU Investire (2003) - which technology?

Advanced Lead-acid

Redox systems

vanadium, Zn/Br, S/Br

Electrolyser + H2 + fuel cell

Nickel-Cd or mH

Flywheels

?

Supercapacitors

Compressed air

Lithium

Sodium/sulphur

Metal-air

Storage Technology Investire (2003)

- A summary of the state-of-the-art of existing storage technologies
- Definition of requirements for storage within the various types of renewable energy systems
- An evaluation report on the promising emerging technologies for intermittent renewable energy applications, based on a database of selected examples and case studies
- A proposal for a mid- and long-term RTD strategy, based on:
  - the renewable energy requirements
  - the present and expected technical performance
  - the cost prospects and the environmental considerations

- The Investire project focus was **standalone systems**

Storage Technologies

- General requirements
- Investire (2003) Storage technology reports, Technical criteria and specifications, Existing data, Economic analysis, Environmental issues, RTD strategies
- Current status of deployment
- Technologies overview

Status of storage deployment - worldwide

- Countries with significant large-scale storage (1996)

	Total installed capacity (MW)	Storage installed capacity (MW)	Penetration of storage
USA	778000	19000	2.4%
South Africa	39000	1500	3.8%
UK	73000	2800	3.8%
South Korea	34000	1700	5.0%
Belgium	14000	1200	8.4%
Italy	56000	5400	9.5%
Japan	219000	21000	9.6%

(source A.Price EESAT 98, and Utility Data Institute)

- Total large-scale storage worldwide
  - 90GW, representing less than 3% of total installed generation capacity
  - pumped hydro storage, with limited potential to expand

(source http://electricitystorage.org/tech/technologies_technologies_pumpedhydro.htm)

Status of storage deployment - UK

- Pumped storage in UK 2800MW total:
- Festiniog (1963) 360MW (several hours discharge)
- Foyers (1975) 300MW + 400MW
- Dinorwig (1984) 1800MW (5 hours discharge)
  - 78% cycle efficiency
  - response time 16s to full power (or 2min from cold start)
- New developments are planned (SSE)

Storage Technologies

- General requirements
- Investire (2003) Storage technology reports, Technical criteria and specifications, Existing data, Economic analysis, Environmental issues, RTD strategies
- Current status of deployment
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Storage Technologies - Overview

- Electrochemical storage
  - Batteries (electrodes are part of the chemical reaction)
    - Lead-acid, Lithium, Nickel, Sodium sulphur
  - Flow cell (electrodes are catalysts for the chemical reaction):
    - Vanadium, Zinc-bromine, Hydrogen (Electrolyser / fuel cell)
- Electromechanical storage
  - Pumped hydro
  - Compressed air energy storage (CAES)
  - Flywheel
- Electrical storage
  - Superconducting magnetic energy storage (SMES)
  - Capacitors

http://www.electricitystorage.org/ESA/technologies/

Electrochemical batteries

- 20MW / 14MWh PREPA, Puerto Rico 1994 (GNB lead-acid batteries)

- 1.4MWh Metlakatla, Alaska 1997

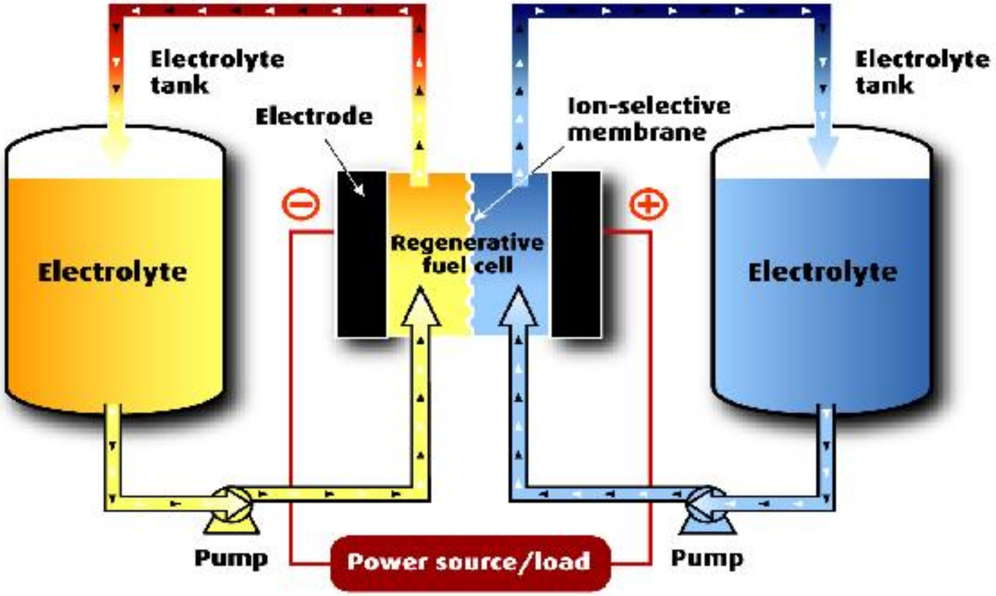
- 27MW / 6.75 MWh (0.25h) Fairbanks, Alaska (2003)
  - cost \$35M (13,760 SAFT NiCd cells)
  - isolated mining community, vulnerable to frequent power cuts
  - operation without a break when the generation and transmission systems fail.
  - savings from a reduction in spinning reserve

SAFT SBH920 (920Ah) 62 kg
13,760 cells

Electrochemical storage – flow cells

- Vanadium (Sumitomo, Japan; Vanteck Technology, Australia; Cellenium Co., VRB, now Prudent Energy)
- Zinc Bromine (Powercell; ZBB)
- Sodium bromide; Sodium disulphide (Regenesys Technologies Ltd)

