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Use of energy storages in Smart Grids management

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Summary

The work done for this report is part of Smart Grid and Energy Market programme (SGEM) of Cluster of Energy and Environment (CLEEN). The report is a delivery for Active resources, WP3.5: Energy storage technologies.

In this study it is made a wide review of latest available energy storage techniques that could be potential in current and future Smart Grid applications. Energy storages altogether can be seen as a developing technology. Energy efficiency, longer battery lifetime and higher cyclic lifetime, safety, environmental issues and lower cost are the most important issues. Most activities exist in lithium-ion battery development but also other battery technologies are developing. Generally the improvements in materials and battery chemistry as well as the development of more intelligent battery and power management systems would bring the currently known energy storage technologies more useful in Smart Grid applications. The currently highly increased funding and R&D could bring also totally new storage technologies available in the long run.

In this study it is also characterized energy storage application areas, possible applications and usability in the Smart Grid management. The main activities currently happen in USA where most evaluations and large demonstration systems have started or been planned. Similar situation as in USA grid might be already in near future in some European countries where renewables penetration is already remarkable high. Most important utility scale energy storage type considered widely in Europe is pumped hydroelectric storage mainly for wind power regulation. New PHS systems are currently installed in Switzerland and planned to install also e.g. in Austria and Portugal. Also new large NaS battery installations are planned in Europe.

In this first project year study it is included also some evaluations of energy storages benefits in Finland where it is not yet easy to find economic benefits for commercial use of energy storages. Future larger renewables penetration level, higher electricity price and lower storage prices can change the storage economics remarkable.

Confidentiality	Public	
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Preface

The work done for this report is part of Smart Grid and Energy Market programme (SGEM) of Cluster of Energy and Environment (CLEEN) financed by Finnish Funding Agency for Technology and Innovation Tekes, industrial partners, universities, and research institutes.

Espoo 29.3.2011

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Contents

Abbreviations and Symbols

AC	Alternated Current
AS	Ancillary services
ATSOI	Association of TSOs of Ireland
BALTSO	Association of Baltic TSOs
BCI	Battery Council International
BEV	Battery Electric Vehicle
CAES	Compressed Air Energy Storage
CAES	Compressed-Air Energy Storage
CCGT	Combined-Cycle Gas Turbine
CCR	Capital Charge Rate
Cl	Chlorine
CSP	Concentrating Solar Power
DC	Direct Current
DG	Distributed Generation
DoD	Depth of Discharge
DOE	Department of Electricity (US)
DSM	Demand Side Management
ECES	Energy Conservation trough Energy Storage
ECN	Energy Research Center of Netherlands
EEC	European Economic Community, EY
ENTSO-e	European Network of Transmission System Operators for Electricity
ESA	Electric Storage Association (US)
ESS	Electric Storage System
EU	European Union
EVs	Electric Vehicles
FACTS	Flexible AC Transmission System
FACTS	Flexible Alternating Current Transmission System
GE	General Electric
GW	Gigawatt
IEA	International Energy Agency
IEEE	Institute of Electrical and Electronics Engineers
IGBT	Insulated Gate
ISO	Independent System Operator
ISO	Independent System Operators
LiBF4	Lithium Tetrafluoroborate
LiClO4	Lithium Chlorite
Li-FePO4	Lithium Iron Phosphate

LiMnO2	Lithium Manganese Oxide
LiPF6	Lithium Hexafluorophosphate
LiTi	Lithium Titanate
MW	Megawatt
NaCl	Sodium Chlorine
NaS	Sodium Sulfur
NERC	North American Electric Reliability Corporation
NiCl2	Nickel Chloride
NiMH	Nickel Metal Hydride
NORDEL	Association of Electric Co-Operation of Nordic Countries
PHES	Pumped Hygroelectrci Storage System
PHEV	Plug in Electric Vehicle
PHS	Pumped Hydro Storage
PV	Photovoltaics
RE	Renewable Energy
SMES	Superconductive Magnetic Energy Storage
SMES	Superconducting Magnetic Energy Storage
SO	System Operator the Entity Responsible for Monitoring and Controlling the Electricity System
T&D	Transmission and Distribution
T&D	Transmission and Distribution
TSO	Transmission System Operator
UCTE	Union for the Coordination of Transport of Electricity
UKTSOA	UK Transmission System Operator Association
V2G	Vehicle to Grid
VRB	Vanadium Redox Battery

1 Introduction

Energy storages are seen as a strategic tool managing variability and capacity in the modern smart grid. The evolution of the Smart Grid will depend on cost effective energy storage, particularly in the early stages while other distribution and demand management solutions are being developed, adopted and implemented. Smart Grid energy storage applications can be divided into three functional classes: generation, transmission and distribution and end-user. Continuously variable energy production like wind and solar energy production can increase the need of energy storages especially in weak grid areas. Energy storages implemented with distributed energy generation can increase overall energy efficiency as well as they can improve smart grid performance and management ability. Also at the end-user level the new type customer applications can have remarkable effects to the power grid. Energy-plus houses, end user level solar and wind power production and especially electric and plug-in hybrid vehicles (cars, busses) can change the end-use role to be a power producer and can have a great impact for the performance of energy systems.

2 Goal

Overall objective of the Cleen Smart Grid, Active resources, Energy storage technologies work package is:

- to have good understanding of development of different energy storage technologies like batteries, super capacitors, flywheels, water heaters and their roles and ability to respond to demand in the different areas of the smart grid
- to determine the concepts (measurements, protection, communication) for network interface of two-way energy storages
- to analyse the impact of energy storages for networks and energy market
- to analyse and investigate the control systems of energy storage environments
- to investigate and analyse could same kind of technologies to be used both in stand-by energy storages and EV batteries. The link between demand response and intelligent grid and business logistics to researched.

Work package includes two tasks: Task 3.5.1: Energy storage technologies and Task 3.5.2: Integration of storage resources to Smart Grids. This document describes the work done for the task 3.5.1. The aim of task is to have deep knowledge of techno-economic development of different energy storage technologies and their roles and ability to respond to demand in different areas of the grid in the economical and technical management.

Energy storage work package work includes VTT's European level co-operation work in IEA ECES (Energy Conservation through Energy Storages) and lately in EERA Smart Grid work.

3 Smart Grid

“Smart Grid” is a world wide adopted term to describe a future transmission and distribution grid. Smart grid is basically a combination of the grid control technology, intelligence information technology and intelligence management of generation, transmission and distribution.

In the report of the EU Commission Task Force for Smart Grids Expert Group 1, a smart grid is defined as follows [1]

“A Smart Grid is an electricity network that can cost efficiently integrate the behaviour and actions of all users connected to it – generators, consumers and those that do both – in order to ensure economically efficient, sustainable power system with low losses and high levels of quality and security of supply and safety.”

Energy storages can be seen as a building block to enable Smart Grid system functions (Figure 3-1).

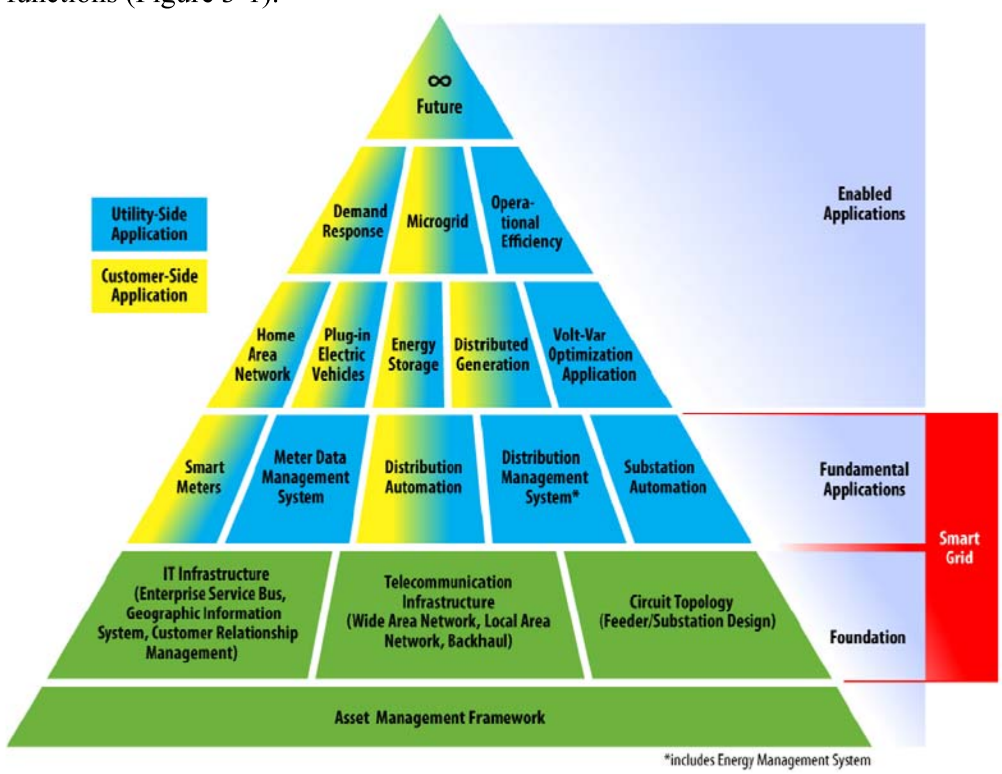


Figure 3-1. Smart Grid building blocks – energy storages [Source: BCHydro, Tom Gutwin].

Energy storages can be an active resource in different areas from transmission grid applications (Figure 3-2) to end user systems as a large pumped hydroelectric power plant to a single rechargeable battery. Energy storage can be also a private customer owned megawatt level “storage power plant” that can have an interesting role in a future energy market.

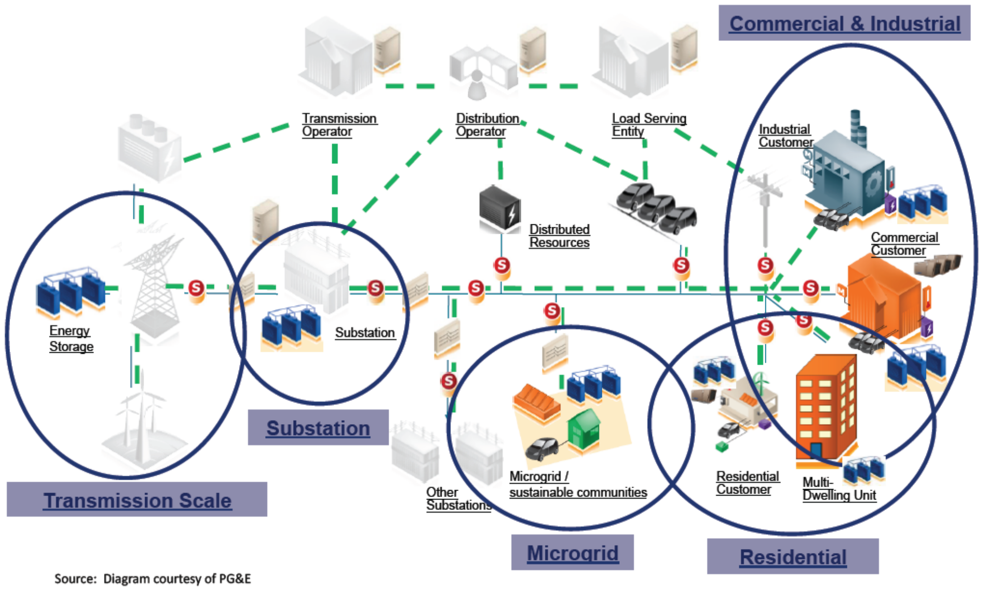


Figure 3-2. Energy storages in different Smart Grid applications [9].

4 Energy Storage Technologies

Current available electrical energy storage technology considered in Smart Grid applications includes different types of electrochemical batteries, high-energy capacitors, super conductive magnetic energy storage technology, flywheels, compressed air storages and pumped hydroelectric storages. Batteries of electric vehicles are also seen as potential storage systems to be used in smart grids. Molten salt storage based solar-thermal power plants are new type of solution of thermal energy storages available for grid management.

4.1 Electric Double-Layer Capacitors (EDLC)

Technology

Electrochemical capacitors with relatively high energy density are often called super- and ultracapacitors. Supercapacitor or ultracapacitor is an electro-chemical double layer capacitor. The capacitor is formed electrochemically between electrolyte and electrode (Figure 4-1). The voltage of the supercapacitor is near linear and drops evenly from full voltage to zero volts.

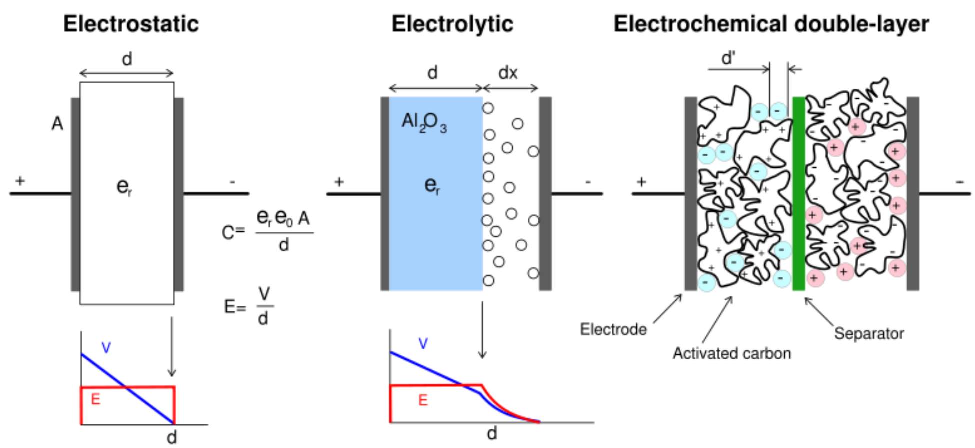


Figure 4-1. Capacitor type schematics [Source: www.ultracapacitors.org].

Technical Properties

Supercapacitors can operate in the full range 0% to 100% SOC but practical operation area is 25% to 100%. Super-capacitor charge-discharge efficiency is around 98%. Cell voltage is typically 1.2 to 1.5 VDC. Charge time is about 10 seconds. For example, an SAFT supercapacitor module (583 F, 15 V, 400 A) can be charged from zero voltage (zero of charge) to the maximum voltage in 22 s at a constant current of 400 A [48]. The initial charge is rapid but the topping charge takes more time. When fully charged they stop accepting more charge.

Control System and Interface

Stringed capacitors need balancing circuits to be able to charge all stringed capacitors properly passing fully charged capacitors. Supercapacitor bank can be connected to the DC-bus by bi-directional DC-DC-converter and to the AC-bus by AC-DC-converter.

Development Trends and Future Expectations

The development of supercapacitors has steadily proceeded during recent years. Supercapacitors can offer specific power levels that are about one order of magnitude higher than those of batteries (15 vs. 2 kW/kg). The specific energy level of the best batteries is about 100 Wh/kg whereas supercapacitors can reach about 5 Wh/kg. The above-mentioned values are for Maxwell BCAP supercapacitor and A123 ANR26650 and Toshiba SCiB batteries. The lifetime of supercapacitors is of the order of 10^6 cycles, which is considerably higher than the best cycle lives promised for batteries (normally 1 000 cycles, for A123 Li-ion 5 000 cycles).

Current efficient material development and especially nanomaterials are giving new features for supercapacitors including increased energy density and lower price. One example of the new promising materials is graphene (one atom thick structure of bonded carbon atoms that are densely packed in a honeycomb crystal lattice) which large surface area (2 630 m^2/gram) can result very high levels of stored charge. Printed or paper supercapacitors are the types under development e.g. in Stanford University. The CSIRO in Australia [national science agency] has developed the UltraBattery, which combines a supercapacitor and a lead acid battery in a single unit.

Economical Aspects

Price level of supercapacitors is around 0.01 to 0.02 $/farad.

The global market for supercapacitors estimated by bcc Research is at $470 million in 2010. Demand for supercapacitors is projected to continue growing at a very healthy rate during the next 5 years, reaching a value of $1.2 billion in 2015, a compound annual growth rate (CAGR) of 20.6%.

Manufactures, Commercial Products and Solutions

Main supercapacitor manufacturers are in USA and in Japan (Figure 4-1).

Table 4-1. An example of supercapacitor manufacturers and product sizes.

Manufacturer	Country of manufacturer	Technology	Electrolyte	Voltage, V	Capacitance, F	Energy density, Wh/kg	Power density, W/kg
Maxwell	USA	Metal/carbon	Non-aqueous	2,5 - 2,7	4 - 2600	0.65 - 5.6	470 - 4100
Bussmann	USA	Carbon aerogel	Organic	2.5 - 5.0	0.1 - 50	0.22 - 2.95	
Cap-xx	Australia	Carbon composite	Organic	2.3 - 4.5	0.09 - 1.8	0.047 - 1.01	
Elna	USA	Charcoal	Organic solvent	2.5 - 6.3	0.047 - 100		
Evans	USA	Hybrid	Sulfuric acid	5.5 - 11.0	0.47 - 1		
MaxFarad	Korea	Nanostructured carbon	Organic	2.3 - 2.5	6 - 220	1.28 - 5.8 (max. 6.6)	>4200
Nec Tokin	Japan	Activeted carbon	Sulfuric acid	2.7 - 11.0	0.01 - 100	0.408 - 4.22	
NessCap	Korea	Carbon		2.3 - 2.7	5 - 5000	2.2 - 5.8	3890 - 5120
Nichicon	Japan	Charcoal		2.5	0.47 - 3300		
Panasonic	Japan	Carbon composite	Organic	2.1 - 5.5	0.022 - 70		
Skeleton Nanolab	Estonia	Nanostructured carbon	Organic	2.7	1450 - 4500	7.1 - 7.3	2300 - 3700
Vinatech	Korea	Metal oxide/Activated carbon		2.5/2.7	3 - 600	1 to 5	2000 to 5000
Vinatech	Korea	Hybrid		2.3	10 - 220	5 to 10	500 to 1000

Potential Application Areas in Smart Grids

Supercapacitors are fast, they have a long cyclic life and they need almost zero maintenance being suitable for smart grid applications. The main application area could be the combination with other longer discharge time storages e.g. with lithium batteries to increase battery system life-time taking care of short high power needs.

4.2 Superconductive Magnetic Energy Storages

Technology

The concept for superconductive magnetic energy storage (SMES) was developed in beginning of 1970. The concept bases on a superconductive coil were direct current is circulated and energy is stored in a magnetic field with nearly zero losses. To maintain a superconducting state, a coil is immersed in liquid helium contained in a vacuum-insulated cryostat. Commercially available low temperature SMES (T < 20K = -253°C) are cooled with liquid helium. Because of the high cost of cooling commercial solutions based low temperature superconductors (LTS) were minor. 1986 was found a ceramic oxide that is conductive in 36 K. High temperature superconductors (HTS) made possible to develop new commercial products (Figure 4-2). Today used materials like bismuth based copper oxide ceramics are conductive in 108 K (-165.2°C). High temperature SMES can be cooled with liquid nitrogen.

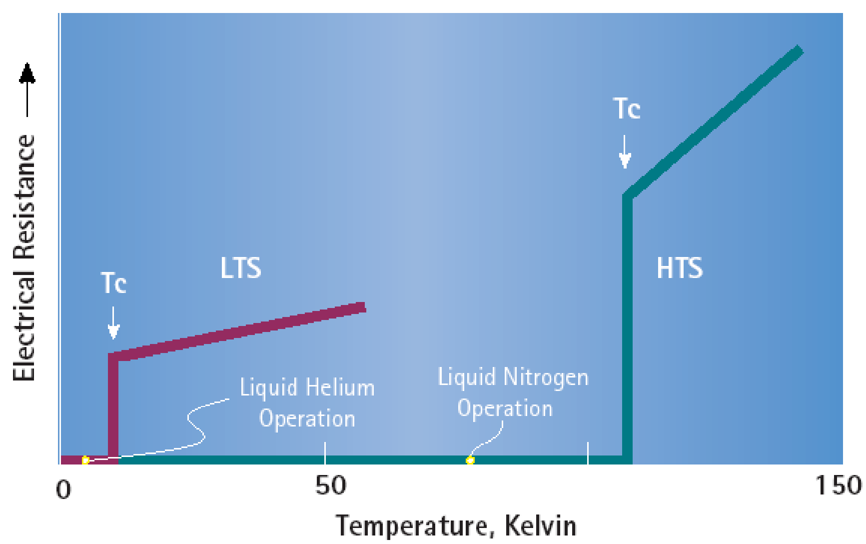


Figure 4-2. Conductivity differences of Low temperature (LTS, Tc < 20 K) (niobium-titan) and high temperature (HTS, Tc > 77 K) (bismuth based copper oxicide ceramics) [Source: American Superconductor].

Technical Properties

SMES can be discharged in a moment with high power over short time periods. Increasing size of windings can be increased energy. SMES system includes also refrigeration system.

In a superconducting magnetic energy storage (SMES) electric current is stored in the superconducting windings with little resistive losses. Relation between energy and current of a superconductive coil is:

$$E = \frac{1}{2} L I^2 \tag{4.1}$$

where L is the inductance of the inductor and I is the charging current.

SMES has high cyclic efficiency, fast response time and deep discharge and recharge ability.

Economical Aspects

Current applications are mainly maid by low temperature superconducting goils. Depending PCS the cost of the storage system is within the range of $85–125 K per megajoule (MJ), while the cost of the PCS is in the range of $150 to $250 per kilowatt (kW). [30]

Control System and Interface

The total system includes superconductive coils, cryogenic refrigeration system and power conditioning system (PCS) (Figure 4-3).

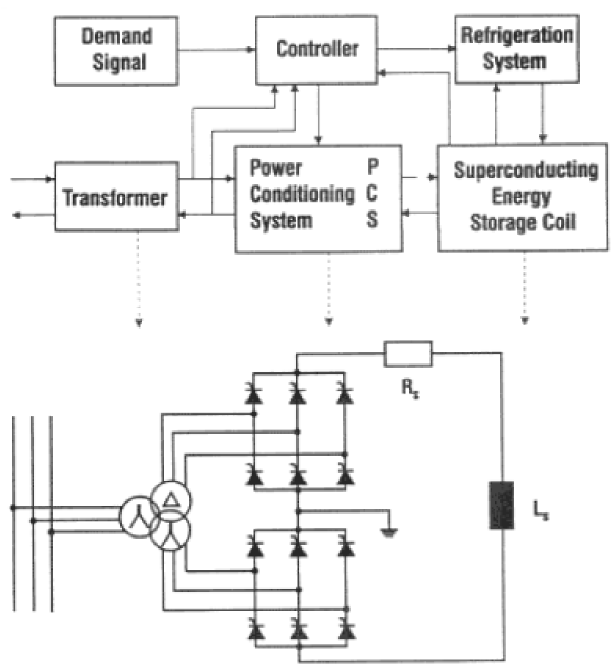


Figure 4-3. Superconducting magnetic energy storage (SMES) system [Source: American Superconductor Corp].