- Regenesys prototype
  - 15 MW 120MWh (8h)
  - cost around £14M
  - Little Barford, Cambs
  - black start
  - TVA, USA
  - deferral of generation / grid reinforcement



(Regenesys Technologies Limited)

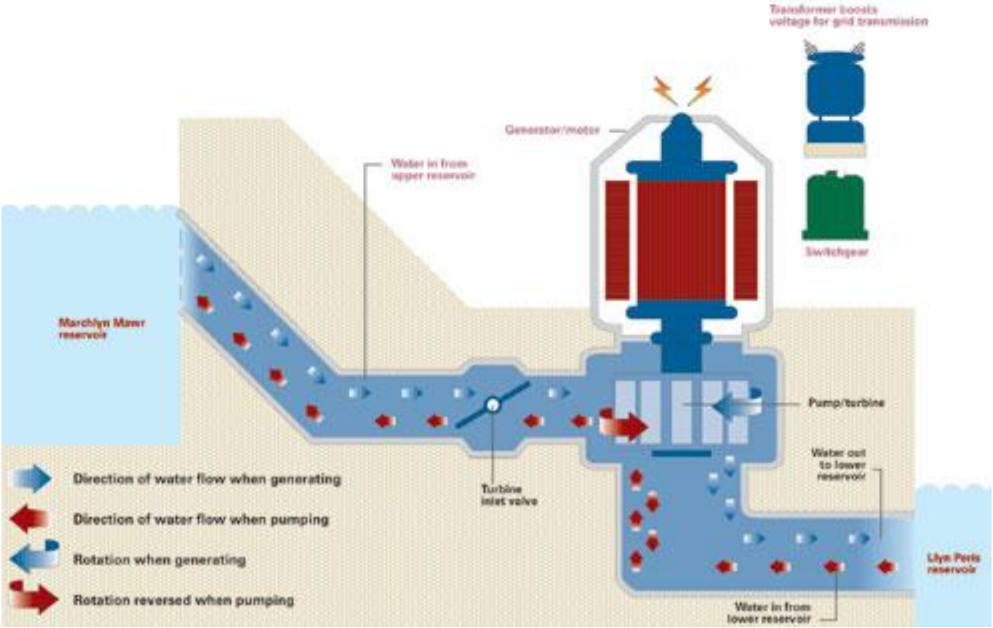
Electrochemical storage - Hydrogen

- Electrolyser - hydrogen storage - fuel cell
- Low overall efficiency 25 - 30%
- Capital cost
- Hydrogen Storage:
  - Large scale, low pressure
    - underground (~10bar)
  - Medium scale
    - large compressed tanks (~70bar)
    - liquid (20K) - uses 30% of energy
  - Other methods
    - metal hydrides (currently 1-2% w/w, R&D aim 7% w/w)
    - carbon structures (potentially 30-40% w/w)

Electromechanical storage – Pumped Hydro

- Pumped hydro storage is currently the dominant technology
  - Used for energy management, frequency control, reserve

First Hydro
http://www.fhc.co.uk/index.asp



Electromechanical storage – Compressed air (CAES)

- Conventional CAES supplying compressed air to a gas turbine (Davidson 1980)
- Fast response
- High power output

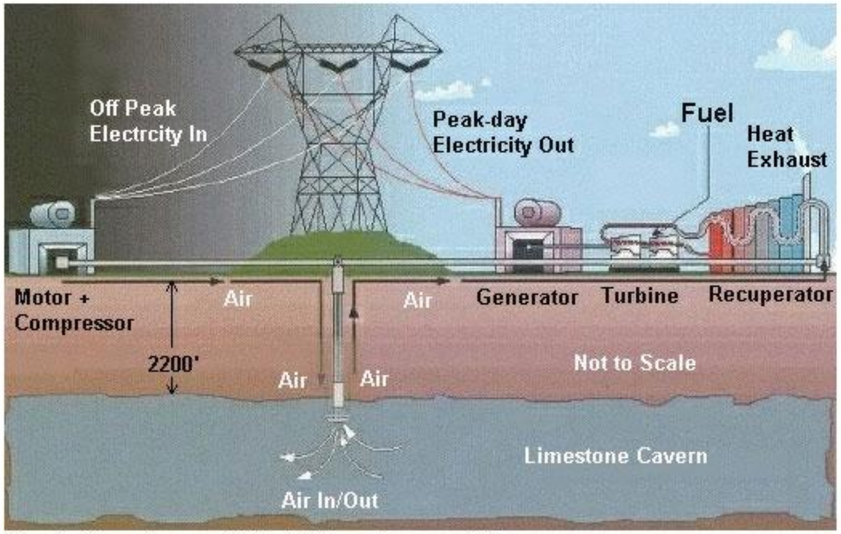


Photo Courtesy of CAES Development Company

- A gas turbine fed with compressed air is very efficient
  - a normal gas turbine uses around 2/3 of the gross output to compress air
  - gross output 300MW = 200MW (compressor consumption) + 100MW (net output)

Electromechanical storage – Compressed air (CAES)

- CAES is a mixture of storage and generating plant, and measures of performance are:

$$\text{charge energy factor (c.e.f.)} = \frac{\text{electrical energy output}}{\text{electrical charge energy}}$$

$$\text{fuel heat rate (f.h.r.)} = \frac{\text{combustion fuel consumed}}{\text{electrical energy output}} \quad [kJ/kWh]$$

$$\text{fuel cost of generation} = \frac{\text{charge energy cost}}{\text{c.e.f.}} + \text{fuel cost} * \text{f.h.r.}$$

- A full evaluation of energy and capital costs is required
- CAES can be developed for various combinations of c.e.f. and f.h.r. depending on operation and economic benefit

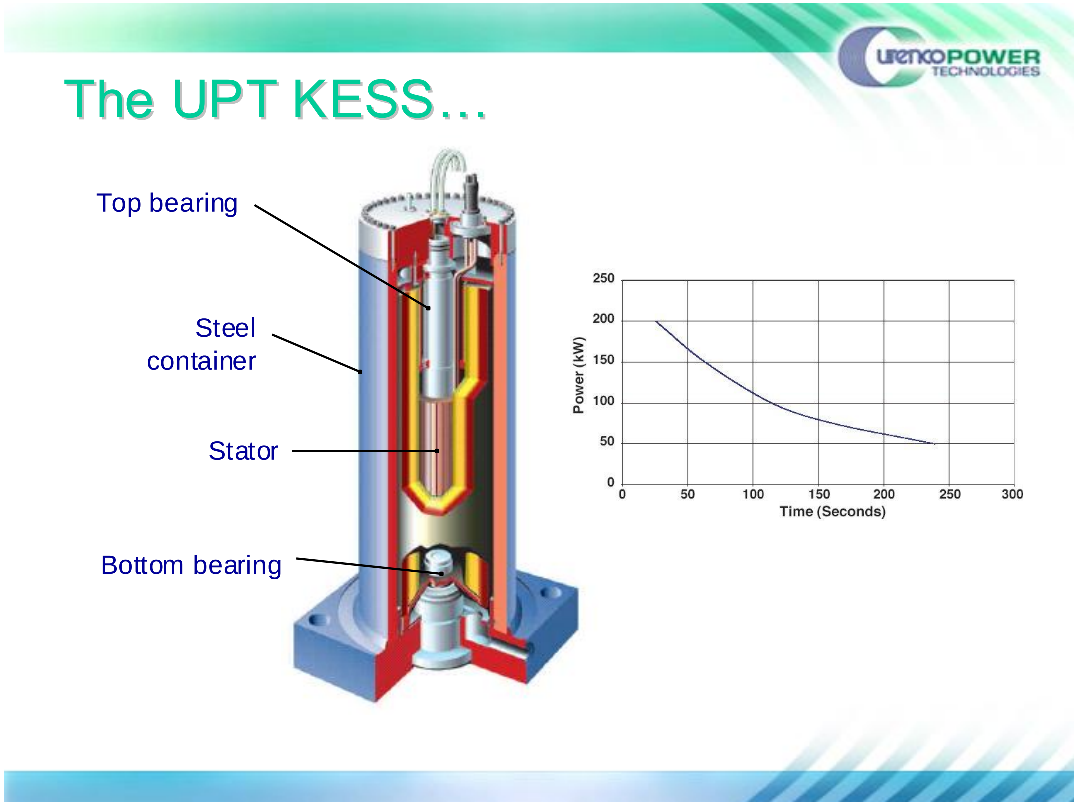
Electromechanical storage – CAES

- 290MW Huntorf, Germany (1978)
  - 70-43 bar, 650m
  - rated specification: 290MW for 3 h = 870 MWh
  - compression using off-peak electrical energy
    - 60MW for 12h = 720MWh
- 110MW McIntosh, Alabama (1991)
  - 75bar, 400m
  - cost $65M
  - online in 14 min
- Proposed: 2700MW Norton, Ohio
  - 100bar, >600m (using an existing limestone cavern)

Electromechanical storage – flywheel

- High speed composite rotor (Urenco Power Technologies, Beacon Energy, and others)

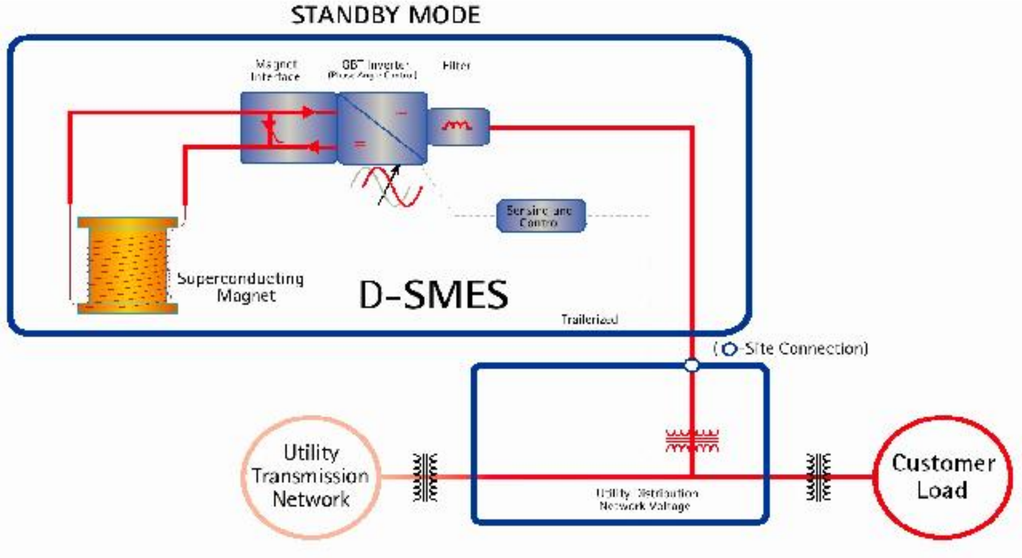
- Beacon Energy 250kW / 25kWh (0.1 h)
- projected cost around $80k
- can be paralleled (e.g. 10 units, to give 2.5MW / 0.25 MWh)