SMES can be categorized into three main groups depending its power conditioning system: thyristor-based SMES (Figure 4-3), voltage-source-converter (VSC) -based SMES (Figure 4-4) and current-source-converter (CSC) -based SMES (Figure 4-5). Thyristor based SMES can control mainly the reactive power and has little ability to control active power. VSC- and CSC-based SMES can control both active and reactive power independently and simultaneously. [29]

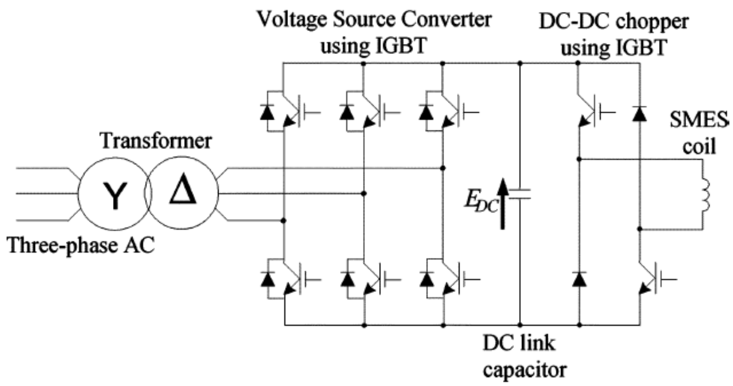


Figure 4-4. Configuration of VSC-based SMES [29].

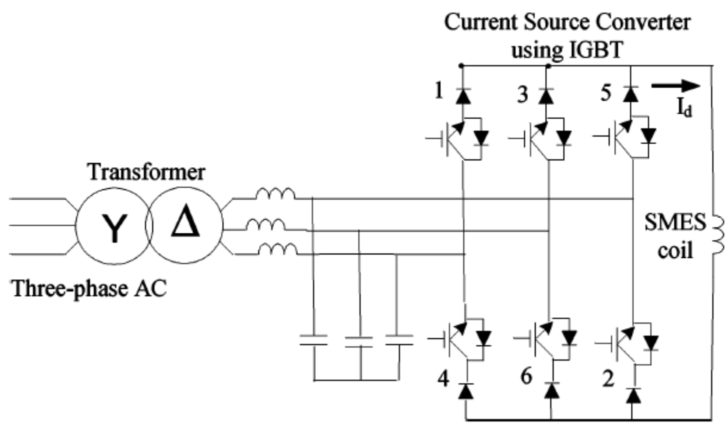


Figure 4-5. Configuration of CSC-based SMES [29].

Life Cycle Aspects

A SMES under normal operating-conditions does not lose any of the stored energy, thus yielding an electrical efficiency of 100%. However, heat leaks through the cryostat create losses that must be compensated for by appropriate cooling. Total efficiency for theoretical 50 kW 450 kWh LTS with liquid-helium cooling SMES system is 5% and life cycle (20 years usage) emissions NOx 563 kg, SO_2 404 kg, CO 133 kg and CO_2 433 tons. A similarly-sized HTS SMES would yield 50% total efficiency. [37]

Manufactures, Commercial Products and Solutions

To date, only micro-SMES (1 to 10 MW) systems are commercialised. American Superconductor Corporation has a typical product that can deliver 1 MW for 1 second. The system response time is within 5 ms of a disruption in the line. They had 9 trailer units (Figure 4-6) installed worldwide in 2000. [31]. Now over 100 MW has been installed worldwide [28].

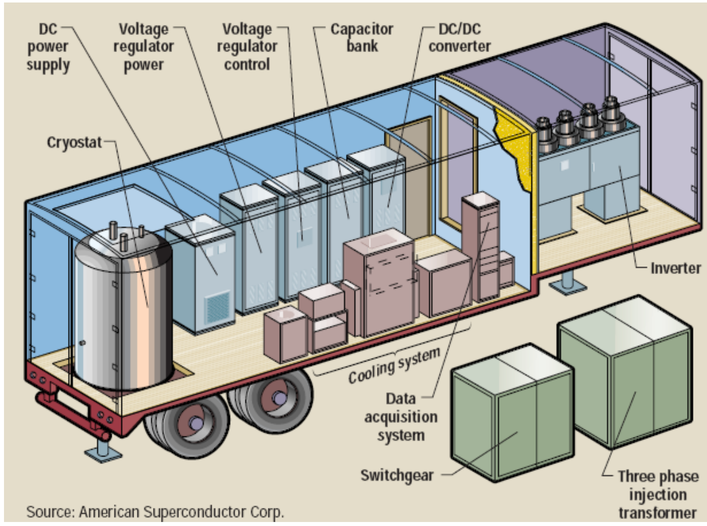


Figure 4-6. Superconducting magnetic energy storage (SMES) trailer [Source: American Superconductor Corp].

Development Trends and Future Expectations

Development of high temperature superconducting coil and more efficient refrigeration system might reduce SMES cost. According to a study by Sandia National Laboratories [32] for SMES systems significant advances would result from development of power electronics that are specifically suited to SMES devices.

Korea Electrotechnology Research Institute (KERI) is one of the research organisations that studied SMES systems and has developed a 3 MJ, 750 kVA SMES system to improve power quality in sensitive electric loads. 2 MJ HTS SMES system is planned to be developed until the end of 2010. [61]

Potential Application Areas in Smart Grids

SMES has high electrical efficiency and SMES system has fast response and capability to control active and reactive power makes it potential in many smart grid applications. Micro-SMES units address applications such as transmission line stability, spinning reserve, static VAR compensation and voltage support for critical loads.

Summary

SMES devices are comparatively expensive with parasitic loses and low total energy density. There are still technology challenges especially for the development of larger higher energy SMES systems. High temperature superconductors, more efficient cryogenic cooling systems, high magnetic field and also mechanically secure structure are the key issues in the future development.

4.3 Flywheels

Flywheel energy storage (FES) system can store energy in the form of kinetic energy of a rotating rotor. On charging, the flywheel is accelerated, and on power generation, it is slowed.

The kinetic energy stored in a rotating mass is:

$$E = 0.5\omega J^2 \quad (4.2)$$

where ω is the angular velocity, and J is the moment of inertia that is a function of the mass and shape of the flywheel.

High-energy flywheels have typically heavy steel wheel and lower speed when high rotor of the power and high speed (20 000 to 50 000 rpm) flywheels is made of high strength carbonfibre-composite filaments. High-speed flywheels have usually a vacuum enclosure and magnetic bearings (Figure 4-7). The motor/generator is usually a high-speed permanent magnet machine and integrated with the rotor.

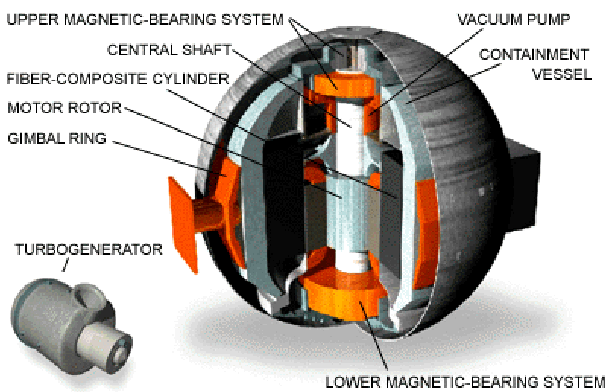


Figure 4-7. Flywheel [Source: www.upei.ca].

Technical Properties

Flywheels are available in different sizes. Output energy of flywheel depends on the type for example energy density of the steel flywheel is about 0.045 MW/h/m^3, composite flywheel 0.323 MW/h/m^3 and advanced 'nano' flywheel even 0.531 MW/h/m^3. The maximum output power is dependant upon the duration required. This is illustrated in figure (Figure 4-8) below. Increased power, duration and/or redundancy can be achieved by adding units in parallel.

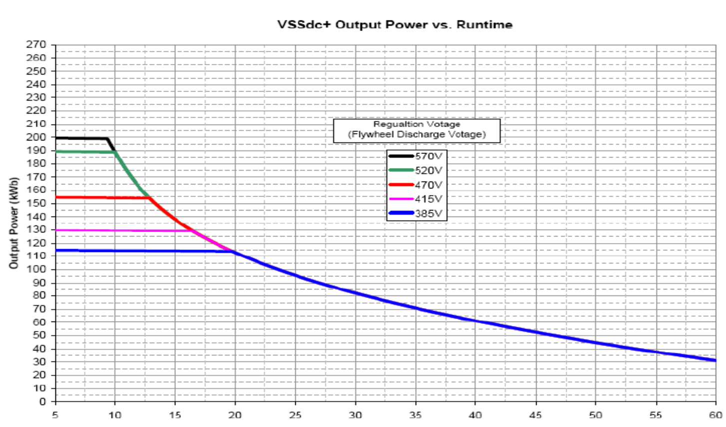


Figure 4-8. Figure of the performance chart. KWb refers to kilowatts on DC bus of the UPS system [Source: Pentadyne].

Typical energy capacities range from 3 kWh to 133 kWh. Flywheel systems include typically several parallel-connected modules e.g. Active Power can provide paralled systems with capacity and power up to around 7 kWh at 2 000 kW using 8 rotors, and URENCO can provide 25 kWh at 2.1 MW for traction applications using ten modular systems. Pentadyne FES basic cabinet has maximum output power 190 kW and recharging time < 15 sec. 1 000 kVA UPS systems include 5 cabinets á 190 kW. VYCON's VDC unit provides up to 220 kW of DC power while the VDC-XE (Xtended Energy) model supplies up to 300 kW of DC power within a single cabinet. For longer run times and higher power capacities, the VDC models can be easily paralleled.

Flywheel systems have long lifetimes. Full-cycle lifetimes range from in excess of 10^5, up to 10^7 cycles of use, high energy densities (~ 130 Wh/kg, or ~ 500 kJ/kg), and large maximum power outputs. The energy efficiency of flywheels can be as high as 90%. Rapid charging of a system occurs in less than 15 minutes.

Economical Aspects

The total cost of a system with a 1-hour storage time will be in the region of $1 000 to $3 000 per kW.

Control System and Interface

Main parts of a flywheel system include a flywheel module, power conversion and control electronics (Figure 4-9). The power electronics interface is usually a pulse width modulated (PWM) bi-directional converter using insulated-gate bipolar transistor (IGBT) technology. The power electronics interface can achieve a full-load efficiency of greater than 90%, however this falls off at low loads. The converter may be single-stage (flywheel a.c. ⇔ d.c. bus), or double stage (flywheel a.c. ⇔ d.c. bus⇔ a.c. network), according to the application requirements.

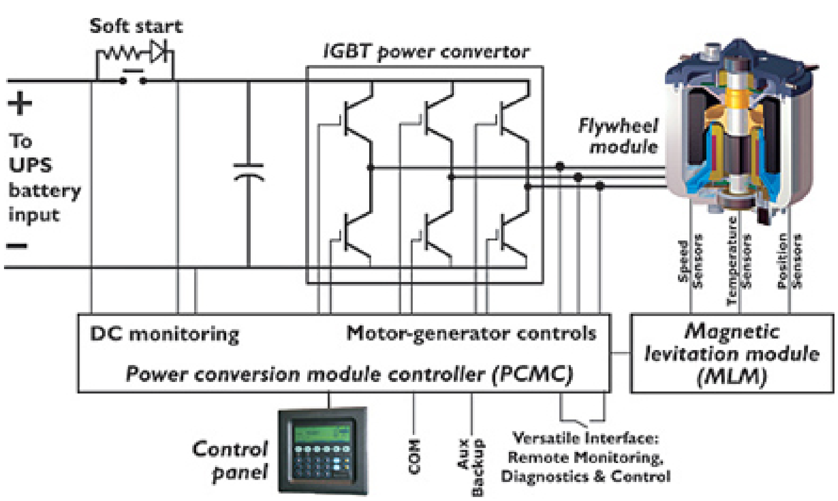


Figure 4-9. An example of the flywheel storage system [Source: Pentadyne].

Life Cycle Aspects

Material used in flywheels is typically steel, carbon fibre, aluminium and copper. In composite rotor handling it can used resin and in power electronics it is used silicon. The materials used in flywheel energy storage systems are mainly not hazardous, and e.g. steel and metal parts can be re-cycled after the end-of-life. There are no significant emissions during normal operation. Acoustics noise levels are generally low. The main hazard during operation is the possible fatigue failure of the rotor and the sudden release of the stored energy in heat and flying debris. The GHG emissions produced of flywheel system under operation are based on the emissions of the production of electricity used for flywheel charging.

Manufactures, Commercial Products and Solutions

The main manufacturers include Active Power, AFS Trinity Power Corporation, Beacon Power, Flywheel Energy Systems, Pentadyne, Piller, TSI (Tribology Systems Inc.), Vycon and Urenco Power Technologies.

Large flywheel plants installed or under construction are e.g. (2008) 3 MW plant in Tyngsboro, (2011) MA, 20 MW (Figure 4-10) in Stephentown, NY, (2011-2012) 20 MW in Hazle Township, PA and (2012) in Chicago Heights, IL.

Figure 4-10. 20 MW, 5 MWh flywheel storage plant for regulation services in Stephentown, NY [63].

Development Trends and Future Expectations

Future research target of flywheels would include improved rotor materials, bearings and safety. Materials research breakthroughs would influence also on flywheel development. Self-discharge is a problem that is under development. Improved magnetic bearings such as those using superconductors could reduce losses but would increase cost with refrigeration and increased maintenance. Reduced cost and improved safety are essential issues for the deployment of flywheels in the residential systems.

Potential Application Areas in Smart Grids

Flywheels can support ancillary service like frequency response, provide short time support for spinning reserve and standby reserve. Flywheels have potential for effectively support Flexible Alternating current Transmission Systems (FACTS) devices but main applications of flywheels in the smaller distributed power systems are in the UPS-systems. Flywheels in UPS applications provide typically power for 15 seconds that covers most power quality events and short power shortages (Figure 4-12). Flywheel system can work as ride-trough power with generators and can be used with batteries to cover short-duration events and save batteries that work for longer outages.

For example ActivePower has battery-free flywheel energy storage system that operates for 15 minutes at 80 kW and CleanSource UPS product line (available between 65 and 900 kVA), utilizing flywheel technology.

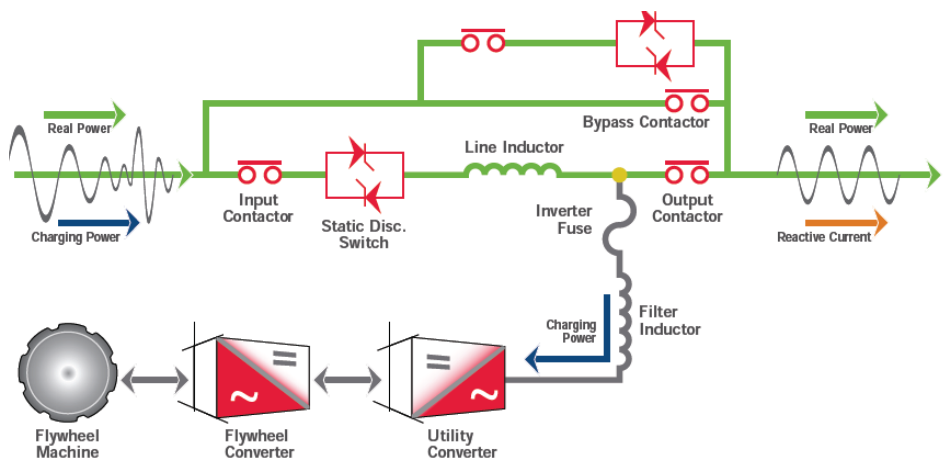


Figure 4-11. UPS–FES system [Source: ActivePower].

Flywheels can react quickly to the changes in demand, which is more efficient than bringing power generators up and down. Flywheels have possibilities in peak shaving in electrical power systems and in power smoothing in renewable energy systems.

Flywheel systems with power conversion electronics can serve customers as a controllable and automatic demand-side management option that can provide premium services, including power quality for sags or surges lasting less than 5 seconds, uninterruptible power supply for outages lasting about 10 minutes, and peak demand reduction to reduce electricity bills.

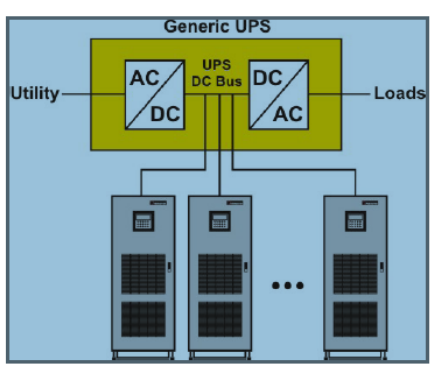


Figure 4-12. UPS – multiunit FES system [Source: Pentadyne].

4.4 Lead Based Batteries

4.4.1 Lead Acid Batteries

Most used battery type is a lead acid (LA) battery. Flooded wet cell (FLA) batteries are widely used in cars. Sealed lead acid (SLA) batteries can be valve regulated (VRLA) (Figure 4-13) and they can include glass matt (AGM) or gel (GEL) technology.

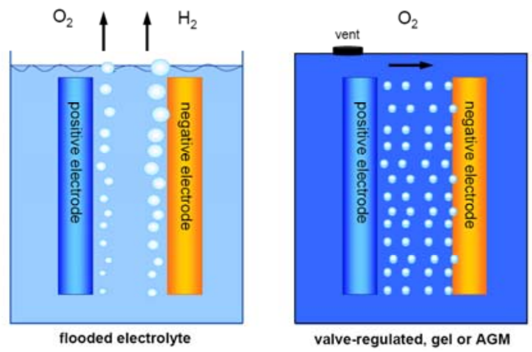


Figure 4-13. Schematic of an open and valve regulated lead acid battery [46].

The SLA is commonly used when high power is required, weight is not a limiting factor and low cost is critical. Especially SLI (starting, lighting, ignition) batteries are the most low cost batteries used typically as a car starting battery. They can have high current for a short time but they have low energy and are not suitable for deep discharge. Because cells in GEL-batteries are sealed and cannot be re-filled with electrolyte, controlling the rate of charge is very important or the battery will be ruined in a short order. Gel cells use slightly lower charging voltages than flooded cells and thus the set-points for charging equipment have to be adjusted. Absorbed Glass Mat (AGM) batteries are the latest step in the evolution of lead-acid batteries. Instead of using a gel, an AGM uses a fiberglass like separator to hold the electrolyte in place. Since they are also sealed, charging has to be controlled carefully or they can be ruined in short order. Gel cells and AGMs require no maintenance. Lead acid lifetime is depending on temperature because every 15°C increase over 25°C halve their lifetime. Energy density is 50 Wh/l, efficiency 80–90%, lifetime 3–12 years, cyclic lifetime 50–2 000 (7 000) cycles, temperature area –25°C – +60°C.

Lead acid battery is in the beginning charged with a constant current and in the second phase with a constant voltage and a balancing (compensates self-discharge) happens with very low current (Figure 4-14).

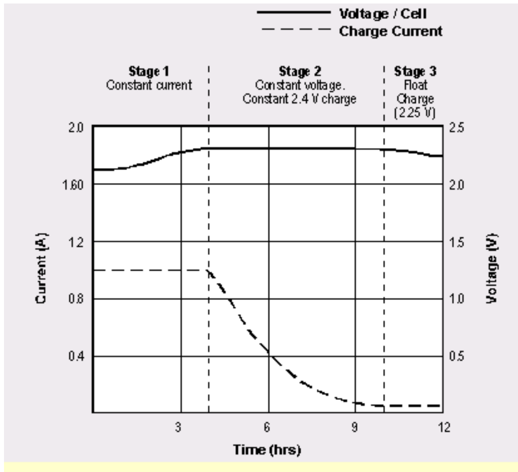


Figure 4-14. Charge stages of a lead-acid battery [Source: BatteryUniversity].

E.g. Exide (XIDE), Enersys (ENS), Johnson Controls, Optima Batteries and C&D Technologies (CHP) manufacturers lead acid batteries.

Advanced Lead Acid technology can be a new possibility for lead batteries in Smart Grid applications. This new improved performance technology is based on carbon electrodes. In the following chapters it is presented PcB and Ultrabattery as a solution of lead carbon technology.

4.4.2 Lead Carbon Batteries: PcB

Lead carbon batteries are a latest development result of lead based batteries. One or both electrodes of lead carbon battery are made from activated carbon as in supercapacitors. The electrode is made of carbon graphite foam that is covered with lead.

If the negative electrode is made from carbon the chemical reaction is:

$$nC_6^{x-}(H^+)_x \leftrightarrow nC_6^{(x-2)-} * (H^+)_{x-2} + 2H^+ + 2e^- \text{ (discharged)} \tag{4.3}$$

As a result of larger surface (1 500 m^2/g) the reaction rate is faster, discharge speed is faster and the weight and size of the battery is smaller (half) than lead acid battery. Also the capacity in cold circumstances is bigger and corrosion is smaller.

Figure 4-15. PbC battery [Source: Axion power].

PbC cyclic life is according to the tests around 1 600 cycles when battery is discharged every 7 hours to a 90% depth of discharge. Cost of PbC battery is 200–300 $/kWh.

Axion Power International Inc., New Castle USA is a developer and seller of lead carbon batteries. Exide Technologies, Inc. a leading global manufacturer of lead-acid batteries recently teamed up with Axion for the manufacturing and distribution of products based on Axion's proprietary lead-carbon technologies.

Grid connected power refers to short-term storage for utility-scale energy producers. Axion's principal focus is short-term storage for renewable energy such as wind and solar power. The rapid recharge and deep discharge capacity of our PbC® battery are well suited for intermittent power sources like wind and solar. Axion has also developed the PowerCube^{TM}. The PowerCube^{TM} is a highly mobile energy storage system that can be configured to deliver up to 1 MW of power for 30 minutes or 100 kW of power for 10 hours.

Figure 4-16. Lead carbon battery systems [Source: Axion Power].

4.4.3 Lead Carbon Batteries: UltraBattery

Ultrabattery is a combination of an ultra capacitor with the negative electrode of lead-acid battery (Figure 4-17).

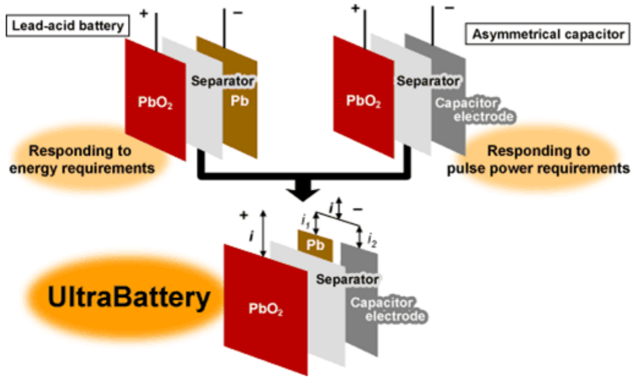


Figure 4-17. Ultrabattery basics [Source: The Furukawa Battery].

In the following picture (Figure 4-18) it is presented a prototype of UltraBattery FTZ12_HEV (12 V, 8.5 Ah) mainly developed for cars and UB1000 (10 h, 1 050 Ah) developed for wind power generation.

Figure 4-18. UltraBattery type [62].

The cyclic life test of UltraBattery is still going on and latest result reported by Furukawa Battery is 1 400 000 cycles. It was discovered that UB1000 valve regulated type UltraBatteries for wind power generation provided a lifetime more than 1.5 times longer than that of the conventional lead-acid battery, and this life test is still underway. [62]

UltraBattery – Grid storage:

> The East Penn Manufacturing Co. has a Smart Grid Demonstration Project that is a U.S. Department of Energy Smart Grid Demonstration Project, which is based in Lyon Station, Pennsylvania. The goal is to demonstrate the economic and technical viability of a 3MW grid-scale, advanced energy storage system using the lead-carbon UltraBattery technology to regulate frequency and manage energy demand. This project will entail the construction of a dedicated facility on the East Penn campus in Lyon Station, PA that will be used as a working energy storage demonstration for UltraBattery modules.

4.5 Nickel-Based Batteries

Nickel Cadmium (NiCd) batteries have a good load characteristics; they are simple to use and economically priced. NiCd batteries can be designed for different speed of charge. Nickel metal hydride (NiMH) provides 30% more capacity over a standard NiCd. The positive electrode of the NiMH battery is nickel hydroxide. The active material for the negative electrode in the NiMH battery is actually hydrogen and the hydrogen ions (protons) are stored in the metal hydride structure that also serves as an electrode. The NiMH is affected by memory to a lesser extent than the NiCd. Periodic exercise cycles need to be done less often. NiCd batteries can be designed for different speed of charge. They need maintenance charge because of self-discharge that is about 5% during 24h after a battery is charged. Constant current charging is recommended for sealed NiCd cells. A figure (Figure 4-19) shows a typical NiCd battery charge curve. Battery system need cell based temperature control to prevent over discharge and control of shallow discharge to prevent voltage depression.

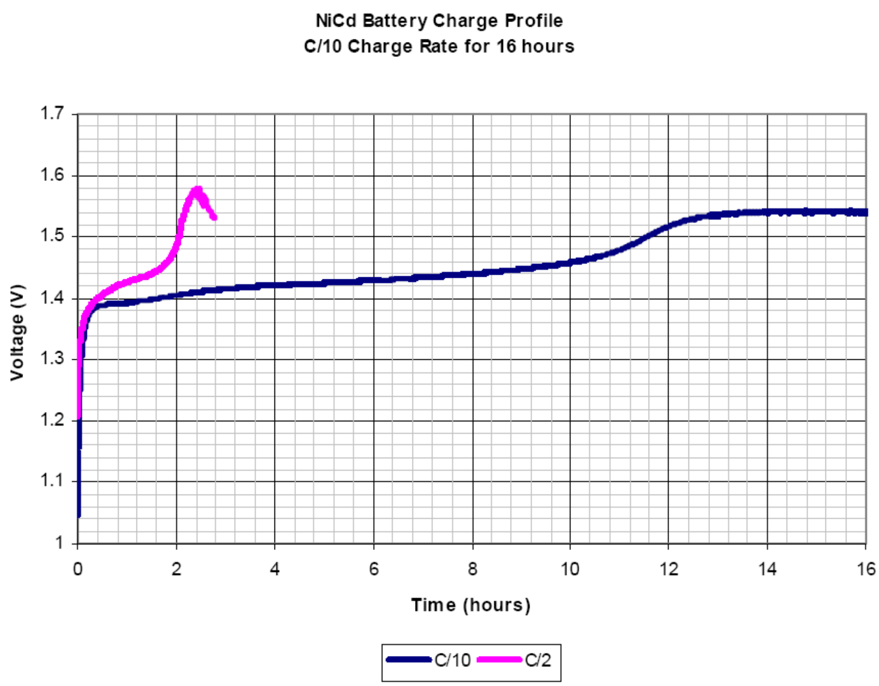


Figure 4-19. Typical charge curve of the NiCd battery [Source: QuestBatteries].

Nickel metal hydride (NiMH) provides 30% more capacity over a standard NiCd. The positive electrode of the NiMH battery is nickel hydroxide. The active material for the negative electrode in the NiMH battery is actually hydrogen and the hydrogen ions (protons) are stored in the metal hydride structure that also serves as an electrode. The NiMH is affected by memory to a lesser extent than the NiCd. Periodic exercise cycles need to be done less often. A figure (Figure 4-20) shows typical charge/discharge curves of a NiMH battery. Because of low toxic metals content, the NiMH is labelled “environmentally friendly”. NiMH batteries are used in the current electric cars.

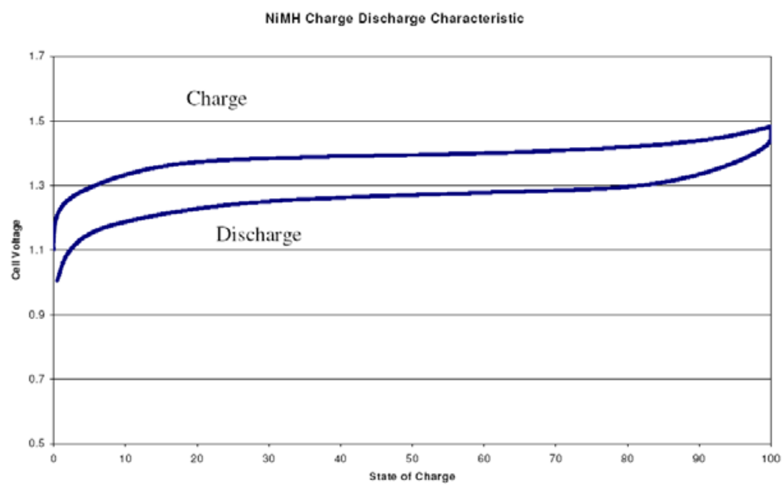


Figure 4-20. A typical charge/discharge curve for the NiMH battery [Source: Cobasys].

Saft and Cobasys among others are manufacturing Ni-batteries.

4.6 Lithium Ion Batteries

Technology

Lithium-ion batteries are one of the most promising battery types for Smart Grid applications. Lithium is very reactive material and translates into have high energy density batteries. Typical material for the anode is graphite. The cathode is generally one of three materials: a layered oxide, such as lithium cobalt oxide, one based on a polyanion, such as lithium iron phosphate (Li-FePO4, LFP), or a spinel, such as lithium manganese oxide (LiMnO2) or titanium disulfide (TiS2) (Figure 4-21). Depending on the choice of material for the anode, cathode, and electrolyte the voltage, capacity, life, and safety of a lithium ion battery can change remarkable. Liquid electrolytes in Li-ion batteries consist of solid lithium-salt electrolytes, such as LiPF6, LiBF4, or LiClO4, and organic solvents, such as ether.

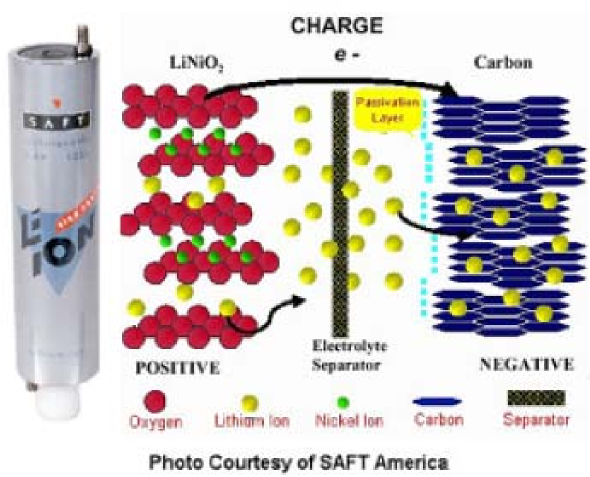


Figure 4-21. An example of lithium-ion battery function [Source: Saft].

Technical Properties

Lithium-ion batteries offer energy densities of 100–150 Wh/kg with charge/discharge efficiencies of 90–100% [28]. Cyclic lifetime is long, depending on a battery type from 3 000 cycles to 16 000 full cycles and even 250 000 partial cycles. Lithium batteries have no memory effect. Lithium batteries are very sensitive to over voltage and need also temperature and current control as well as deep discharge control and a battery balancing system for larger series connected systems. Lithium-ion batteries should be stored in low temperature (0–25°C) rather at 40% than at 100% charge to decrease ageing process. Most lithium-ion battery electrolytes freeze at approximately –40°C. New lithium battery system solutions include also intelligent control system and are packed in the standard lead acid Battery Council International (BCI) format sizes. Lithium batteries are seen as future electric car batteries because of lightweight and high energy. Lithium batteries are very promising technology but it is still under development for longer lifetime, better safety and efficiency and lower price.

Control System and Interface

Large Li-ion battery system requires two-level battery management system. Each cell should be protected against over/under voltage and overtemperature. Stringed cells are protected against overvoltage in charging by cell balancing system that can be thermistor or electronics based circuit. The battery string should be protected against over- and undervoltage, overcurrent and overtemperature and reverse polarity. A balancing system takes care of voltage balancing of series-connected battery cells. Advanced management system includes also communication bus connections and local database that includes information of lowest and highest voltage and temperature, highest current used, number of cycles done and messages and alarms. Main battery management unit takes care of the communication with battery chargers and can include charge and discharge control relays to ensure safety of charging.

Lithium-ion batteries are charged with constant current and after that charging continues with constant voltage until charge current is zero or generally 7%.

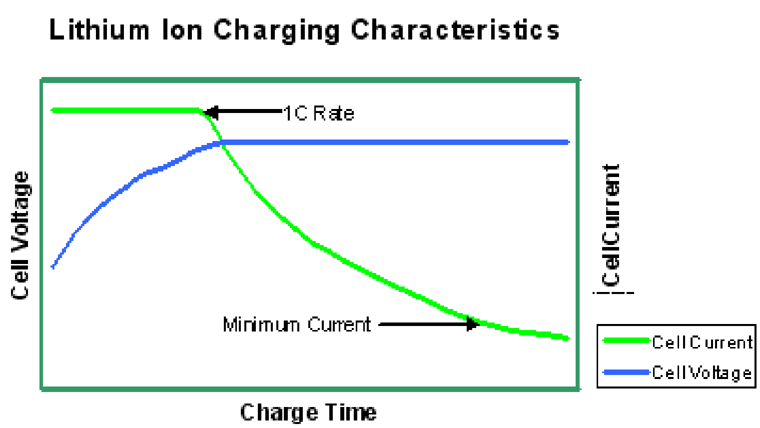


Figure 4-22. Constant current, constant voltage charging of lithium-ion battery [Source: mpoweruk].

Lithium ion cells cannot tolerate overcharging and balancing circuits are needed to prevent overcharging cells but ensure charging all cells to the similar voltage level. Current cells can be charged in an hour or some cell types in 10 minutes. Fast and quick charging requires specific chargers according to the cell chemistries. Battery capacity depends on the discharge current (Figure 4-23).

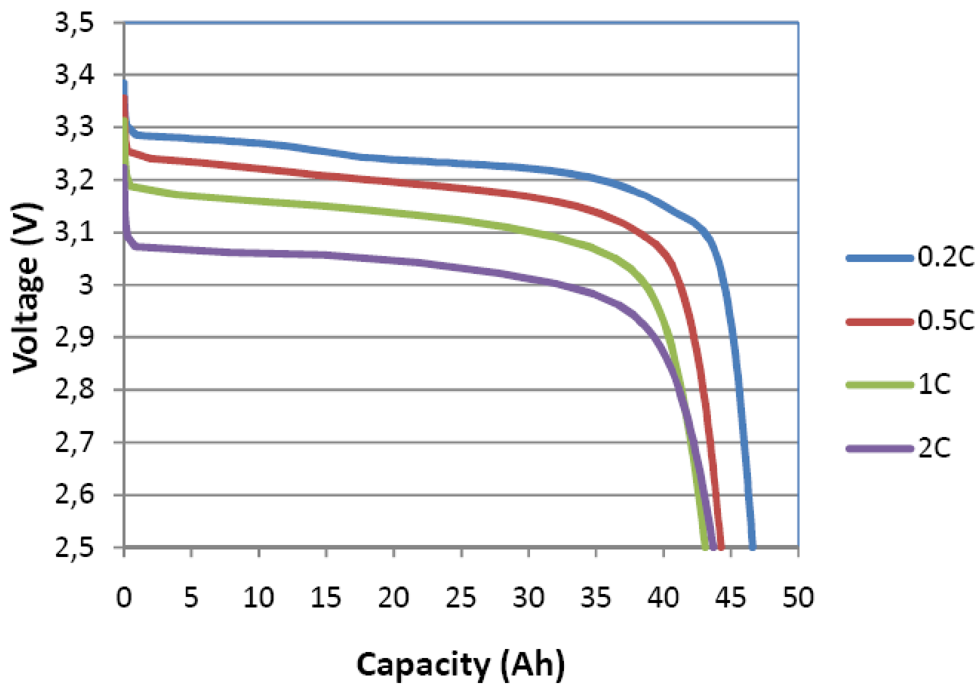


Figure 4-23. Capacity and voltage vs. discharge current [Source: http://www.europeanbatteries.com/solutions/cells].

Cyclic life depends on lithium-ion battery type and depth of discharge (DoD) (Figure 4-24 and Figure 4-25).

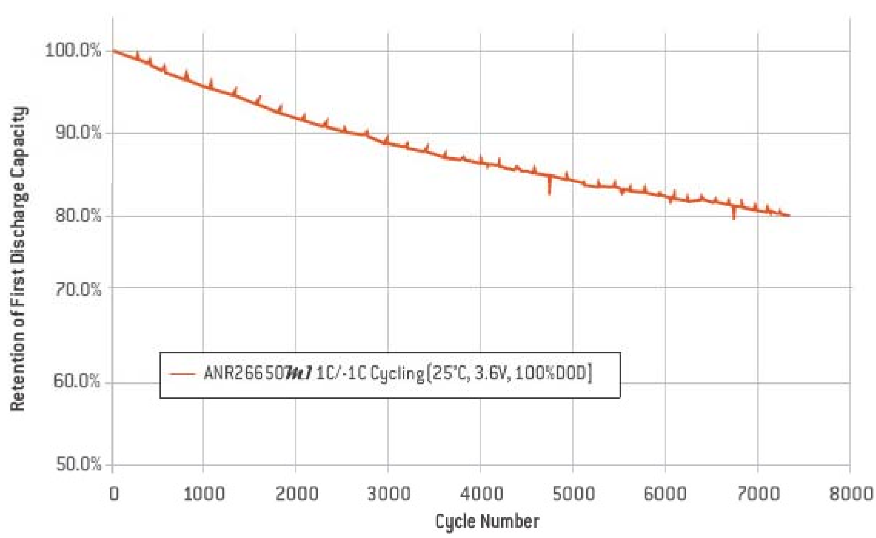


Figure 4-24. Capacity of a lithium-phosphate battery as a function of charge-discharge cycles [Source: A123 Systems].

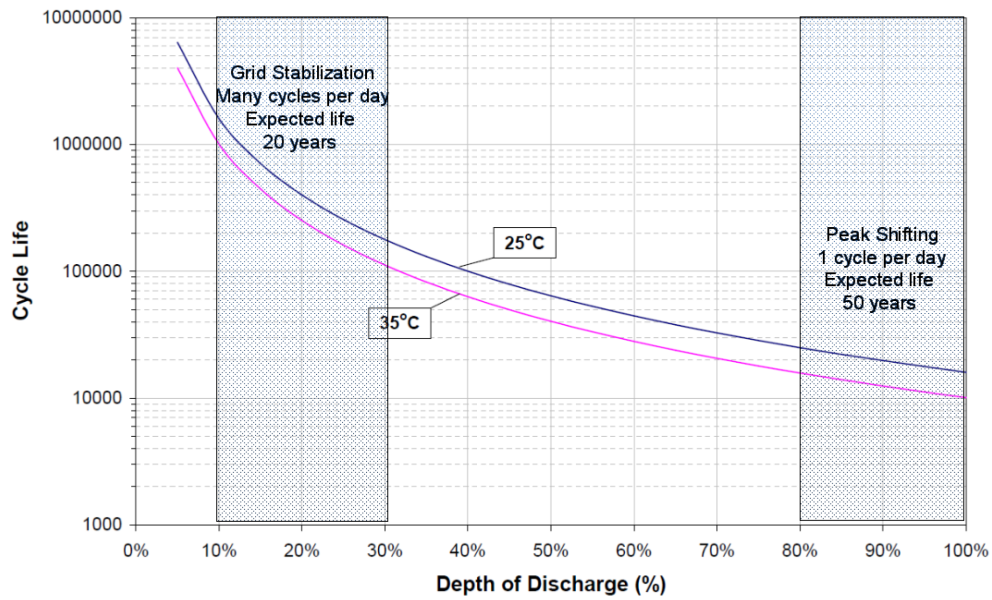


Figure 4-25. Cyclic life vs. Depth of Discharge of Lithium Titanate battery [Source: Altairnano].

In the following pictures (Figure 4-26 and Figure 4-27) it is presented examples of an large lithium-ion battery system constructions (Altairnano LiTi-batterysystem, 1 MW for 15 minutes at 750 V to 1 050 V and A123 scalable solution).

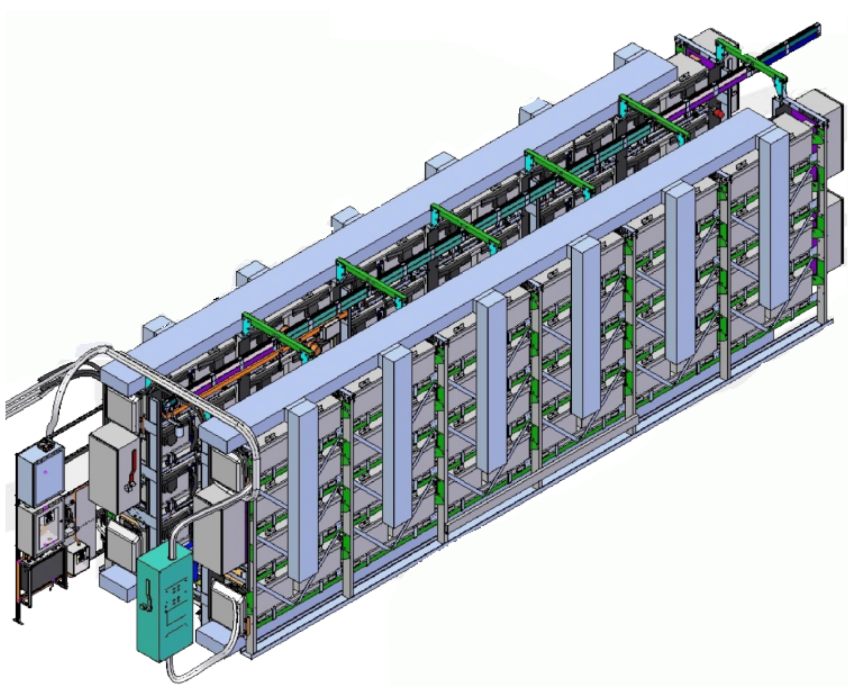


Figure 4-26. An example of the large lithium-ion batterys system construction [Source: Altairnano].

Figure 4-27. An example of the large lithium-ion batterys system construction. A123's Smart Grid Stabilization System (SGSS™) [Source: A123 Systems].

Economical Aspects

Li-ion batteries are still the high cost (above €420/kWh) storage systems due to special packaging and internal overcharge protection circuits. [28]

Manufactures, Commercial Products and Solutions

Lithium-ion battery manufacturers e.g. A123 Systems, European Batteries and International Battery (Lithium-iron-phosphate), Valence Technologies (VLNC), China BAK (CBAK), Altairnano, LiFeTech (Lithium-titanate), Saft (Lithium-nickel-oxide) and Advanced Battery Technologies (ABAT).

Finnish lithium-ion manufacturer European Batteries started production in 2010. European Batteries Oy develops and manufactures large, rechargable lithium-ion based prismatic cells and battery systems with battery management systems (BMS). The modules are EBattery™ 10, EBattery™ 20, EBattery™ 30 and EBattery™ 40. The nominal energy content of a module ranges from 1.1 kWh to 4.3 kWh. BMS monitors critical battery system parameters, maximizes available capacity, energy efficiency and the cycle life of the battery system. Its main benefits are high balancing current, scalability and intelligent balancing algorithm.

Large-scale grid storage systems include:

A123 installations in Chile: 12 MW A123 (LifePO4) lithium battery system for frequency regulation in 2009. 20 MW A123 lithium battery system for spinning reserve in 2011.

Potential Application Areas in Smart Grids

Lithium-ion batteries have long cyclic lifetime, high energy density, and high efficiency and with proper BMS and advanced chemistry also reliability is increased making Li-ion batteries suitable in many application areas of Smart Grid. As an example of the suitable application areas can be seen in A123 Systems plan.

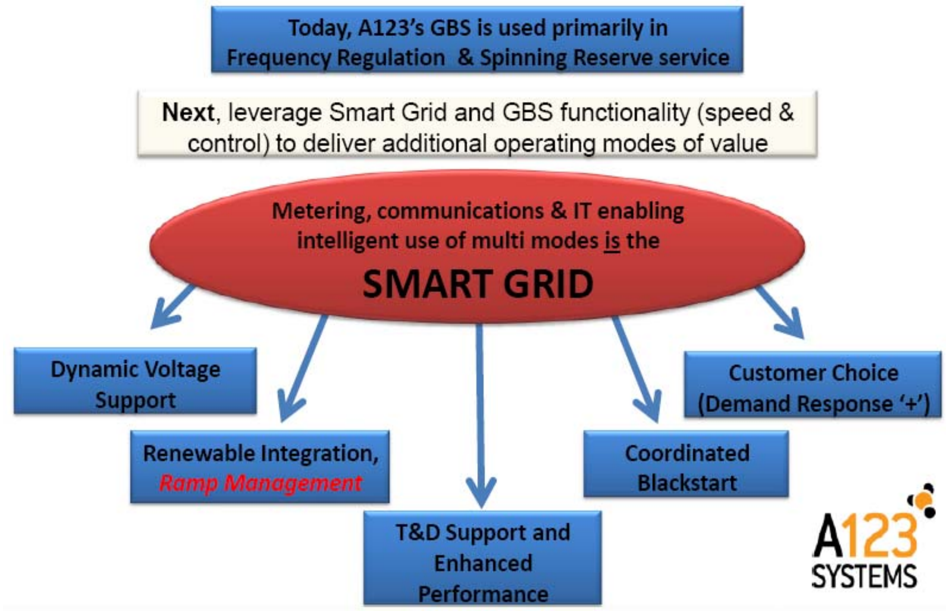


Figure 4-28. A123 Li-ion battery systems in application areas of Smart Grid [Source: A123 Sysems].