Electrical storage: Superconducting magnetic energy storage (SMES)

- LTS (~4K) Niobium-based Superconductor developed in 1960s - facilitates making large efficient magnets
- HTS (~70K, liquid nitrogen temperature) ceramic material
  - 90% efficiency / rapid response / high power
  - aimed at PQ applications, 1 - 2 kWh (storage time of seconds)

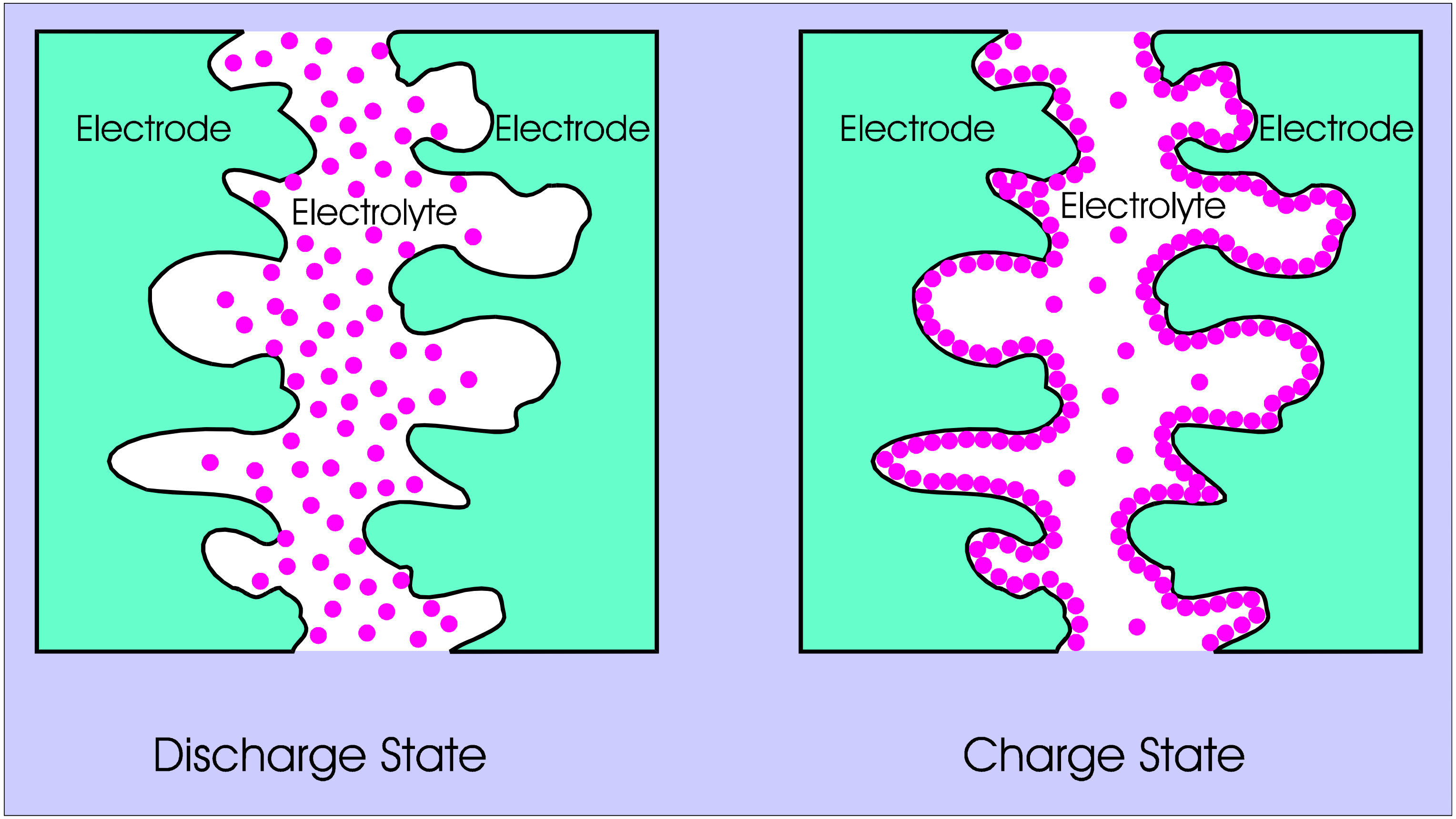
- e.g. American Superconductor, 3MW distributed storage for PQ improvement
- US DOE funding HTS product dev’t



Electrical storage: Supercapacitor

- energy stored electrostatically
- maximum energy stored: $E = \frac{1}{2} C V^2$
- energy density up to 5Wh/kg
- porous carbon-based electrodes
  - surface area up to 2000 m^2/g, charge separation distance < 10 angstroms
- electrolytes are organic (2.3V) or aqueous (1V)
- faradic efficiency is nearly 100%
- energy efficiency depends on the current
  - e.g. ranging from 77% (5s discharge) to 96% (30s discharge)
- self-discharge is high, e.g. 6.5% loss after 12h at 25°C

Electrical storage: Supercapacitor



Principle of a double-layer capacitor

(from Investire ST3 Supercaps report)