4.7 Sodium Based Batteries

4.7.1 NaS Batteries

Technology

NAS battery consists of sulphur at positive electrode, sodium at negative electrode as active materials, and Beta alumina of sodium ion conductive ceramic, which separates both electrodes (Figure 4-29).

This hermetically sealed battery is operated under the condition that the active materials at both electrodes are liquid and its electrolyte is solid.

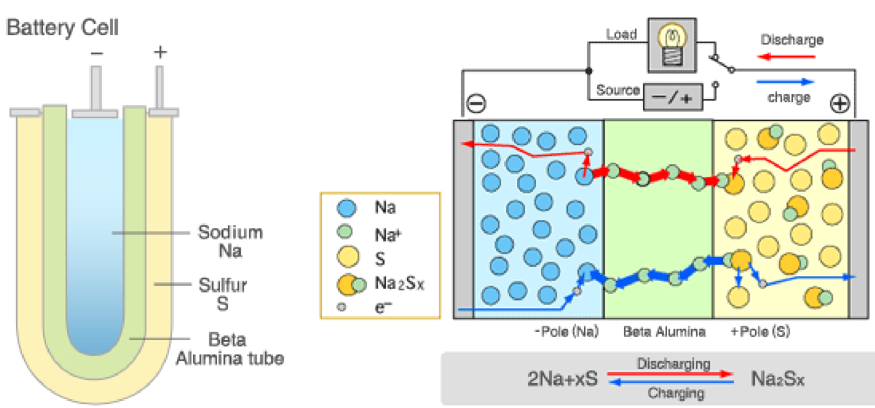


Figure 4-29. Sodium sulphur cell and principle of NaS battery [Source: NGK Insulators].

Approximately 2V is generated between the positive and the negative electrodes at about 300°C. If a load is connected to terminals, electric power is discharged through the load. During the discharge, sodium ions converted from sodium in a negative electrode pass through solid electrolyte then reach to sulphur in positive electrode. The electrons finally flow to outside circuits. The electric power is generated by such current flow.

With the progress of the discharge, sodium polysulfide is formed in positive electrode; on the contrary, sodium in negative electrode will decrease by consumption. During the charge, the electric power supplied from outside form sodium in negative electrode and sulphur in positive electrode by following the reverse process of the discharge. Because of this, the energy is stored in the battery.

Technical Properties

NAS battery has two types of modules PS type for load levelling or peak-shaving (energy density 151 kWh/m^3 or181 kWh/m^3) and PG for power quality and spinning reserve (energy density 151 kWh/m^3). Single cell voltage is approximately 2V at about 260 to 360°C working temperature. Response time is 2ms and rise time 100% 10s. NaS battery has 15-year service life and high cycle life (2 500 cycles at 100% DOD – 4 500 at 90% – 6 500 at 65%).

A sample commercial battery pack capacity is 50 kW in 64 V or 128 V and includes 320 cells. Typical System capacity is 2 000 kW and includes 50 kW Module x 40 Units (Figure 4-30). Commercial product specifications are given in Table 4-2.

NAS Module	"PS-G50" Module (320 T5 Cells)	"PS-E50" Module (384 T5 Cells)
Module Energy Density & Avg DC Efficiency	151kWh/m^3 85% @ 100%DOD	181kWh/m^3 85% @ 100%DOD
Rated Capacity & Power (AC, based on 95% efficiency)	360kWh @ 50kW (60kW max)	430kWh @ 50kW (60kW max)
Cell Configuration & Module Voltage	(8Sx10P)x4S, 64V or (8Sx5P)x8S, 128V	(8Sx12P)x4S, 64V or (8Sx6P)x8S, 128V
Operating Temp & Standby Heat Loss	290 to 360C 3.4kW	
Dimensions (WxDxH) & Weight	2224 x 1786 x 732 mm 3500kg	
Electrical Protection	Internal fuses within each 8S string	

NAS Module	"PQ-50" Module
Module Energy Density & Avg DC Efficiency	151kWh/m^3 85% @ 100%DOD 90% @ 40%DOD
Rated Capacity & Power (AC, based on 95% efficiency)	360kWh @ 50kW (250kW max)
Cell Configuration & Module Voltage	320S, 640V
Operating Temp & Standby Heat Loss	290 to 360C 2.2kW (PQ) 3.4kW (PQ & PS)
Dimensions (WxDxH) & Weight	2224 x 1786 x 732 mm 3500kg
Electrical Protection	External DC breaker, external fuse at terminal

Table 4-2. Characteristics of NaS 50 KW modules [Source: NGK Insulators].

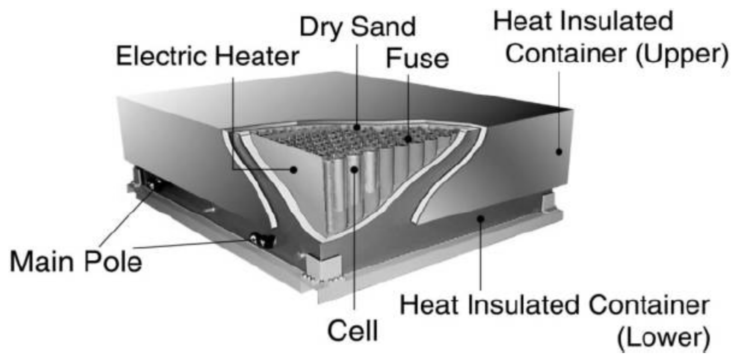


Figure 4-30. NaS 50 KW module construction [49].

NaS battery can give max. 5xPn pulsepower when discharged in 30 sec. (Figure 4-31).

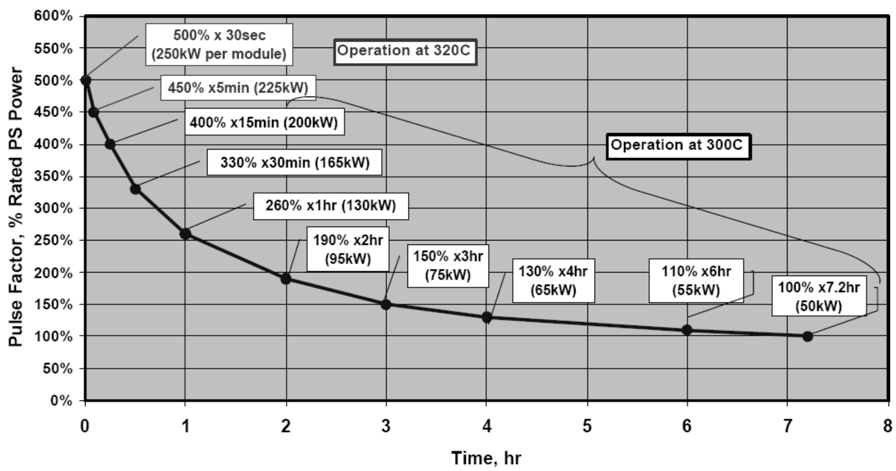


Figure 4-31. NaS pulse (or PQ factor) vs. Discharge duration [49].

Economical Aspects

Costs per unit for NAS battery is about 1 300–1 500 $/kW, 200 $/kWh. According to NGK Insulators the target price for NaS battery is 140$/kW by mass production 1600 MWh/year.

Control System and Interface

NaS battery system can be connected to grid with AC-DC converter (Figure 4-32).

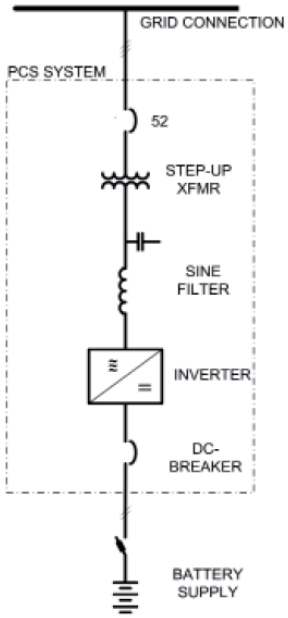


Figure 4-32. Battery storage grid connection system [Source: ABB].

Life Cycle Aspects

One module alone provides 2 500 full charge/discharge cycles. This value is equal to 15 years in operation. (at 100% DOD – depth of discharge), or 4 500 cycles (at 80% DOD).

Table 4-3. Comparison of NAS with other batteries [Source: NGK].

Item \ Battery		NAS (Base)	Lead-Acid (Current)	Lithium Ion	Ni-H
Continuous Discharge Duration with rated output		6 hours	2 hours	3 hours	2 hours
Expected Lifetime (at standard conditions)		15 years	3 to 5 years	10 years	7 years
Size	MWh(1MW x 6h)	1	3 times	2 times	3 times
Weight	MWh(1MW x 6h)	1	6 times	2 times	6 times
Price	MWh x 15years	1	3 to 5 times	8 times	6 times
Notes	Self Discharge	No	Yes	Yes	Yes
	Memory Effect	No	No	No	Yes

Note: These data are typical values and change by the manufacturers

Manufactures, Commercial Products and Solutions

A Japanese company NGK Insulators LTD has been only NaS battery manufacturer with production capacity 150 MW/year in 2010. NGK Insulators has installed 302 MW across 215 systems worldwide. There are close to 279 MW of NaS batteries on the grid in Japan and 9 MW of NaS in USA. Within last two year NKG has announced two large order 150 MW of EDF and 300 MW to United Arab Emirates. POSCO in Korea and Eagle Picher Technologies have also informed to developing large capacity NaS batteries.

Potential Application Areas in Smart Grids

NAS batteries can function as a power station to charge electric power in the base power source at low demand and discharge it at peak demand. By applying it to a consumer, reduction of an electricity bill and the improvement of electric power quality will be possible. Hybrid system of NAS battery combined with wind turbine generations and with solar PV generations has made possible maximum use of these unlimited power generation resources without producing CO2. For ancillary services NAS system can provide fast acting reserves (spinning reserve), standby reserves, black start and frequency regulation control without the emissions of conventional generating plant. NaS system can also support islanded sections of the grid.

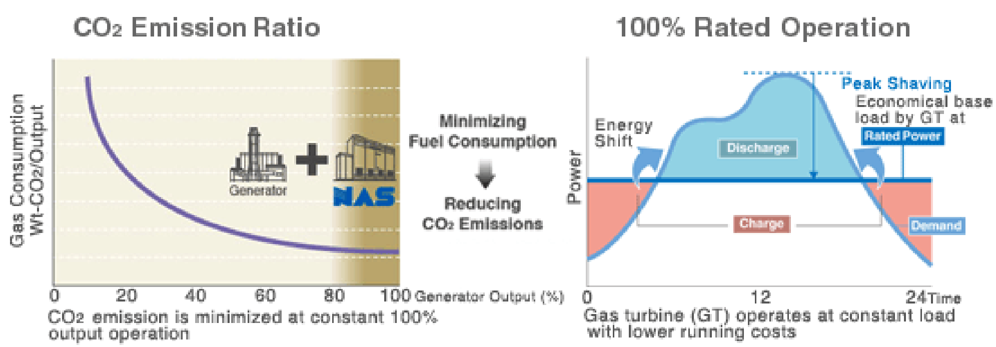


Figure 4-33. NaS system as peaking generation unit [Source: NGK].

Figure 4-34. NaS system stabilizating intermittent renewable energy [Source: NGK].

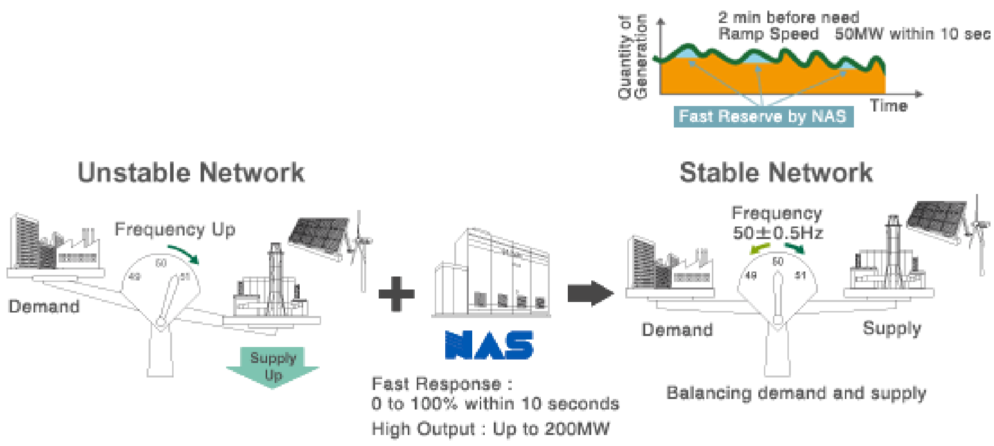


Figure 4-35. NaS system provides ancillary services.

4.7.2 Sodium-Metal Chloride Batteries – ZEBRA and Durathon Batteries

ZEBRA Battery

ZEBRA batteries are based on sodium nickel chloride technology. Sodium/nickel chloride batteries are produced on a commercial scale in Switzerland by MES-DEA. The battery has to be maintained at an internal operating temperature of between 270°C and 350°C for efficient operation.

In Figure 4-36 it is shown a principle of the ZEBRA battery chemistry.

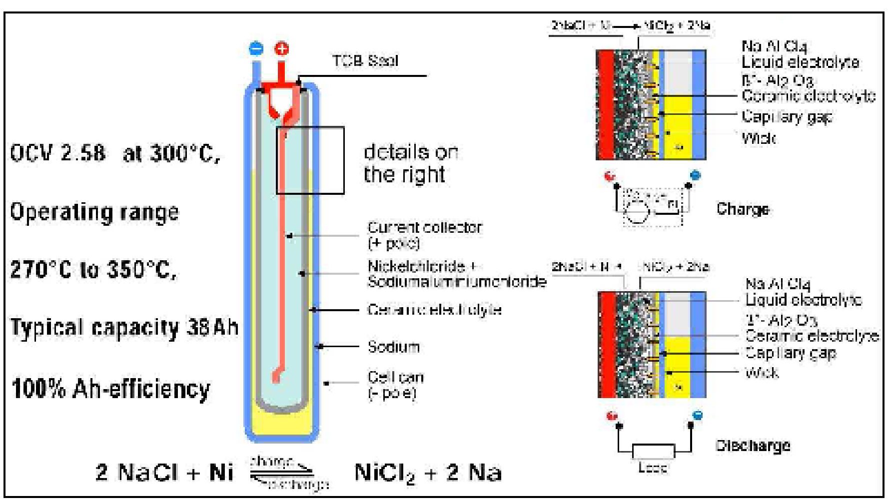


Figure 4-36. Zebra basic cell reactions [50].

In the following picture it is presented typical values of a single ZEBRA cell.

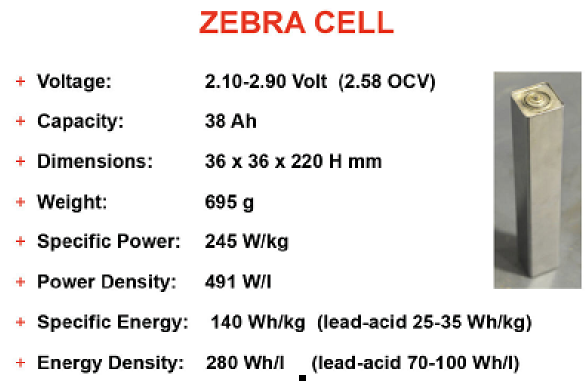


Figure 4-37. ZEBRA cell characteristics [Source: FZ Sonic].

ZEBRA batteries are produced as 24 V – 1 000 V, 2 kWh – 50 kWh systems. Batteries are maintenance free. Weight is around 40% of lead acid battery weight. ZEBRA Battery technology has proven calendar life of more that 10 years and cycle life of 1 000 nameplate cycles dependent on operating parameters [50].

ZEBRA batteries are used in Marine applications and in electric cars (e.g. Th!nk City). Zebra® is complete self-contained off-shelf battery system, and not a building sub-block. Fitted with battery Management Interface controlling battery operation, Zebra® battery therefore is easy to install and use – only one unit as supplied from the factory has to be mounted in the vehicle. The BMI, with integrated main circuit breakers is the "brain of the battery system" and it provides:

- temperature control
- S.O.C. measurement
- nameplate cycles counter
- charger control
- measurement of the battery insulation resistance
- supervision of current and voltage current limits
- Life-Data-Memory like a "black box"
- CAN-BUS communication with the system controller.

To increase total energy storage on board, BMI allows up to 16 Zebra® batteries to work together in parallel. Initial warm up time after cold storage is about 24 hours. Therefore it is best if the battery is used continuously. Once at working temperature, the battery performance is not affected by ambient temperature which can be -40°C...+50°C.

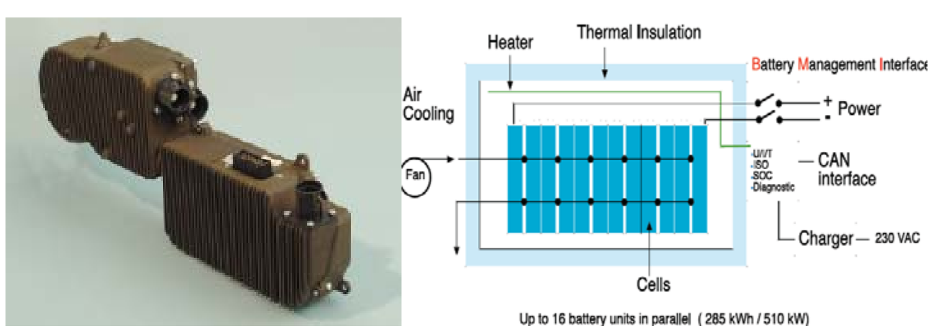


Figure 4-38. ZEBRA-battery and battery block diagram [Source: FZ Sonic].

On February 1st, 2010 FIAMM and MES-DEA constituted a new company FZ Sonick SA that continues producing ZEBRA salt batteries.

Durathon Battery

GE Transportation has launched molten salt battery by the name Durathon in 2010. GE's sodium-metal-halide battery consists of a nickel chloride cathode, a beta alumina separator and a liquid sodium anode. During charging, Cl is extracted from NaCl and combined with Ni to form NiCl2 (Figure 4-39). The Na ions are then transported through the beta alumina to the anode reservoir. Discharge is the reverse of this process. Because sodium ions move easily across the beta alumina but electrons cannot, there are no side reactions, and therefore no self-discharge. All of the materials are housed in a hermetically sealed steel case, which becomes the individual cell. Cells are then contained in a thermally insulated battery module (Figure 4-40). An integral battery management system is installed on all battery modules and controls charge/discharge, monitors battery parameters, provides battery protection, and passes information to the outside world through common modbus protocol.

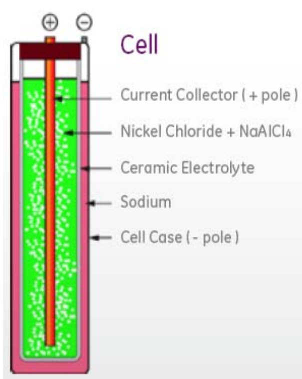


Figure 4-39. Durathon battery cell [Source: GE Transportation].

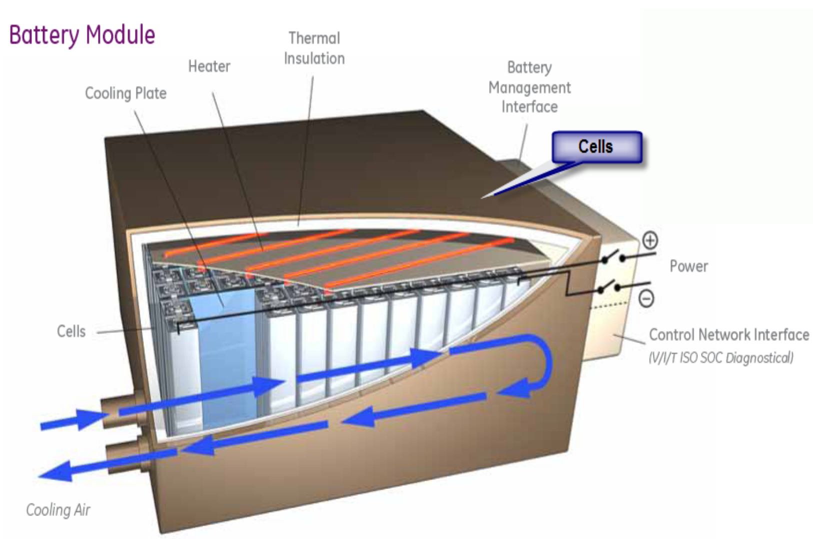


Figure 4-40. Durathon battery module [Source: GE Transportation].

Durathon battery system is meant to serve various Smart grid application areas:

1. Renewable-Energy Sources
   - Improve integration and increase utilization of energy generated from photovoltaics and wind turbines
2. Community Energy Storage
   - Provide numerous benefits including load levelling, backup power, renewables integration and ancillary services
3. Residential Energy Storage
   - Enable demand-side management and time-of-use applications with placement of batteries in residential homes
4. Smart Grid/Microgrid
   - Create a new and more flexible grid by combining smart devices and real-time communication with energy storage
5. Transmission & Distribution
   - Defer upgrades, relieve congestion, control voltage and improve reliability
6. Ancillary Services
   - Spinning reserves, supplemental reserves, load following and other ancillary services.

Development Trends and Future Expectations

Newest innovation of sodium-nickel chloride battery is planar cell design by Pacific Northwest National Laboratory. The planar design allows for a thinner electrolyte that reduces the area of specific resistance and may be operated at reduced temperatures. The lower operating temperatures would alleviate adverse temperature effects that impact cycle life and overall cost and allows the battery to deliver 30 percent more power at lower temperatures. [60]

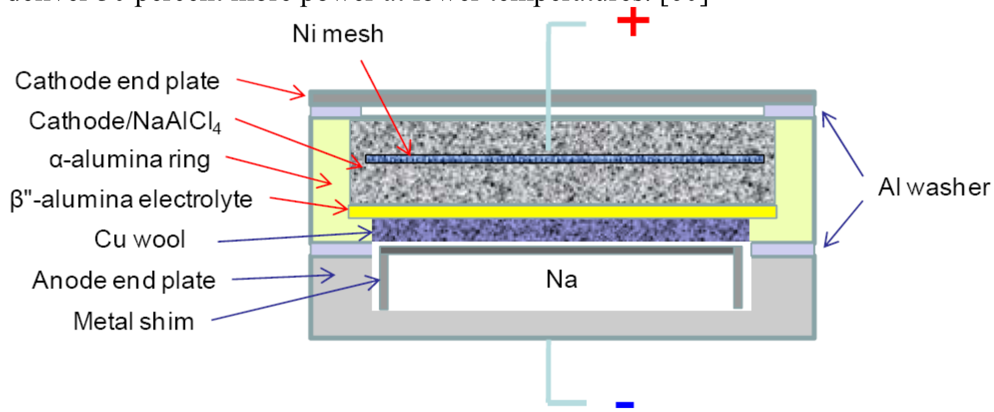


Figure 4-41. Schematic of a sodium-nickel chloride cell with planar design [60].

Molten salt is used also in solar thermal storages in solar power plant where solar energy is collect with reflectors to warm up liquid molten salt that is pumped from holt salt tank via steam generator to cold salt tank and back to receiver tower.

4.8 Flowbatteries

A flow battery is an electrochemical energy storage device that converts the chemical energy in the electroactive materials directly to electrical energy. Most redox flow batteries consist of two separate electrolytes, one storing the electro-active materials for the negative electrode reactions and the other for the positive electrode reactions. Power of the flow battery system is depended on electrodes and energy capacity depends on external storage components.

In table 4-5 are described characteristics of some flow battery systems.

Table 4-5. Characteristics of some flow battery systems [38].

System	Reactions	E_{cell}^{o}	Electrolyte
Redox			Anode/Cathode
All Vanadium [3]	Anode: $V^{2+} \xleftrightarrow{charge\ discharge} V^{3+} + e^-$ Cathode: $VO_2^{+} + e^- \xleftrightarrow{charge\ discharge} VO^{2+}$	1.4 V	H_2SO_4/H_2SO_4
Vanadium-Polyhalide [5]	Anode: $V^{2+} \xleftrightarrow{charge\ discharge} V^{3+} + e^-$ Cathode: ½ $Br_2 + e^- \xleftrightarrow{charge\ discharge} Br^-$	1.3 V	VCl_3-HCl/NaBr-HCl
Bromine-Polysulfide [6]	Anode: $2\ S_2^{2-} \xleftrightarrow{charge\ discharge} S_4^{2-} + 2e^-$ Cathode: $Br_2 + 2e^- \xleftrightarrow{charge\ discharge} 2\ Br^-$	1.5 V	NaS_2/NaBr
Iron-Chromium [7]	Anode: $Fe^{2+} \xleftrightarrow{charge\ discharge} Fe^{3+} + e^-$ Cathode: $Cr^{3+} + e^- \xleftrightarrow{charge\ discharge} Cr^{2+}$	1.2 V	HCl/HCl
H_2-Br_2 [8]	Anode: $H_2 \xleftrightarrow{charge\ discharge} 2H^+ + 2e^-$ Cathode: $Br_2 + 2e^- \xleftrightarrow{charge\ discharge} 2Br^-$	1.1 V	PEM*- HBr
Hybrid			
Zinc-Bromine	Anode: $Zn \xleftrightarrow{charge\ discharge} Zn^{2+} + 2e^-$ Cathode: $Br_2 + 2e^- \xleftrightarrow{charge\ discharge} 2\ Br^-$	1.8 V	$ZnBr_2/ZnBr_2$
Zinc-Cerium [9]	Anode: $Zn \xleftrightarrow{charge\ discharge} Zn^{2+} + 2e^-$ Cathode: $2Ce^{4+} + 2e^- \xleftrightarrow{charge\ discharge} 2Ce^{3+}$	2.4 V	CH_3SO_3H (both sides)

*Polymer Electrolyte Membrane

In the following text it is described more detailed two flow battery types: ZnBr batteries and Vanadium redox batteries.

4.8.1 ZnBr Batteries

Technology

ZnBr battery was developed by Exxon in the early 1970's. ZnBr battery consists of a zinc negative electrode and a bromide positive electrode separated by a micro porous separator. An aqueous solution of zinc/bromide is circulated through the two compartments of the cell from two separate reservoirs.

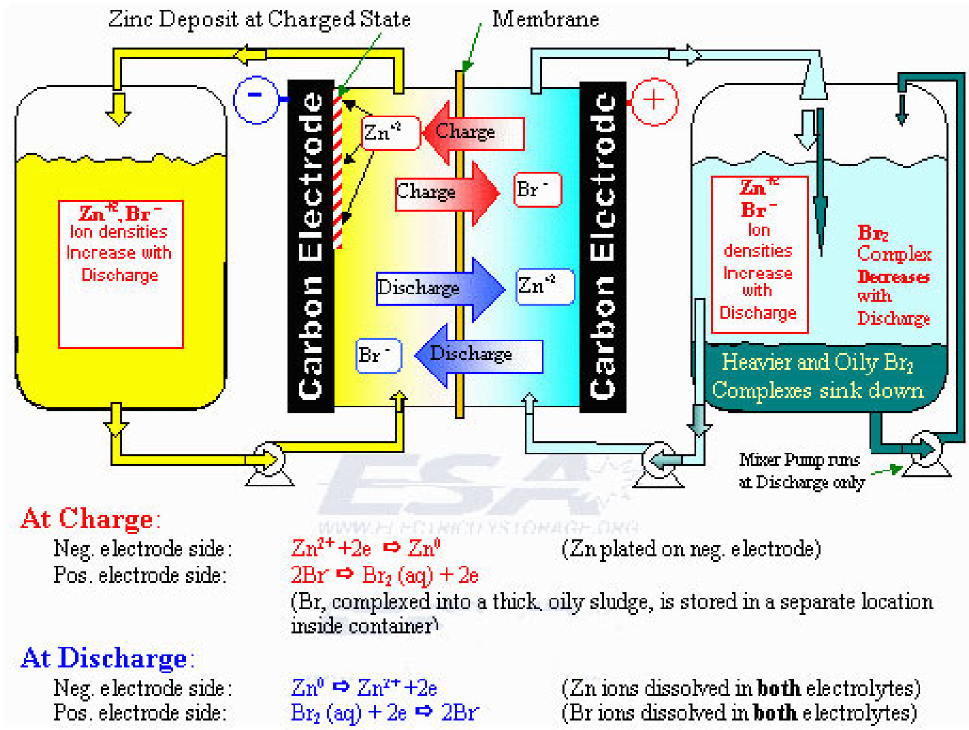


Figure 4-42. Principle of ZnBr battery storage [Source: http://electricity.ehclients.com].

The electrodes do not take part in the reactions but serve as substrates for the reactions. During the charge cycle metallic zinc is plated from the electrolyte solution onto the negative electrode surfaces in the cell stacks. Bromide is then converted to Bromine at the positive electrode surface of the cell stack and is immediately stored as a safe, chemically complex organic phase in the electrolyte tank. When the battery discharges, the metallic zinc plated on the negative electrode dissolves in the electrolyte and is available to be plated again at the next charge cycle. In the fully discharged state the ZnBr battery can be left indefinitely.

Technical Properties

Technical properties of ZnBr batteries:

Specific energy	34.4–54 Wh/kg (124–190J/g)
Energy density	75–85 Wh/kg
Round trip efficiency	(AC to AC) 70–75%
Time durability	> 20 years
Cycle durability	> 2 000 cycles even >> 10 000 cycles

Nominal cell voltage 1.8 V (typically falls to 1.3 V at an operating current density of 100 mA cm-2)
100% depth of discharge capability on a daily basis.

Economical Aspects

Current capital cost of Zn/Br batteries is $250/kWh–$500/kWh [34].

Control System and Interface

A fully integrated system is available that comprises energy storage, power conditioning, system control, and thermal management subsystems in a packaged, portable, turn-key, building block.

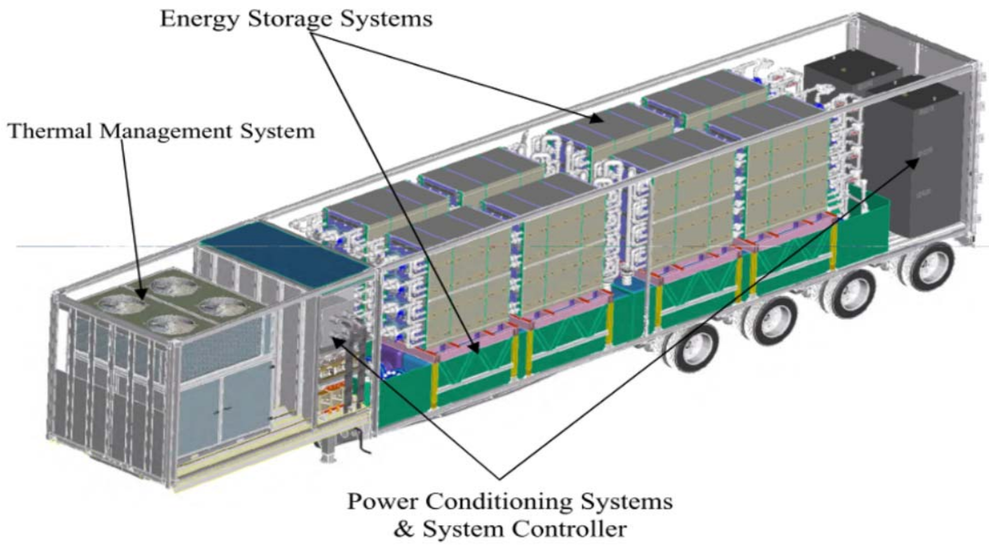


Figure 4-43. Integrated ZnBr battery system (500 kW, 7.4 hours, 3.8 MW-Hr) with DC-DC converter and power control unit [Source: PremiumPower].

Life Cycle Aspects

A major technical problem is the chemical reactivity of bromine towards most plastic components, while there is also concern over safety in the event of leakage of bromine vapour. [35]

Manufactures, Commercial Products and Solutions

ZBB Energy has 50 kWh and 500 kWh ZESS battery solution. ZESS 500 provides 250 kW discharge rate and 125 kW max. charging rate.

RedFlow's Power+BOS® ZB system provides 5 kW to 10 kW of power. Total energy capacity is 10 kWh to 30 kWh.

PremiumPower provides TransFlow, PowerBlock and Zinc-Flow systems. PowerBlock 150 (Figure 4-43) integrated system (Nominal continuous power 100 kW, maximum power (inline) 150 kW/10 sec and (grid parallel) 300 kW/10 sec., voltage 480/415 VAC and nominal current 120 A). TransFlow 2000 system provides up to 500 kW of power and 2.8 MWh of energy storage capacity in a single enclosure. Zinc-Flow® regenerative fuel cell technology has 45 kWh energy storage capacity and energy ratings: 1,875 Amp-hour @ 24 VDC, 938 Amp-hour @ -48 VDC, 360 Amp-hour @ 125 VDC and it meets wide range of power requirements up to 30 kW.

Examples of the Installations

- 250 kW, 2 MWh unit at Castle Valley, Utah
- 200 kW, 800 kWh unit at King Island, Tasmania
- MW, 6MWh unit at Tomamae, Hokkaido, Japan
- 100 kW (10 modules/30 inverters), 500 kWh, Newcastle, Australia (ZESS 500)
- Various smaller units 5–50 kW.

Planned installations e.g:

7 500 kW, 6 hour unit in Sacramento, California, Everett, Massachusetts, and Syracuse, New York (Premium Power projects)

25 MW, Alameda California (Primius Power project, ZnCl flow battery)

Development Trends and Future Expectations

Latest development trend has been to build compact, modular, and scalable overall system architecture to be flexible and easy to install and maintain. A membrane durability and overall improved efficiency are the future targets among other things.

Potential Application Areas in Smart Grids

ZnBr batteries can be used in various areas of the smart grid management including frequency response, load levelling, peak shaving, power quality and reliability, rapid reserve, system stability and renewable energy management.

4.8.2 Vanadium Redox Batteries

Technology

Vanadium redox flow battery is based the use of solubility of vanadium in four different oxidation states in sulphuric acid. The overall reactions at both electrodes during charging/discharging of the VRB are:

At the negative electrode: $V^{2+} \underset{carge}{\overset{discharge}{\leftrightarrow}} V^{3+} + e^{-}$, $E^0 = -0.26V$ (4.1)

At the positive electrode: $VO_2^{+} + e^{-} + 2H^{+} \underset{charge}{\overset{discharge}{\leftrightarrow}} VO^{2+} + H_2O$, $E^0 = 1.0V$ (4.2)

The principle of the VRB is shown in more detail in (Figure 4-44 – it consists of two electrolyte tanks, containing active vanadium species in different oxidation states.

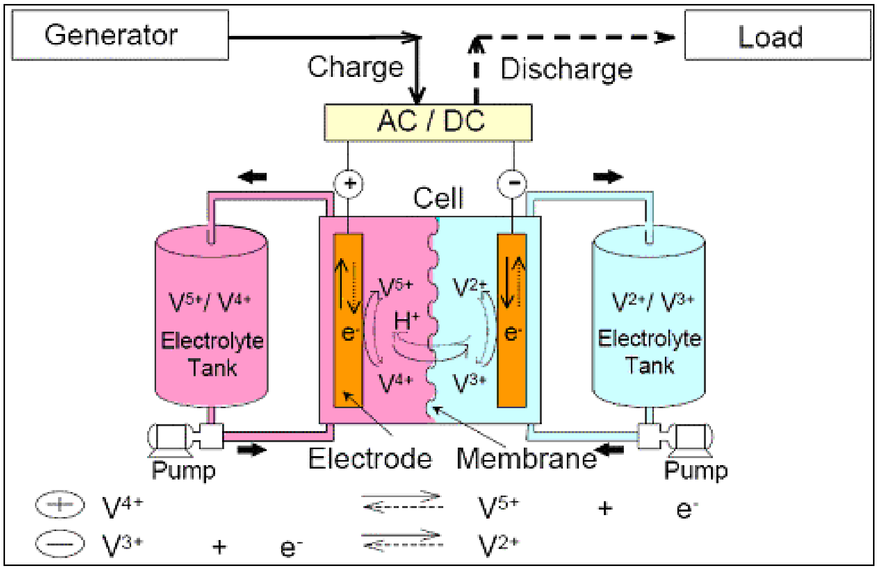


Figure 4-44. Principle of VRB [Source: Sumimoto Electric].

Output power and energy storage capacity are independent. Energy storage capacity is determined by the concentration and volume of the electrolyte. The output power depends on the number of flow cells (stacks) and the surface area of the electrodes. The electrolytes can be fed through the stack of cell in parallel or in series (Figure 4-45) that decrease bypass currents. VRB operates at normal temperature.

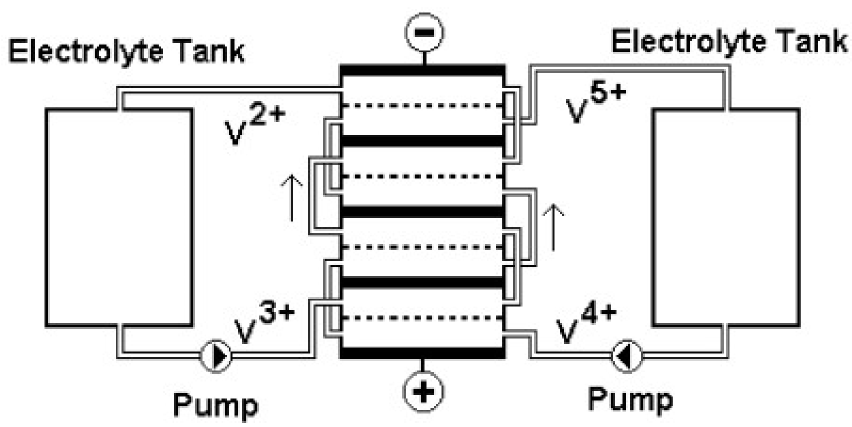


Figure 4-45. Series flow with bipolar electrodes [Source: Cellenium].

Technical Properties

Technical properties of VRB

Specific energy	10–20 Wh/kg (36–72 J/g)
Energy density	15–25 Wh/L (54–65 kJ/L)
Charge/discharge efficiency	75–80%
Time durability	10–20 years
Cycle durability	> 10 000 cycles
Nominal cell voltage	1.15–1.55 V

Typical charge/discharge curves for a 100-cell VRB-stack are presented in Figure 4-46.

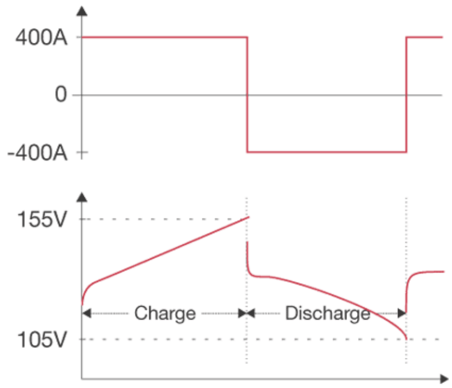


Figure 4-46. Typical charge and discharge curves for a 100-cell VRB stack [33].

Economical Aspects

Capital cost of VRB systems is for 20 kWh systems $1 800/kWh and for 100 kWh -level systems $600/kWh [34].

Life Cycle Aspects

VRB has a long cyclic life > 10 000 cycles and a long time durability 10–20 years. The environmental impact of vanadium battery is smaller than lead-acid battery [36].

Manufactures, Commercial Products and Solutions

Vanadium Redox Battery (VRB) technology was first developed and patented by the University of New South Wales in Australia in the 1980s. Pinnacle VRB was the original holder of the vanadium redox battery patents then were sold to VRB power Systems and lately acquired by Prudent Energy (http://www.pdenergy.com/products_mwclasssystems.html) based in China. Prudent has 7.5 kW, 25 kWh basic system that can be used to build 175 kW modules, which are scalable up to 10 MW -size systems. Round-trip efficiency AC-AC is 65–75%, cycles greater than 100 000 V and life time 10 years without material deterioration.

Cellstrom GmbH is an Austrian manufacturer that manufacturers product named CellCube. Cellstrom sells a 10/100 kWh VRB (Figure 4-47) and plans to launch in 2011 a 200 kW/400 kWh VRB designed for solar and wind farms.

Figure 4-47. Cellstrom Cellcube FB10/100 [Source: Cellstrom].

Fuel Pty Ltd holds rights to the second generation of VRB technology. Fuel Pty has cell modules ranging from 5 kW to 550 kW power output. Cellenium Company Ltd (Thailand) had one of the original licencees and is developing system further. Sumimoto Electric Industries has built grid load levelling applications. [39]

Colden Energy Fuel Cell GEFC is a Chinese manufacturer of VRB's. GEFC-50V50A-VRB rack has rated voltage 50 V and rated power 2.5 kW including 40 single cells. GEFC VRB rack rated efficiency is 78% and operating life 10 Years. GEFC VRB sizes are 20 kW/100A 40 kW/200A, 80 kW/400 A and 100 kW/200A. GEFC 100 kW VRB has rated time 2 h, efficiency 72%, operating life is 20 years.

VRB systems have been installed over 20 MWh capacity around the world. Installations include:

- A 1.5 MW UPS system in a semiconductor fabrication plant in Japan.
- A 275 kW output balancer in use on a wind power project in the Tomari Wind Hills of Hokkaido.
- A 200 kW, 800 kWh (2.9 GJ) output leveller in use at the Huxley Hill Wind Farm on King Island, Tasmania.
- A 250 kW, 2 MWh (7.2 GJ) load leveller in use at Castle Valley, Utah.
- Two 5 kW units installed at Safaricom GSM site in Katangi and Njabini, Winafrique Technologies, Kenya.
- Two 5 kW units installed in St. Petersburg, FL, under the auspices of USF's Power Center for Utility Explorations.

Development Trends and Future Expectations

The future development includes improvements of energy density and overall efficiency. Further development will be done for the performance of membranes and power stacks. The development trend is towards larger MW-level systems.

Potential Application Areas in Smart Grids

VRB systems have been installed for load levelling applications and for wind and solar system storage. VRB system has also potential for power quality applications, demand side management and distributed power applications as well as UPS and emergency power systems.

4.9 Compressed Air Energy Storage Systems (CAES)

Compressed Air Energy Storage (CAES) is typically a large-scale energy storage system. The energy is stored mechanically by compressing the air. A typical CAES system is a combination of natural gas combustion and high pressure of the compressed air to drive the turbines. In the most common designs, the excess electricity, generally at times of peak load, the air from the atmosphere is compressed and stored in underground caverns or mines. When electricity is required, the compressed air is drawn from the cavern, then heated in gas burners and expanded in a gas turbine. [42–43]

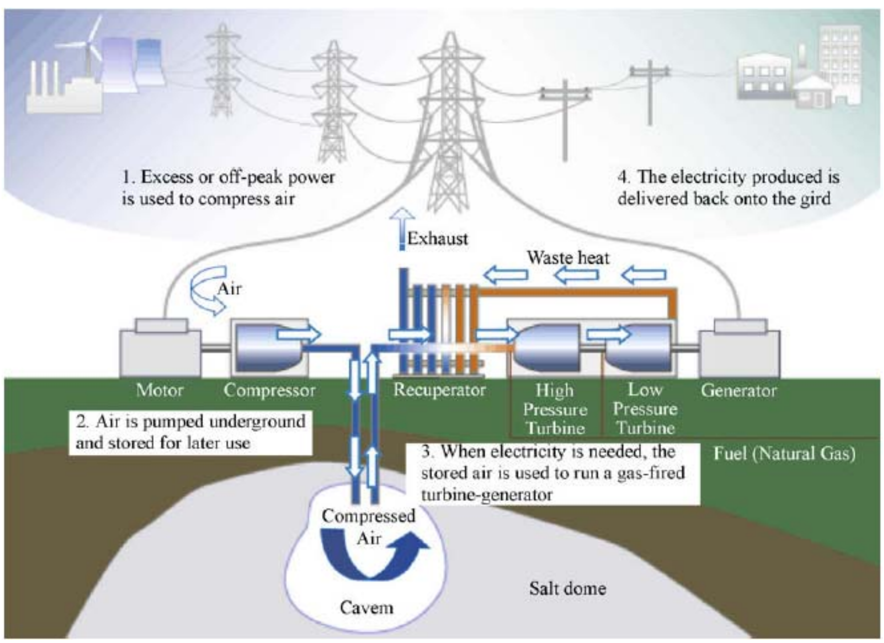


Figure 4-48. CAES system. [28].

CAES plant consists of five major components defined below [28].

- A motor/generator, which produces electricity and supplies power to the grid.
- An air compressor with intercoolers and aftercoolers, which cools the air, achieves the compression, reduces the moisture content of the compressed air and drives the air below ground. Typically the pressure attains between 4.0–8.0 Mpa.
- A cavity/container for storing compressed air, which can be underground hard rock caverns or mines, salt domes, aquifers or depleted gas fields, etc. Above ground containers, such as high-pressure tanks, can also be used for small-scale CAES systems.

- Turbines, for high- and low-pressure air. The compressed air is drawn from the storage container, heated and expanded through a high-pressure turbine. The air is then mixed with fuel and combusted with the exhaust expanded through a low-pressure turbine. The compression cycle of a gas turbine is decoupled from its expansion cycle over time.
- The control equipment and auxiliaries such as fuel/gas storage, cables etc.