Electrical storage: Supercapacitor

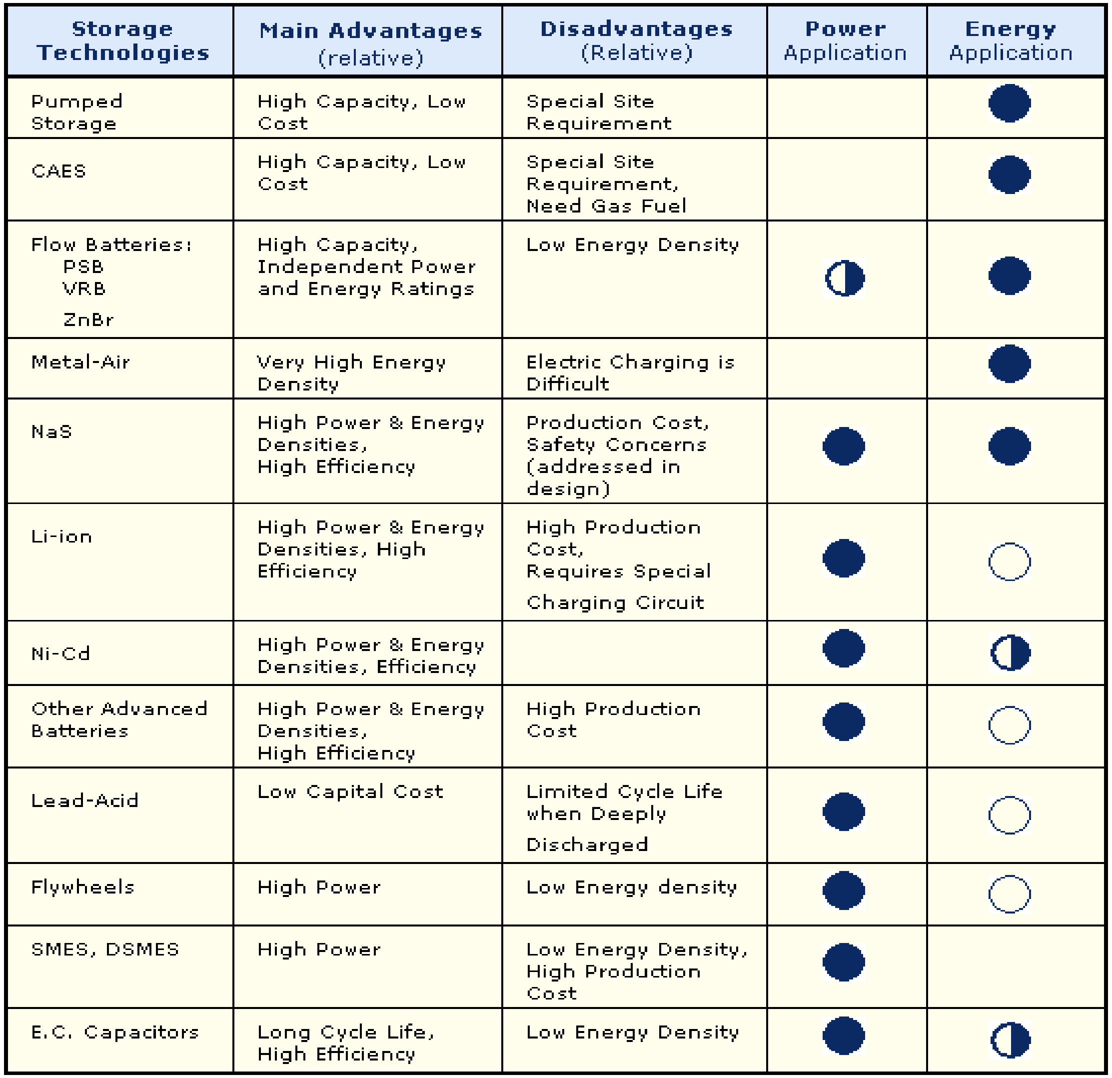
- Maxwell Technologies
  - Boostcap Ultracapacitors

Passive or Active voltage balancing module

2600 F 2.3 V	2700 F 2.3 V	435 F 14V
525g, 0.42 l	725g, 0.6 l	6kg, 7.5 l
max 8125J (2.2Wh)	max 8400J (2.3Wh)	max 42500J (11.8Wh)
max 600A (1.38kW)	max 625A (1.44kW)	max 600A (8.4kW)

Technology comparisons

from http://www.electricitystorage.org/ESA/technologies/



Storage Technologies	Main Advantages (relative)	Disadvantages (Relative)	Power Application	Energy Application
Pumped Storage	High Capacity, Low Cost	Special Site Requirement		●
CAES	High Capacity, Low Cost	Special Site Requirement, Need Gas Fuel		●
Flow Batteries: PSB VRB ZnBr	High Capacity, Independent Power and Energy Ratings	Low Energy Density	◐	●
Metal-Air	Very High Energy Density	Electric Charging is Difficult		●
NaS	High Power & Energy Densities, High Efficiency	Production Cost, Safety Concerns (addressed in design)	●	●
Li-ion	High Power & Energy Densities, High Efficiency	High Production Cost, Requires Special Charging Circuit	●	○
Ni-Cd	High Power & Energy Densities, Efficiency		●	◐
Other Advanced Batteries	High Power & Energy Densities, High Efficiency	High Production Cost	●	○
Lead-Acid	Low Capital Cost	Limited Cycle Life when Deeply Discharged	●	○
Flywheels	High Power	Low Energy density	●	○
SMES, DSMES	High Power	Low Energy Density, High Production Cost	●	
E.C. Capacitors	Long Cycle Life, High Efficiency	Low Energy Density	●	◐

Comparison of high Power/Energy Technologies

	Supercapacitor	Flywheel	SMES
Power range [kW]	10 to 100	10 to 1000	1000 to 10 000
Storage time [s]	10	5 to 30	1
Energy related cost [US$ / kWh]	82 000	25 000	72 000
Power related cost [US$ / kW]	300	350	300
Lifetime [cycles]	10 000	10^5 to 10^7 (20 years)	(30 years)

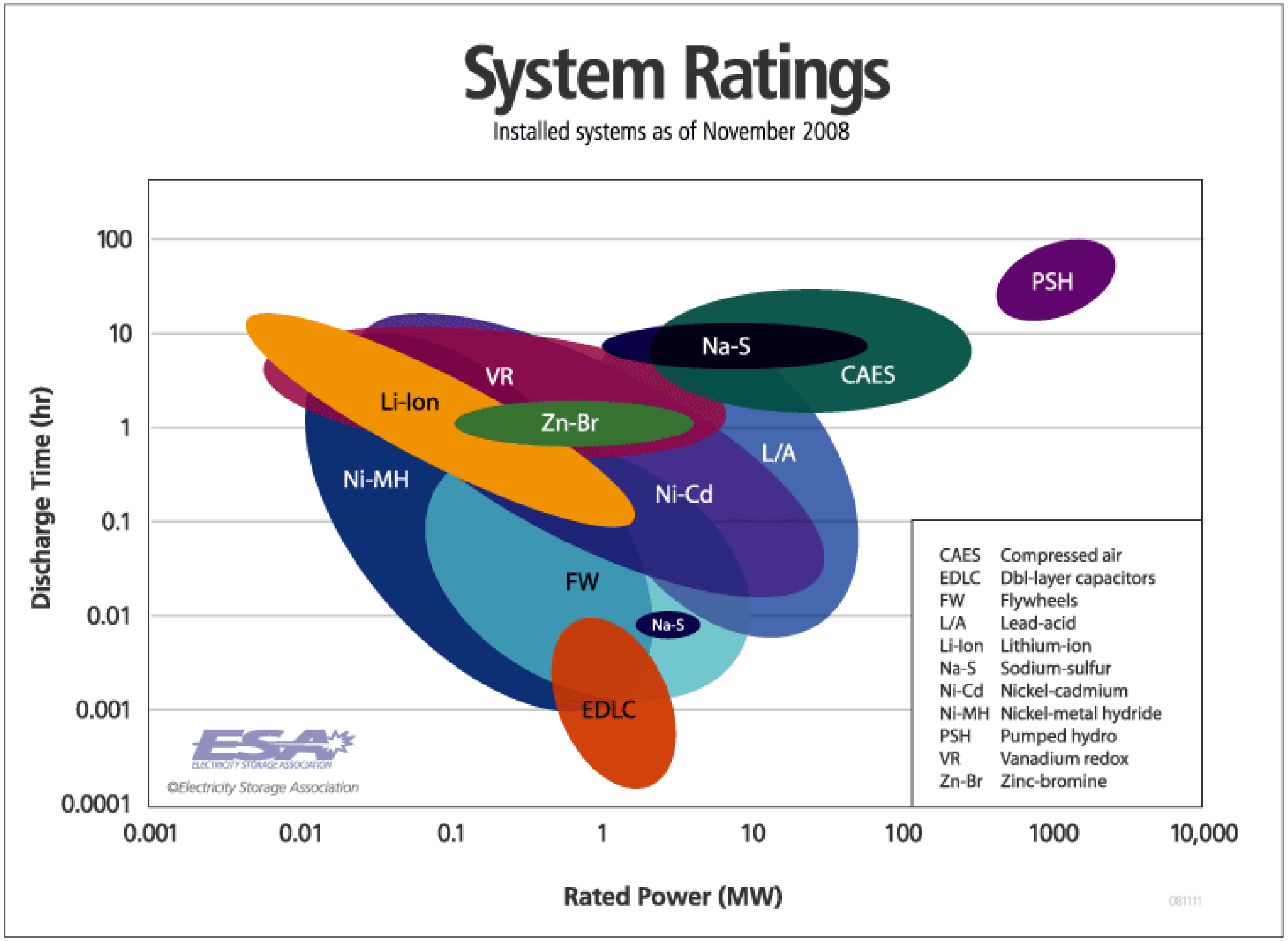
- High cycle lifetime of flywheels means low energy throughput cost, potentially as low as 0.01 € / kWh