There are three basic types of CAES system:

- Diabatic CAES, which is the technology currently used in the two German and American plants, and follows the operation process described above. The compressed air is stored and the heat from the compression is lost. When energy is needed, gas turbines are used to reheat the compressed air.
- Adiabatic CAES (AA-CAES), which stores the heat resulting from the compression process. This heat is then reused when the compressed air is released. Heat can be stored in solid, fluid or molten salt solutions, at temperatures from 50 to 600°C. Adiabatic process is more efficient (70%) than diabatic process (50%). AA-CAES does not need additional gas co-firing (Figure 4-49).

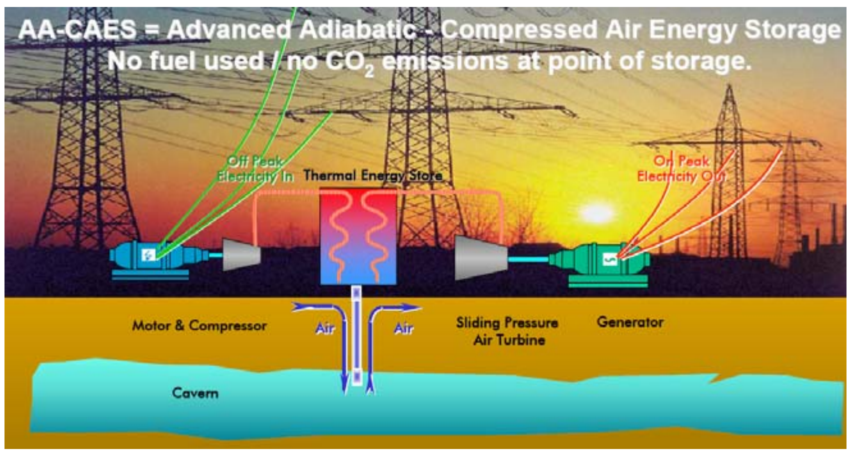


Figure 4-49. Schematic arrangement of the main elements of an adiabatic CAES plant [43].

Isothermal compression, which employs a thermo-dynamically reversible cycle, approaching a theoretical efficiency value of 100%. In practice, the cycle is not perfectly isotherm as energy/heat losses occur in the compression and generation processes.

Technical Properties and Economical Aspects

CAES plants are typically seen as large capacity storages (above 100 MW). Small-Scale CAES with fabricated small vessels, Advanced Adiabatic CAES with Thermal Energy Storage and Compressed Air Storage with Humidification are just proposed or under investigation. Storage efficiency of the CAES is in the range of 70–89% [28]. The round-trip efficiency diabatic CAES is 42–54% including natural gas consumption. Capital costs for CAES facilities depend on the underground storage conditions, ranging typically between $400 and $800 per kW [28]. The economics of the Alabama CAES plant is estimated at 400 €/kWh [42].

Manufactures, Commercial Products and Solutions

The CAES technology is commercially available from several manufacturers e.g. Alstom Power LTD (France), Dresser-Rand (USA), RWE (Germany), General Compression (USA).

There are two existing facilities in operation:

- The CAES plant in Huntorf, Germany has rated output power capacity of the 320 MW for 2 hours. The plant was built by Alstom Power in 1978. The plant includes a salt cavern. The system is used for grid support 3h/day.
- The CAES McIntosh unit with a rated power output of 110 MW, located in the US Alabama, was built by Dresser-Rand in 1991. The plant is owned by Alabama Electric Co. The plant includes a salt cavern with 26 hours of storage.

There several new installation planned or under construction worldwide e.g. ADELE project on AA-CAES in Germany, Iowa Stored Energy Park, USA, and The Norton, Ohio Project (300 MW), 150 MW in Watkins Glen; Ny, USA (Iberdrola project.)

Development Trends and Future Expectations

Pike Research estimates that the CAES market will grow from 453 MW in 2010 to nearly 7 GW by 2020, which will describe e.g. the technology's role in helping integrate renewables on the grid.

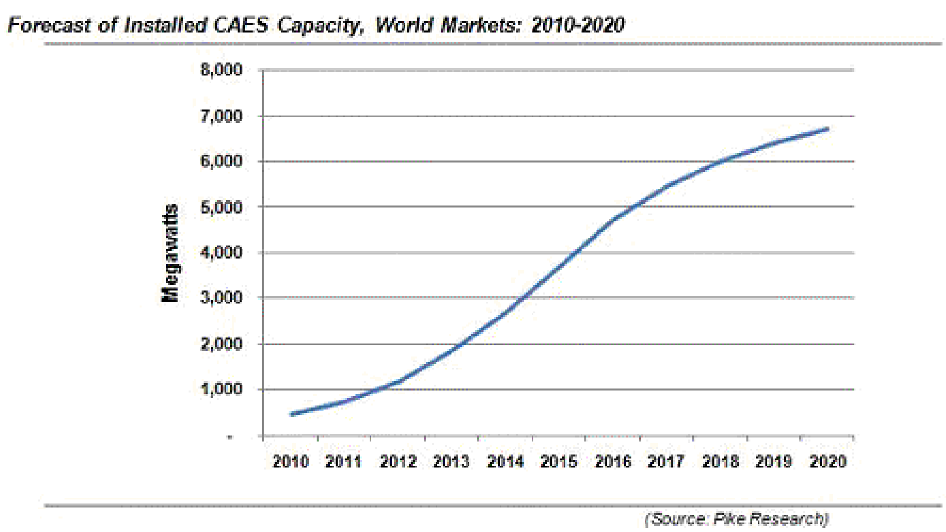


Figure 4-50. Forecast of installed CAES capacity 2010–2020 [Source: Pike research].

Potential Application Areas in Smart Grids

CAES can be seen as a real bulk energy storage technology. Bulk systems can store megawatt-scale amounts of energy produced during off peak times. The German CAES plant is used for peak shaving and the provision of spinning reserves; the American plant is also used for load management and price arbitrage opportunities.

CAES plants may be closely integrated with wind farms, representing a means of storing additional power generated off-peak. CAES is a candidate for firming capacities of wind energy source. [28]

4.10 Pumped Hydroelectric Storage System (PHES)

PHES is the oldest and largest of all commercially available energy storage technology, being first used in Italy and Switzerland in the 1890's. Worldwide, there are hundreds of PHES stations operating with total capacity of 127 GW [45].

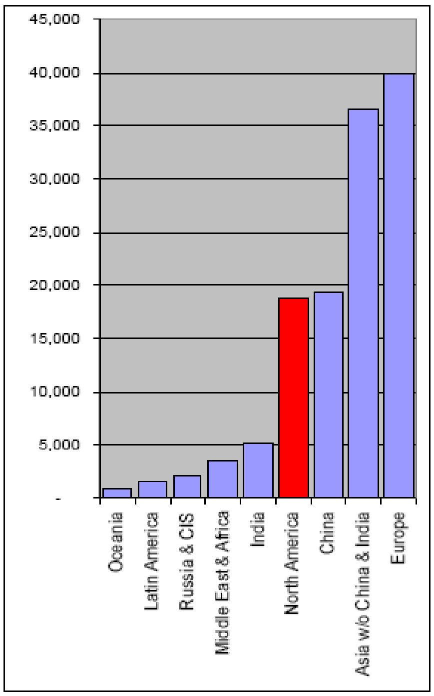


Figure 4-51. Pumped storage systems in operation (MW) in 2010 [63]

As of 2009, the European Union has an installed PHES capacity of 36 GW accounting for 4.3% of total generating capacity within the region. USA has an installed capacity of 21.8 GW with over 39 PHES plants and Japan with 34 plants (Plant with installed MW capacity > 200 MW) has an installed capacity of 24.5 GW [44]. The largest plant currently in operation is the Iberdrola owned Villarino plant in Spain with a capacity of 745 MW. An additional 76 GW PHES capacity worldwide is expected by 2014 and in Europe 7.43 GW (Table 4-6).

Table 4-6. New PHES plants proposed in Europe [44].

Country	Proposed PHES (MW)
Switzerland (CH)	2140
Portugal (PT)	1956
Austria (AT)	1430
Germany (DE)	1000
Spain (ES)	720
Slovenia (SL)	180
Total	7426

The fundamental principle of PHES is to store electric energy in the form of hydraulic potential energy. Pumped hydro storage works in a very simple principle with two water reservoirs at different altitudes (pump-back PHES). Reservoirs can natural like lakes or artificially established. Old miners are typically used for lower reservoirs or open sea.

Water is pumped to upper reservoir and energy is created by the downflow of water (Figure 4-52). Generating units can achieve maximum output from zero within few seconds. New planned PHES plant will use variable speed pump/turbine units that help to control the system and allows turbines to operate closer their optimal efficiency point.

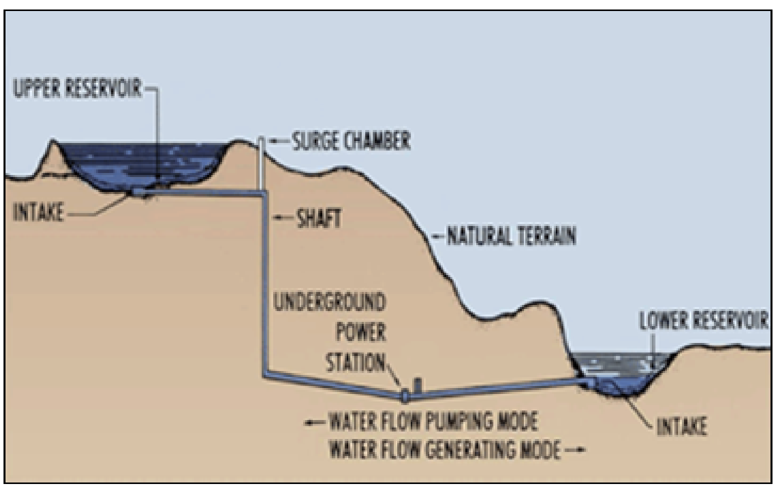


Figure 4-52. A schematic of a typical pumped storage [Source: Image courtesy of Eagle Crest Energy].

Technical Properties and Economical Aspects

There are a lot of installations with one stage pumps and 300–600 m heads. Multistage pump systems need higher heads. For seasonal storages a capacity have to larger than one billion cubic meters. For producing 1 000 MW in four hours at 400 m head it is needed 4 million cubic meter reservoir capacity. Efficiency of PHES is 65–80%.

Cost for PH storage varies but is approximately 350 €/kW or higher. The cost of new PHES planned in Portugal and Spain varies from 486 €/kW to 2 170 €/kW.

Table 4-7 Cost of planned PHES in Portugal and Spain [44].

Facility	Size	Published cost	Developer	Operational date
Alto Tâmega Complex	1200 MW turbine, capacity 900 MW pumping capacity	1.7 billion Euros [28]	Iberdrola	2018
Baixo Sabor	170 MW	369 million Euro [31]	EDP	2013
Foz Tua	324 MW	340 million Euro [32]	EDP	2018
Fridão/Alvito[a]	256 MW + 136 MW	510 million Euro [33]	EDP	2016
Alqeueva II (expansion)	240 MW	150 million Euro [34]	EDP	2012
La Muela II (extension)	720 MW	350 million Euro [35]	Iberdrola	2012

[a] Subject to the confirmation by INAG (the Portuguese Water Institute).

Development Trends and Future Expectations

Latest development trend is to utilize underground reservoirs instead of natural reservoirs especially in "flat" country areas. Also recycled wastewater as water resource is proposed where PHES operation may actually improve the quality of the water it uses to operate. The pumping operation can be designed to aerate the water, and storage could become an extended aerobic biological treatment. [45]

Potential Application Areas in Smart Grids

PHES plants have been built in many countries such as the USA and Japan to act as fast response peaking plant to complement high inertia nuclear power plants, but more recently there has been a renewed interest in the technology as an integrator for variable wind power [44]. Pump storage generation offers a critical back-up facility during periods of excessive demand on the grid system. PH storage can have different roles: night-day storage, seasonal storage and rapid power balancing resource. For example when the wind howls in Denmark and energy demand is low, turbine farms can store energy in a Norwegian reservoir for use the next day.

Requirement for the head and water volume- reservoir capacity are the liming factors to the placements.

4.11 Plug-In Hybrid Vehicles (PHV) and V2G

Number of cars is fast increasing all over the world. According to Automobile World Book Encyclopedia Chicago (World Book 2001), "About 450 million passenger cars travel the streets and roads of the world". In 2002 the world's passenger car fleet hit 531 million. Plug-in hybrid cars are not widely commercial available yet although there are conversion kids available for converting some basic hybrids into plug-ins.

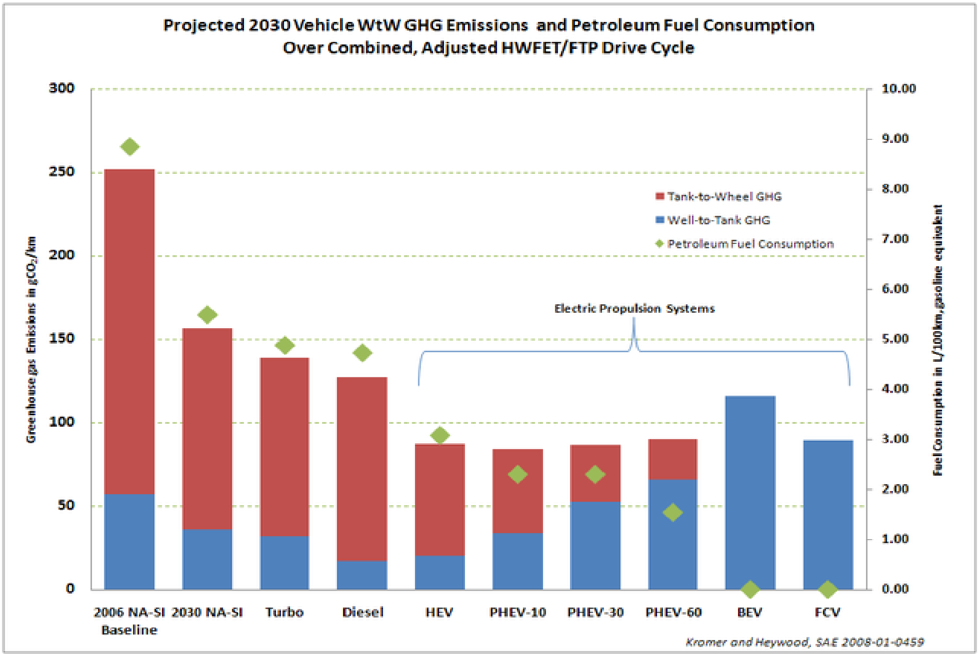


Figure 4-53. Overview of projected 2030 greenhouse gas and fuel consumption for different car types, done at MIT by Matthew Kromer and professor John Heywood.

Capabilities to support ancillary services

Vehicle to grid (V2G) with their batteries can support electric power grid but charging the batteries can also perform technical challenges for the grid. Battery requirements are very sensitive to vehicle design (Figure 4-54) and e.g. single PHEV design has not been agreed upon.

Electric vehicles (EV's) electric motors can be either alternating current (AC) or direct current (DC) converting about 75% of the chemical energy from rechargeable batteries to power the wheels. The demand of the high-energy density, long life batteries are the most challenging part of the EVs. Lead-acid and NiMH batteries are currently typically used batteries in EVs but advanced Lithium based batteries are increasing in EVs. Also supercapacitors or supercapacitor-battery combinations like ultrabattery are seen as future EV battery possibilities that would have better energy efficiency and lighter weight.

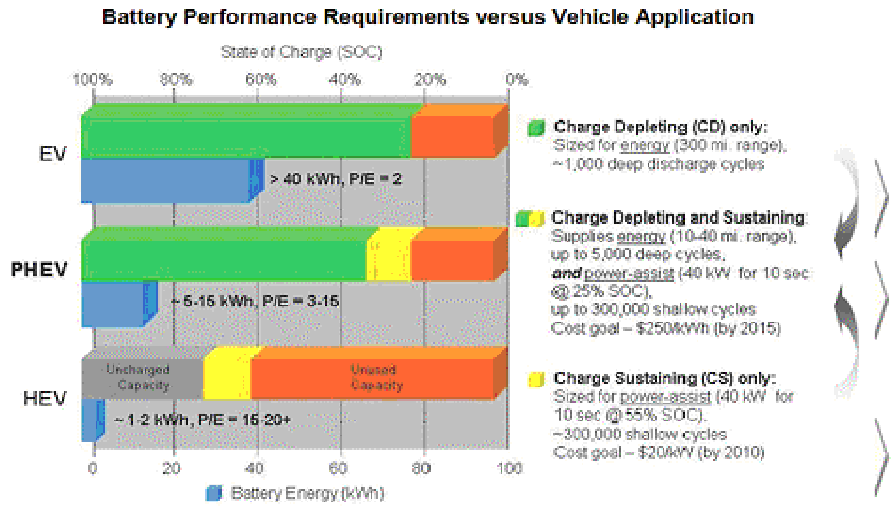


Figure 4-54. Battery performance requirements versus Vehicle Application [Source: DOE].

If the EV motor is an AC motor, it can be a three-phase AC motor running e.g. at 240 volts AC with a 300 volt battery pack. A DC motor may run on anything from 96 to 400 volts. EVs can be slow- or fast-charged. Slow recharging takes typically 6 to 8 hours. A slow-charging unit comprises a transformer to reduce voltage and a rectifier to charge the cells using direct current. Fast charging units usually require the use of alternating current – these can take as little as 10 minutes for a 50% charge. EVs can go about 100–300 km before recharging.

Figure 4-55. Electricity charging of cars [Source: Fortum].

The technical challenges for the electric power grid depend on the level of deployment of the EVs and charging practices. For example according to the DOE (PHEV Discussion Meeting, May 4–5, 2006) low volume deployment of PHEVs combined to the slow, overnight charging would be manageable – the existing electric power distribution system would be adequate to support the recharge demands. With the extra custom-side energy storages also the high current fast charging of EVs would be more easily possible if the extra batteries or other electrical energy storage would be slow-charged by a low-energy-consumption time. Removable battery packs can be swapped for full batteries that have been charged from the grid (Figure 4-56).

Figure 4-56. PHEV removable battery pack [Source: MIRA & Skoda Fabia].

Longer term, with a much larger vehicle population, off-peak pricing, smart metering and charge control would be required to ensure off-peak charging, maximize overall system efficiency (vehicle plus grid) and minimize the impact of PHEVs.

Future BEVs with large batteries (e.g. ZENN 16 kWh) that could be fast-charged in 5 minutes might cause problems because of high current and energy needed in the charging point. Even smaller car batteries like NEC 21 Ah Lithium-manganese battery as charged in 5 minutes would mean 250 A current. Fast charging stations would need their own energy storage systems and/or direct medium voltage grid connections.

BEVs and PHEVs daily usage is typically < 4hours/day that means typically 10 kWh energy and 5 kW power available about 20 h/day. On the other hand an extra battery capacity could give possibilities to provide regulation services, spinning reserves and peak power demand.

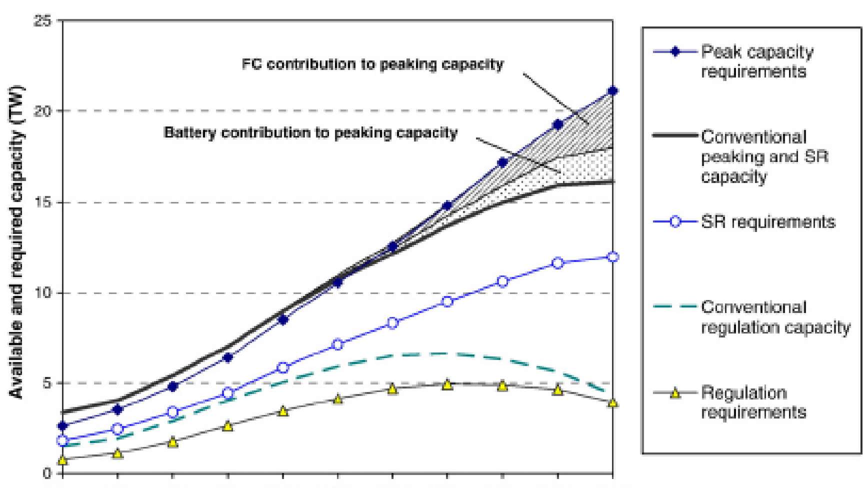


Figure 4-57. Contribution of Vehicle-to-Grid to global market services (peak power, spinning reserves (SR) and regulation services) [40].

As a grid-supporting unit EV can be seen as a controllable load and energy storage facility that is able to support the local or residential microgrid in blackout or high peak load situations by recharging batteries into grid. Inverter quality is in an important role to ensure power quality in vehicle to grid connection. EEtrex is an inverter supplier for V2G connections. EEtrex inverter power is 6 kW, with various input and output voltages, 12–30 amps and efficiency 0.95.

The power factor of the installation can be improved when the battery and grid coupling converter act as a small Statcom, or active providing the reactive power other loads need. This could give benefits particularly for a commercial customer if it is allowed to deliver reactive power into the grid.

4.12 Emerging Technologies

As emerging technologies can be seen rechargeable metal-air batteries, regenerative fuel cells e.g. zinc-air fuel cells (Zinc Air Inc.) and liquid-metal systems [7].

4.13 Comparison of different energy storage technologies

Application area, needed technical and economical requirements are the key features for the selection of suitable energy storage type. In the following table (Table 4-8) it is compared weaknesses and strengths of different storage technologies.

Table 4-8. Comparison of the strengths and weaknesses of energy storage technologies.