Data from:
- Investire ST6 report
- Sandia report SAND2001-0765

See also: http://www.electricitystorage.org/ESA/technologies/

Installed system ratings

from http://www.electricitystorage.org/ESA/technologies/

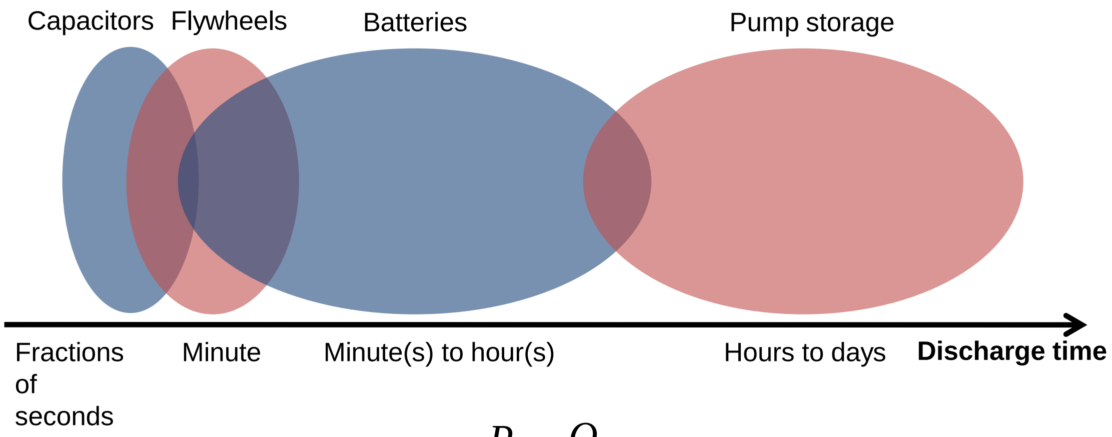


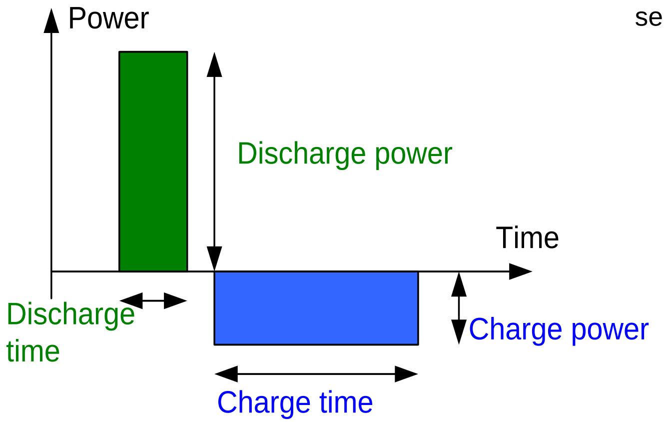
Storage Systems

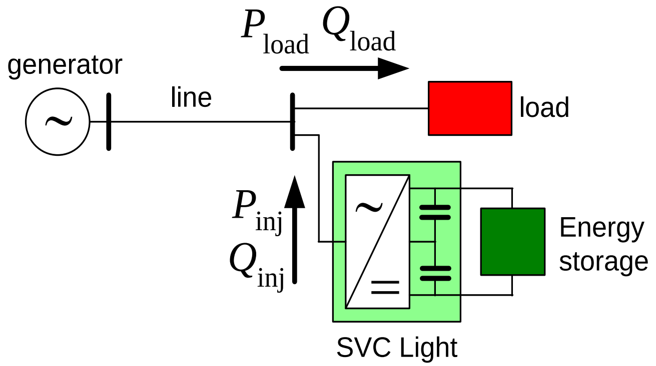
- ABB - DynaPeaQ SVC-Lite with energy storage
- Saft
- Converteam - ProNRG
- Alstom – Pumped Hydro
- Siemens
- ReStore (Exide Technologies)

Storage Systems – ABB

- ABB DynaPeaQ SVC Light with Energy Storage
- 5 to 60 mins
- 5 to 50 MW
- 5 MWh
- Li-ion battery







Storage systems - Converteam

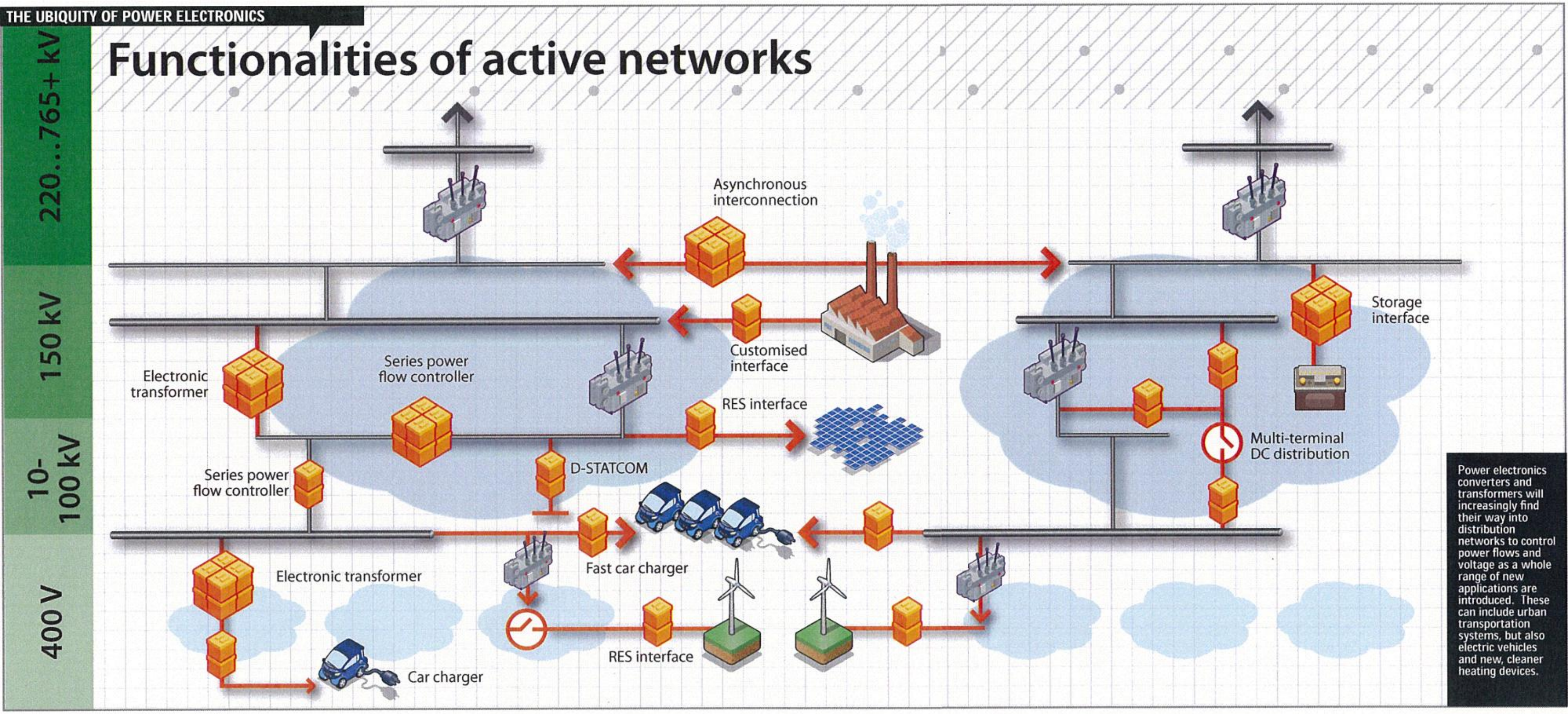
- Converteam Variable Speed Power Generation for Pump Storage Hydro Plants
  - Vattenfall Europe, Germany
    2x265MW Pump Storage Hydro Plant of Goldisthal - 2x100MVA Cyclo Converter
  - EnBW Kraftwerke AG
    Pump Storage Hydro Plant of Forbach - 20MW Synchrodrive, fully speed controlled
- Converteam ProNRG
  - a standard range of high power converters available for use in energy storage systems (including super-capacitors, advanced batteries, flywheels and flow cells) according application