Storage type	Strengths	Weaknesses	Size	Storage time
Supercapacitors	Fast, efficient	Low energy density Self discharge	Wh W – x00W	10 ms – 1 min
Flywheels	Fast, efficient	Low energy density Self discharge	kWh kW – x00 kW	10 ms – tens min
Rechargeable lithium batteries	High energy- and power density (120–160 Wh/kg) Light No memory effect Low self discharge (5%/m) Long cyclic life (3 000–5 000) Long service life Lithium oxides and salts can be recycled	Needs heat control High investment cost Needs battery cell balancing and protection	kWh – 1MW	Min – h
Lead acid	Widely used Cost efficient Low selfdischarge (2–3%/m) Small service cost (closed LA) Rechargeability (90%) New tech. Lead-carbon.	Low energy density (25–50 Wh/kg) Environmental hazard (Lb) Narrow temperature area Low efficiency (75–85%)	kWh – MWh kW -> 10 MW	Min – h
Zn-Br flow batteries	High energy density (75–85 Wh/kg) Cyclic life (> 2 000 cycles) Fast response time	Low efficiency (70–75%) No small systems Cost Complex construction Few manufacturers	kWh – MWh kW ->10 MW	Min – h
Vanadium Redox flow batteries	Cyclic life (> 10 000 cycles) Fast response time Small service cost No self-discharge	Low energy density (25–35 Wh/kg) Low efficiency (65–75%) Cost Complex construction Few manufacturers	kWh – MWh kW -> 10 MW	Min – h
NaS	High efficiency (89–92%) High cyclic life (~2 500 cycles) High energy density (150–200 Wh/kg) No memory effect No selfdischarge (Low capital cost) Suitable for MW size systems	High work temp. (300–350°C) Few manufacturers (NGK Insulators, GE Energy plans to start production in 2011	MWh kW -> 10 MW	Min – h
NaNiCl	High energy and power density (120 Wh/kg, > 150 W/kg) High efficiency (> 85%) Environmentally friendly and 100% recycleable	High work temp. 270–350°C Cyclic life 1 500–3 000 cycles Few manufacturers (MES-DEA)	kWh kW	Min – h
CAES	High energy Cost efficient in large size systems Environment friendly	Low efficiency (< 70%) Technically complex Safety issues (pressure tank) Large size systems	MWh – GWh 100 MW ->	h – d.
PHES	Most installed high energy system Cost efficient in large size systems Fast response time Long lifetime	Geographical limits for placement High capital cost compared to CAES Low energy density	MWh – GWh 100 MW ->	h – m – y

According to the cyclic life comparison test of Sandia Laboratories Li-ion battery had a far better cyclic life (8 000 cycles) than conventional VRLA battery (2 000 cycles) but new type lead-carbon battery reached 17 000 cycles. Batteries compared were: Furukawa UltraBattery (lead carbon battery), East Penn (VRLA), Lifebatt Li-ion (Li-FePO4, LFP) and C&D CPV (vented LA).

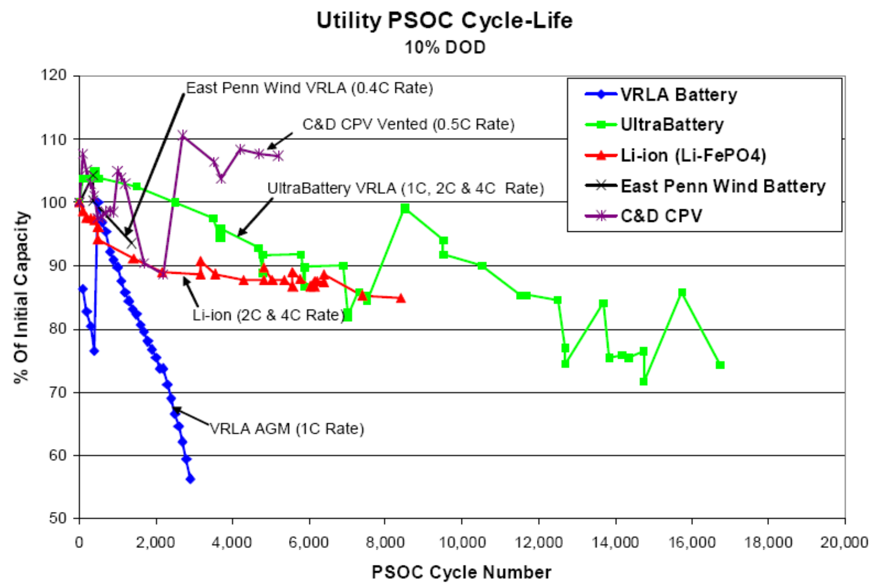


Figure 4-58. Cyclic-life of different battery technologies [47].

Building cost of modular energy storage system consists of energy-related cost (purchase cost/kWh), power-related cost (interconnection devices, power electronics, /kW) and balance of plant (installation, engineering, basis) cost (Table 4-99).

Table 4-9. Comparison of modular energy storage cost [47].

Technology	Energy- Related Cost ($/kWh)	Power–Related Cost ($/kW)	Balance of Plant ($/kW)
Lead-acid Batteries (Flooded Cell)	150	175	50
Lead-acid Batteries (VRLA)	200	175	50
Ni/Cd	600	175	50
Zn/Br	400	175	0
Na/S	250	150	0
Li-Ion	500	175	0
V-redox	350	175	30
Lead-carbon asymmetric caps	500	350	50
CAES-surface	120	550	50
High-speed flywheel	1,000	300	0
Low-speed flywheel	380	280	0
Hydrogen fuel cell	15	1500	0
Electrolyzer (to accompany fuel cell)	None	300	None

Cost of large energy storage systems is highly depending on the case. In the following study it is compared energy storage costs in four different applications:

- load levelling high voltage grid
- load levelling medium voltage grid
- load levelling low voltage grid and
- village power supply.

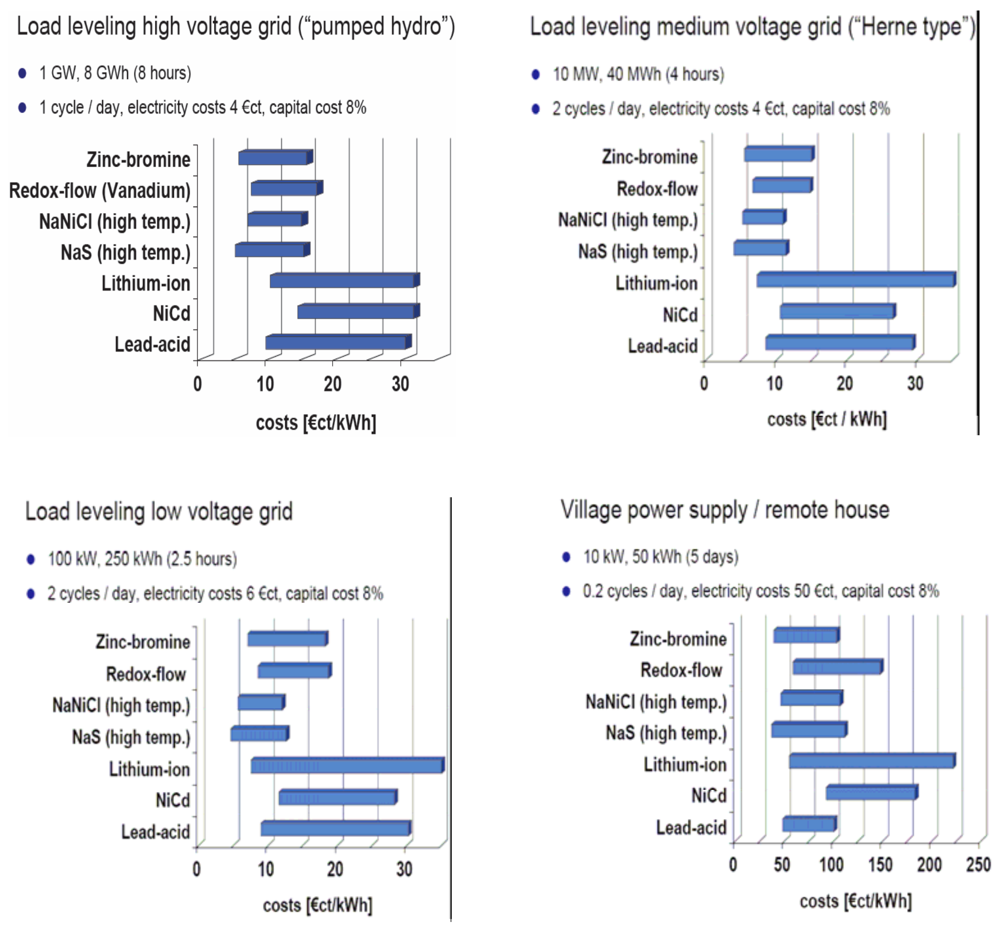


Figure 4-59. Cost of energy storages in high, medium and low voltage grid load levelling and in local net [46].

5 Energy Storages in Smart Grid Applications

5.1 Energy Storage Technology Landscape vs. Smart Grid

The storage market is still in a very nascent stage, with no clear technology leader. However, a variety of battery technologies hold promise for supporting Smart Grid needs (Figure 5-1). The grid applications for these technologies can be loosely divided into power applications and energy management applications, which are differentiated based on storage discharge duration. Storage technologies for grid applications include electrochemical capacitors, high-speed flywheels, traditional and advanced lead-acid (LA) batteries, high-temperature sodium batteries (e.g., sodium-sulphur (NaS) and sodium-nickel-chloride), lithium-ion batteries, flow batteries (e.g., vanadium redox (VRB) and zinc bromine (ZBr)), compressed-air energy storage (CAES) and pumped hydro (PH). Superconductive magnetic energy storages (SMES) are still under development as well as other advanced battery chemistries, such as metal-air, nitrogen-air, sodium-bromine, and sodium-ion. [3]

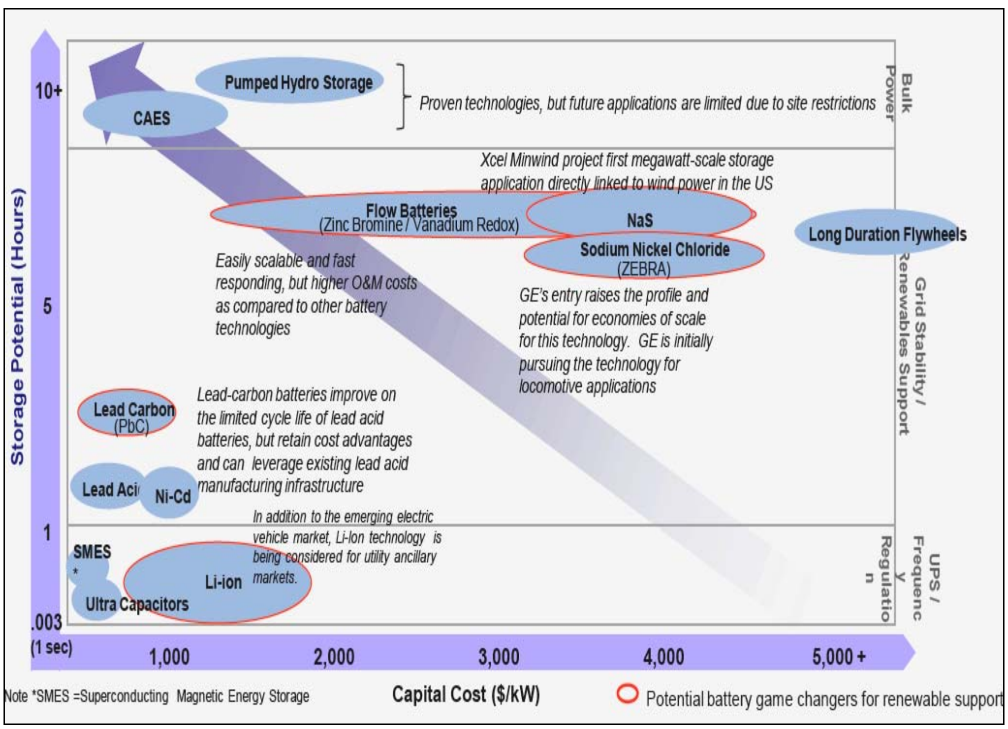


Figure 5-1. Storage technology landscape [3].

Highest market value of energy storages technologies in Smart Grid in 2020 will still have lead acid batteries (Figure 5-2). Growth rate of energy storage manufacturing capacity is 25% (Figure 5-3). Grid-scale stationary energy storage system revenues are expected to grow from $1.5 billion this year increasing to $35.3 billion in next 10 years, according to a new report from Pike Research.

The most significant growth will be in compressed air energy storage (CAES), Li-ion batteries and flow batteries.

Figure 5-2. Smart Grid – Energy Storage Technologies. Market Value 2020 [Source: Frost & Sullivan].

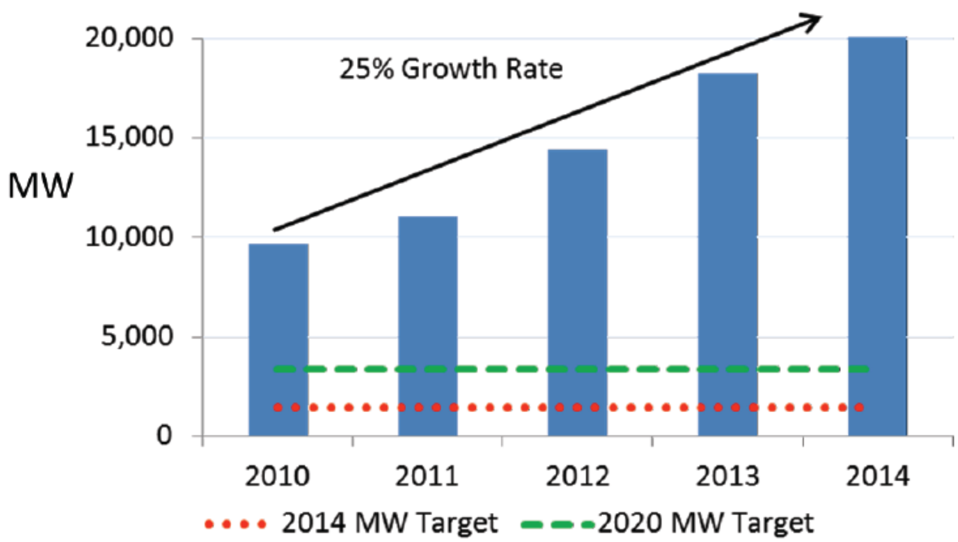


Figure 5-3. Energy storage annual manufacturing capacity worldwide [14].

5.1.1 Installed Energy Storage Capacity

Pumped hydro storages comprise over 99% of the installed storage capacity (Figure 5-4) [14]. NaS comprise most of the battery capacity being 300 MW (LA 125 MW and NiCd 26 MW). The amount of compressed air energy storage power will be remarkable increasing if the proposed 270 MW CAES, Iowa Stored Energy Part (ISEP) is built.

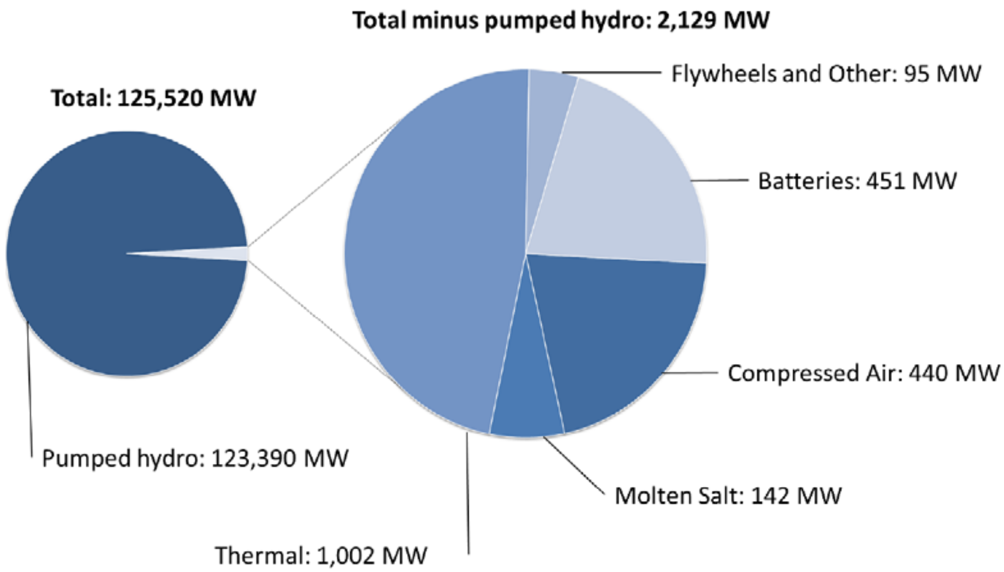


Figure 5-4. Installed energy storage capacity worldwide [63].

The growth rate of energy storage annual manufacturing capacity is forecast to be 25% (Figure 5-3) [14].

5.1.2 Drivers and Restraints

Frost & Sullivan has evaluated drivers and restraints for energy storage market (Figure 5-5). The study handles energy storages for renewable energy market but the similar questions can be seen with energy storages in whole Smart Grid applications.

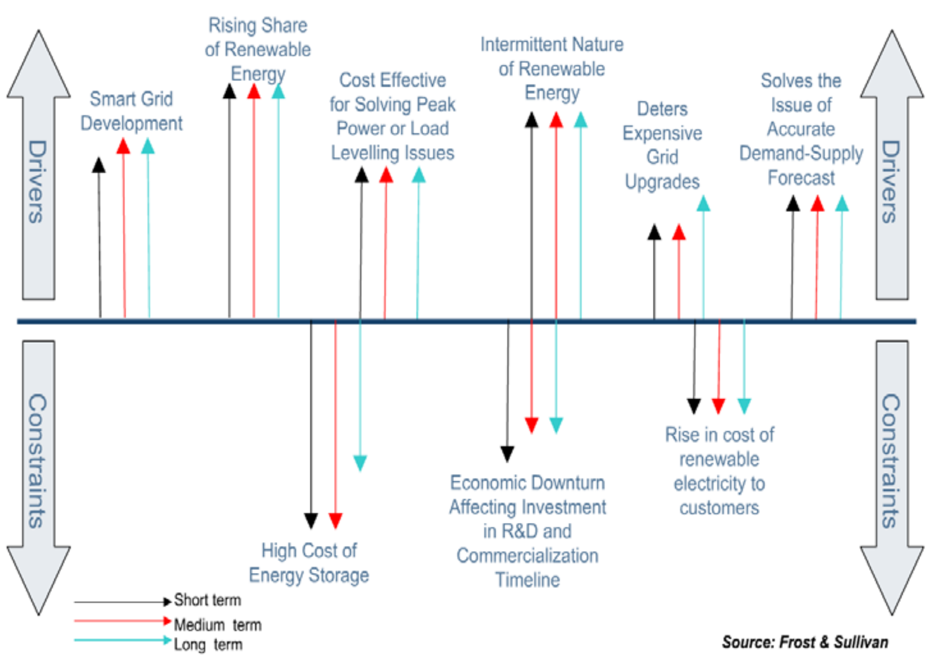


Figure 5-5. Renewable energy storage market: Drivers and restraints (Europe), 2009–2020 [5].

5.1.3 Development Trends and Future Expectations of Energy Storages

Energy storages altogether can be seen as a developing technology. Energy efficiency, longer battery lifetime and higher cyclic lifetime, safety, environmental issues and lower cost are the most important issues. Most activities exist in lithium-ion battery development but also other battery technologies are developing. New type of lead acid batteries (lead-carbon batteries) have to a long cyclic lifetime and development carbon electrodes and other materials of lead batteries can keep them a relevant alternative also for future applications. Traditional lead acid and MH battery systems have not typically had an advanced batterycell-based control system and development of inexpensive battery cell-based measurement and control system would help to maintain large battery packs and forecast better the individual battery cell performance and lifetime. Development of lithium-ion batteries include improvements of all materials especially electrode materials to achieve higher charge currents. Also widening operation temperature area especially low temperature performance is an essential issue. To decrease operating temperature of sodium-based batteries as well as to increase operating temperature of SMES would increase energy efficiency and decrease cost. Flow batteries have interesting features like power and energy capacity independent of each other and zero self-discharge but they need improvement of stacks, membranes and overall storage system performance. The ultimate goal could be non-aqueous flow-battery. The goal of electrochemical capacitors R&D is to achieve higher energy capacity. Generally the improvements in materials and battery chemistry as well as the development of more intelligent battery and power management systems would bring the currently known energy storage technologies more useful in Smart Grid applications. The currently highly increased funding and R&D could bring also totally new storage technologies available in the long run.

As an example of a European energy provider interest on energy storages its presented NREL's energy storage roadmap (Figure 5-6).

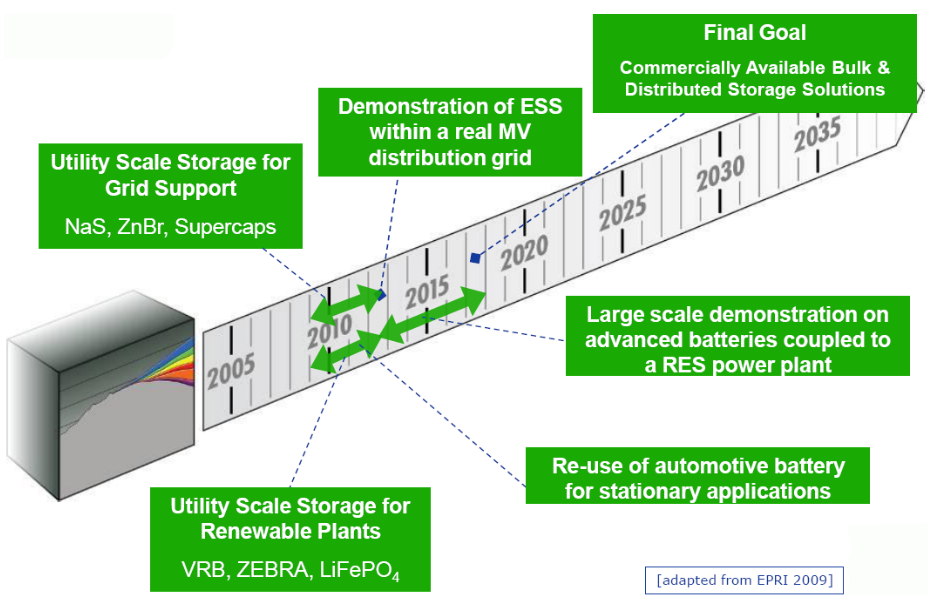


Figure 5-6. Energy storage roadmap [Source: NREL].

5.2 The Role of Energy Storages in Smart Grids

Energy storages can serve different application areas of the Smart Grid [2]

Electric Supply

- Electric Energy Time-shift
- Electric Supply Capacity

Ancillary Services

- Load Following
- Area Regulation
- Electric Supply Reserve Capacity
- Voltage Support

Grid System

- Transmission Support
- Transmission Congestion Relief
- Transmission & Distribution (T&D) Upgrade Deferral
- Substation On-site Power

End User/Utility Customer

- Time-of-use (TOU) Energy Cost Management (to shift high peak usage to low cost time)
- Demand Charge Management (to lower high peak fixed charge)
- Electric Service Reliability
- Electric Service Power Quality

Renewables Integration

- Renewables Energy Time-shift
- Renewables Capacity Firming
- Wind Generation Grid Integration.

Main stationary energy storage solution areas are ancillary services and bulk storage [15].

In principle there are two types of energy storage applications, power applications and energy applications. Storage technologies, which suits for power applications can deliver high power in very short time (in few seconds to couple minutes) such as capacitors, SMES and flywheels. CAES, pumped hydro and most batteries are better suitable for energy applications where is needed longer discharge times.

In the following picture (Figure 5-7) it is presented power ratings and discharge time required for different type of network services.