Storage systems – Alstom

- 45% of global pumped storage plant

- Key installations:
- Huizhou - 2007, Baoquan - 2007 and Bailianhe - (China)
  3 pumped-storage plants
  16 x 306 MW turbine/generator units, BOP, control systems.
- Alqueva (Portugal), 2012
  4 x 130 MW turbine/generator units, control system.
- New Tyin (Norway), 2004
  2 x 220 MW generators, BOP, control system

Storage systems - Alstom



Power electronics converters and transformers will increasingly find their way into distribution networks to control power flows and voltage as a whole range of new applications are introduced. These can include urban transportation systems, but also electric vehicles and new, cleaner heating devices.

Storage systems - Siemens

- Siemens Turbine Load Control (TLC)
  - allows turbine installation on sites where the wind conditions exceed the design criteria of the turbine.
  - monitors turbine loads in real time and adjusts turbine operation if actual loads exceed design loads
- Use the rotor inertia for energy storage?

Storage systems: ReStore

- Lead-acid batteries
  - PV standalone power supplies
  - standby power in offshore / onshore windfarms

- Li-ion battery for submarine propulsion
- 48V 24Ah (1.15 kWh) 8.8kg
- Stack of small 3V nom. cells

Supergen Wind

Supergen Wind
Theme 3 Task 4 Integration of Storage

- In offshore substation
  - enhance stability in steady state
  - enhance stability following external/internal disturbances & transients
- Onshore
  - enhance stability following external disturbances
  - avoidance of curtailment
- Storage solutions – What?/Where?

Supergen Wind
WP4.1 Energy storage requirements

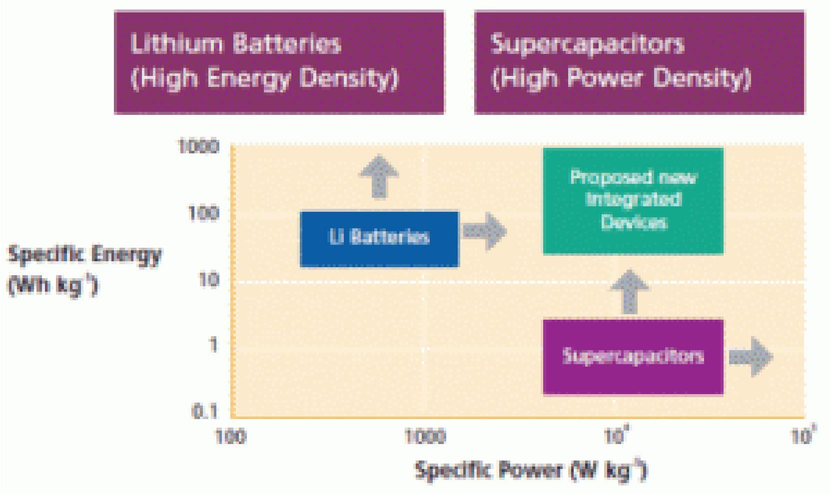
- Storage requirements
  - Providing frequency response and stability
  - Avoiding turbine trips during fault conditions
  - Curtailment of wind farm output to grid
- Assessment of appropriate storage technologies
  - lead-acid & lithium cells; flywheels; flow cells; capacitors

Application	**Power**	**Storage time**	**Response**	**Cycling**	**Technology**	**location**
a) stability	low - medium	seconds	sub-sec	high	supercapacitor, flywheel	offshore
b) turbine trips	high	seconds - minutes	sub-sec	low	flywheel, battery	offshore
c) avoiding curtailment	high	hours	slow	low	battery, flow cell	onshore

1. a hybrid solution for a) and b) could be possible
2. a high energy solution for c) offers other services, e.g. arbitrage
3. a fast response solution for c) could also offer stability improvements

Synergy with other UK projects

- AuRA-NMS Autonomous Regional Active Network Management System (EPSRC EP/E003583/1)
  - Includes UK demo of ABB SVC Lite with Lithium-ion energy storage
  - http://www.aura-nms.co.uk/
- Supergen Storage
  - Supercapacitors and Lithium ion batteries (and hybrid)
  - http://www.energystorage.org.uk/



Summary (1)

- Storage is applicable to renewable energy integration in:
  - existing grid / distribution networks
  - isolated networks in developing countries
  - stand-alone power systems
- Storage needs:
  - low cost (capital, running)
  - efficient, long cycle life, high reliability

Summary (2)

Storage assists grid integration of renewable energy:

- increase utilisation of renewable energy (avoid curtailment)
- facilitate high levels of embedded generation
- match supply to demand
  - short-term / diurnal / seasonal storage
  - provide firm power, facilitate energy trading
- reduce overall primary fuel consumption
  - provide spinning reserve
  - peak power lopping
- **improve power quality, network stability, supply security**

Sources of information

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