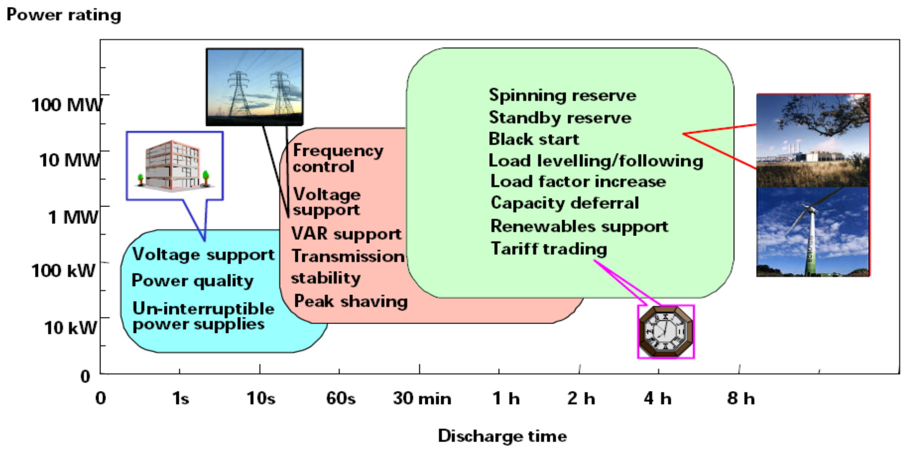


Figure 5-7. Power rating and discharge time of storage applications for different network services [Source: ESA 2000, Energy storage: a solution in network operation].

Energy storage power and discharge duration are the key storage design criteria for the storages in different applications. In the following table it is presented typical assumption values for storages and benefits, potential and economics in USA (Table 5-1). Highest benefits are seen in substation on-site power, area regulation, load following, T&D upgrade deferral and in wind generation grid integration.

Table 5-1. Typical energy storage power, discharge duration and approximated benefits (in USA) in different applications [2].

		Discharge Duration*		Capacity (Power: kW, MW)		Benefit ($/kW)**		Potential (MW, 10 Years)		Economy ($Million)†	
#	Benefit Type	Low	High	Low	High	Low	High	CA	U.S.	CA	U.S.
1	Electric Energy Time-shift	2	8	1 MW	500 MW	400	700	1,445	18,417	795	10,129
2	Electric Supply Capacity	4	6	1 MW	500 MW	359	710	1,445	18,417	772	9,838
3	Load Following	2	4	1 MW	500 MW	600	1,000	2,889	36,834	2,312	29,467
4	Area Regulation	15 min.	30 min.	1 MW	40 MW	785	2,010	80	1,012	112	1,415
5	Electric Supply Reserve Capacity	1	2	1 MW	500 MW	57	225	636	5,986	90	844
6	Voltage Support	15 min.	1	1 MW	10 MW	400		722	9,209	433	5,525
7	Transmission Support	2 sec.	5 sec.	10 MW	100 MW	192		1,084	13,813	208	2,646
8	Transmission Congestion Relief	3	6	1 MW	100 MW	31	141	2,889	36,834	248	3,168
9.1	T&D Upgrade Deferral 50th percentile††	3	6	250 kW	5 MW	481	687	386	4,986	226	2,912
9.2	T&D Upgrade Deferral 90th percentile††	3	6	250 kW	2 MW	759	1,079	77	997	71	916
10	Substation On-site Power	8	16	1.5 kW	5 kW	1,800	3,000	20	250	47	600
11	Time-of-use Energy Cost Management	4	6	1 kW	1 MW	1,226		5,038	64,228	6,177	78,743
12	Demand Charge Management	5	11	50 kW	10 MW	582		2,519	32,111	1,466	18,695
13	Electric Service Reliability	5 min.	1	0.2 kW	10 MW	359	978	722	9,209	483	6,154
14	Electric Service Power Quality	10 sec.	1 min.	0.2 kW	10 MW	359	978	722	9,209	483	6,154
15	Renewables Energy Time-shift	3	5	1 kW	500 MW	233	389	2,889	36,834	899	11,455
16	Renewables Capacity Firming	2	4	1 kW	500 MW	709	915	2,889	36,834	2,346	29,909
17.1	Wind Generation Grid Integration, Short Duration	10 sec.	15 min.	0.2 kW	500 MW	500	1,000	181	2,302	135	1,727
17.2	Wind Generation Grid Integration, Long Duration	1	6	0.2 kW	500 MW	100	782	1,445	18,417	637	8,122

*Hours unless indicated otherwise. min. = minutes. sec. = seconds.
**Lifecycle, 10 years, 2.5% escalation, 10.0% discount rate.
†Based on potential (MW, 10 years) times average of low and high benefit ($/kW).
†† Benefit for *one year*. However, storage could be used at more than one location at different times for similar benefits.

5.3 Electric Supply

5.3.1 Electric Energy Time-shift

Electric energy time-shift (time-shift) on principle means of buying energy during low prices like by nights to charge storage and to sell energy (discharge storage) at high price time.

5.3.2 Electric Supply Capacity

Energy storage can defer or reduce the need to install new central station generation capacity or to 'rent' generation capacity from the wholesale market [Source: ESA].

5.4 Ancillary Services

5.4.1 General

In smart grid technology, an ancillary service is anything that supports the transmission of electricity from its generation site to the customer. Services may include load regulation, spinning reserve, non-spinning reserve, replacement reserve and voltage support. In the following picture it is presented a classification of power system stability (Figure 5-8).

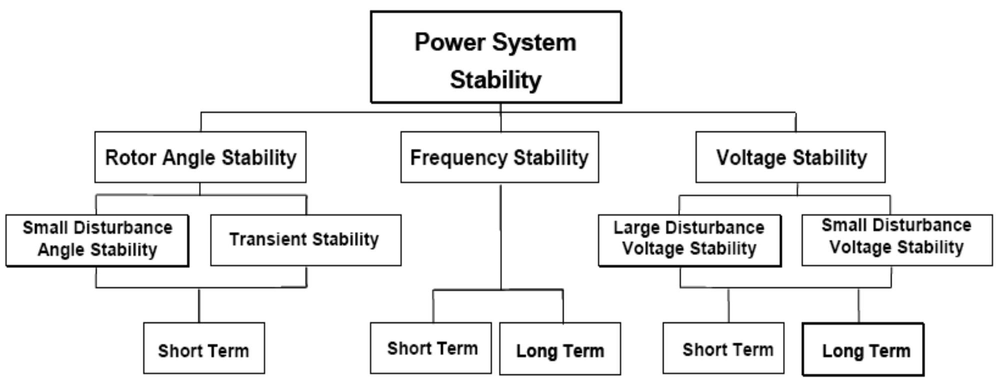


Figure 5-8. Classification of Power System Stability.

Ancillary services will play a critical role in supporting power generation, transmission, and distribution. Frequency stability is an important part of ancillary services. Frequency regulation balances the fluctuations between electricity generation and electrical load and manages the variability in the grid's frequency output. Frequency ranges for European areas are defined General requirements for power generating units by Entso-e working draft 20.10.2010 [16]. In Table 5-2 it is presented frequency ranges and minimum time operation. The fast response requirements that match for the capabilities of advanced Lithium Ion (Li-ion) batteries and flywheels. Other technologies such as pumped hydro, compressed air, and flow batteries will all have a role in providing ancillary services.

Table 5-2. Frequency ranges and minimum time operation.

Synchronous Area	Frequency Range	Time period per event
Continental Europe	46.5 Hz – 47.5 Hz	10 sec
	47.5 Hz – 48.0 Hz	10 min
	48.0 Hz – 51.5 Hz	Unlimited
	51.5 Hz – 53.0 Hz	10 sec
Nordic	47.5 Hz – 49.0 Hz	30 min
	49.0 Hz – 51.0 Hz	Unlimited
	51.0 Hz – 52.0 Hz	30 min
	52.0 Hz – 52.5 Hz	3 min
Great Britain	47.0 Hz – 47.5 Hz	20 sec
	47.5 Hz – 48.5 Hz	90 min
	48.5 Hz – 51.0 Hz	Unlimited
	51.0 Hz – 51.5 Hz	90 min
	51.5 Hz – 52.0 Hz	15 min
Ireland	47.0 Hz – 47.5 Hz	5 min
	47.5 Hz – 49.5 Hz	60 min
	49.5 Hz – 50.5 Hz	Unlimited
	50.5 Hz – 52.0 Hz	60 min
Baltic	not available yet	not available yet

A study on "Energy Storage Systems for Ancillary Services" by Pike Research provides a detailed analysis on the opportunities for ESS-based ancillary services in the global market. One key area within the ESS market is the Ancillary Services sector, which comprises applications such as frequency regulation, spinning reserve, voltage control, and other fast response storage services. According to a new report from Pike Research, global investment in ancillary services systems for electric power will grow from $227 million in 2010 to $6.6 billion by 2019. Biggest growing storage system is Li-ion batteries for ancillary services and flywheels have an opportunity in frequency regulation. [15]

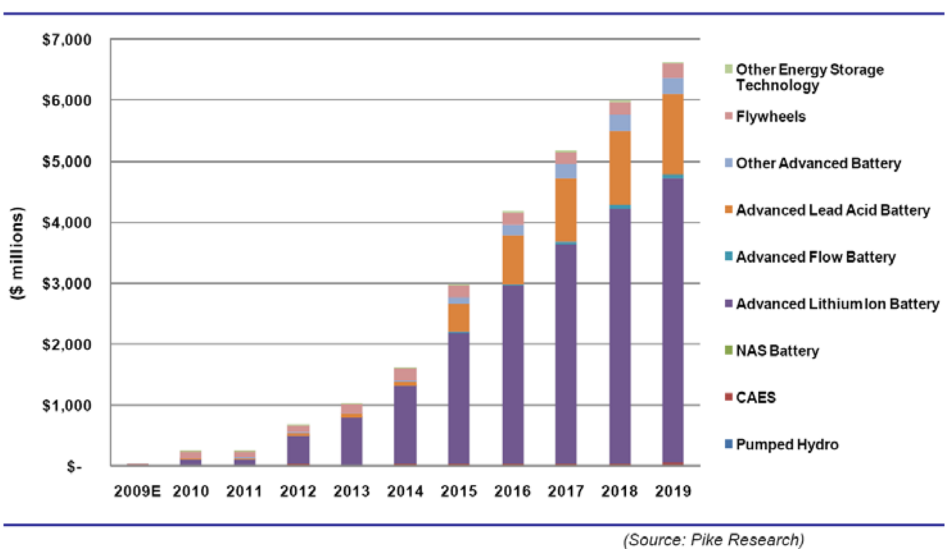


Figure 5-9. Ancillary services installed system revenue by energy storage technology. World markets: 2009–2019 [15].

5.4.2 Load Following

Load following and load regulation address the temporal variations in load. Load following and load regulation differ each other in tome period over which load fluctuation occurs. Load following responds to slower changes (5–30 minutes) when load regulation timescale is faster (on the order of one minute) [8]. Normally load following action is done with generators that increase output according to the load increase and normally works on lower level than design or rated output. At part load operating is not optimal for generators and may increase fuel consumption and emissions. In distribution network load changes are typical e.g. in community areas where energy consumption increases in the morning and late afternoon. Also specific industrial customers can have either slowly or rapidly fluctuating loads. Load buffering function is suits well for energy storages and especially in local distribution networks and for those storages that can work with partial output levels such as lithium-ion batteries. To be optimal the storage systems must be sized (oversized) properly to be able to charge during low load (and low price) and discharge during high load spikes.

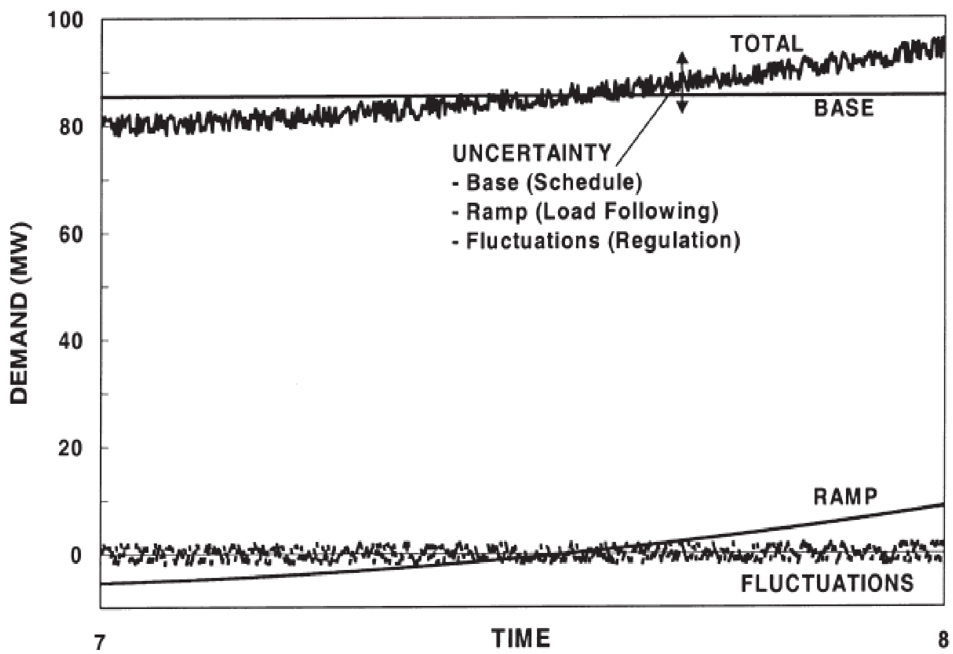


Figure 5-10. Theoretical differences between load regulation and load following functions [8].

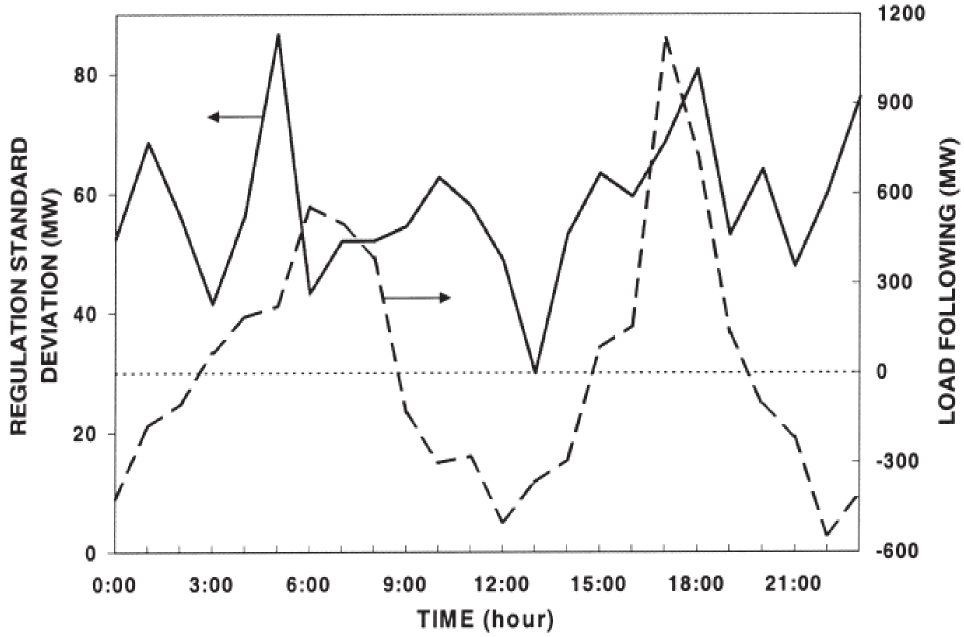


Figure 5-11. Hourly load-following and regulation requirements for a utility during a winter weekday [8].

5.4.3 Area Regulation

Energy storages can maintain a state of frequency equilibrium for the system's 50 Hz (cycles per second) during regular and irregular grid conditions. Large and rapid changes in the electrical load of a system can damage the generator and customers' electrical equipment.

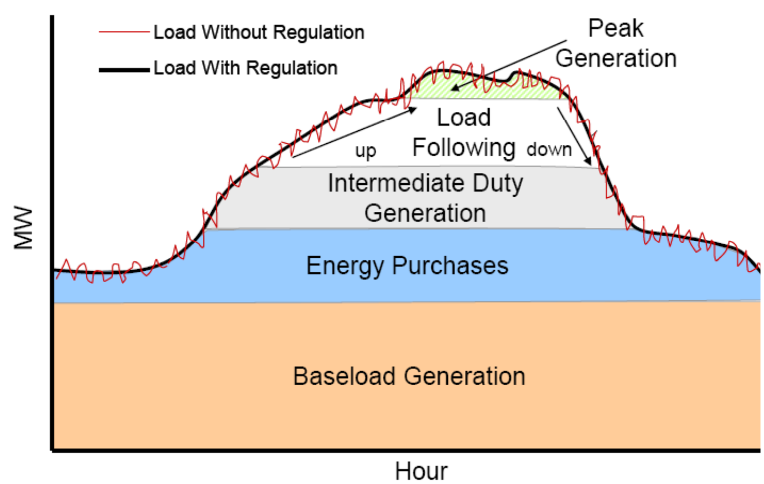


Figure 5-12. Load regulation [8].

Frequency regulation requirements are increasing mainly because of large penetration of wind power e.g. in USA from current 1.0% to 2.0% in ten years according to Pike Research forecast (Figure 5-13).

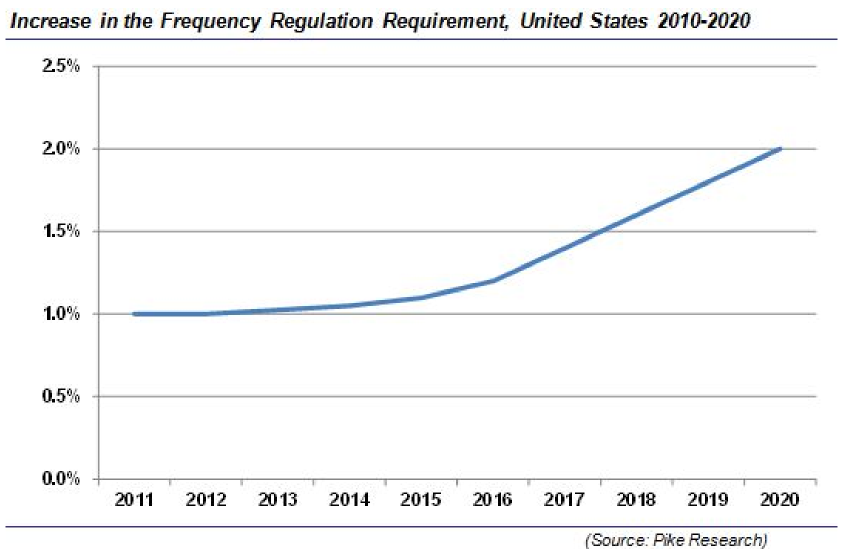


Figure 5-13. The increase of frequency regulation requirement in USA [Source: Pike Research].

Fast energy storages with high cyclic capacity are one effective solution for regulation (Figure 5-17 and Figure 5-14).

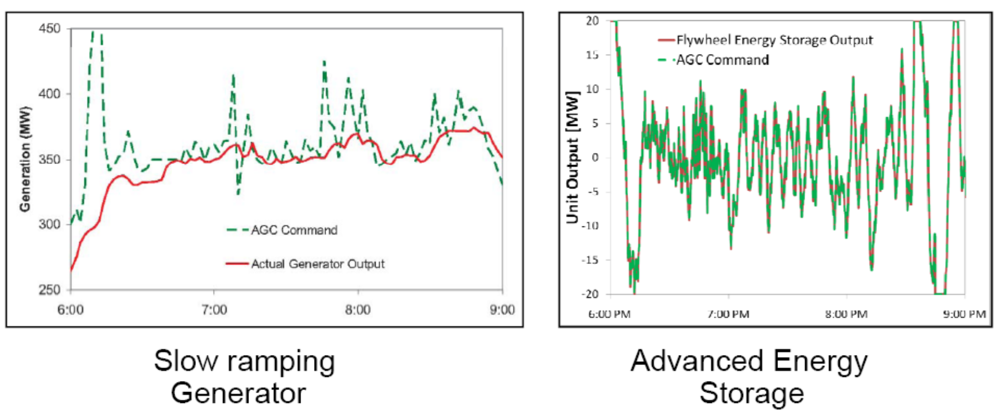


Figure 5-14. Generator vs. energy storage (flywheel) as regulation provider [55].

In the following figure (Figure 5-15) it is compared effectiveness of regulation resources. According to KEMA studies “A 30 to 50 MW storage device is as effective or more effective as a 100 MW combustion turbine used for regulation purposes.” [11]

Based on ISO-NE empirical study results, 1 MW of regulation capacity from a generator produces 10 MW of “regulation service”. Empirical data from Beacon flywheels in the pilot show 1 MW of fast-response flywheel storage produces 20–30 MW of regulation service. [55]

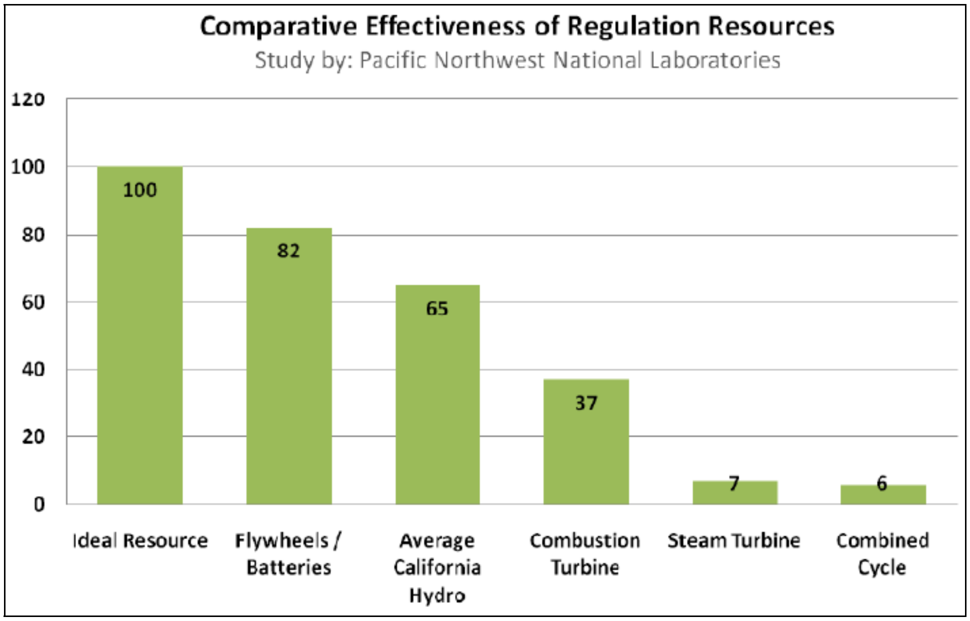


Figure 5-15. Comparative effectiveness of regulation resources [10].

Energy storage system can reduce CO_2 emissions compared to other technologies (Figure 5-16).

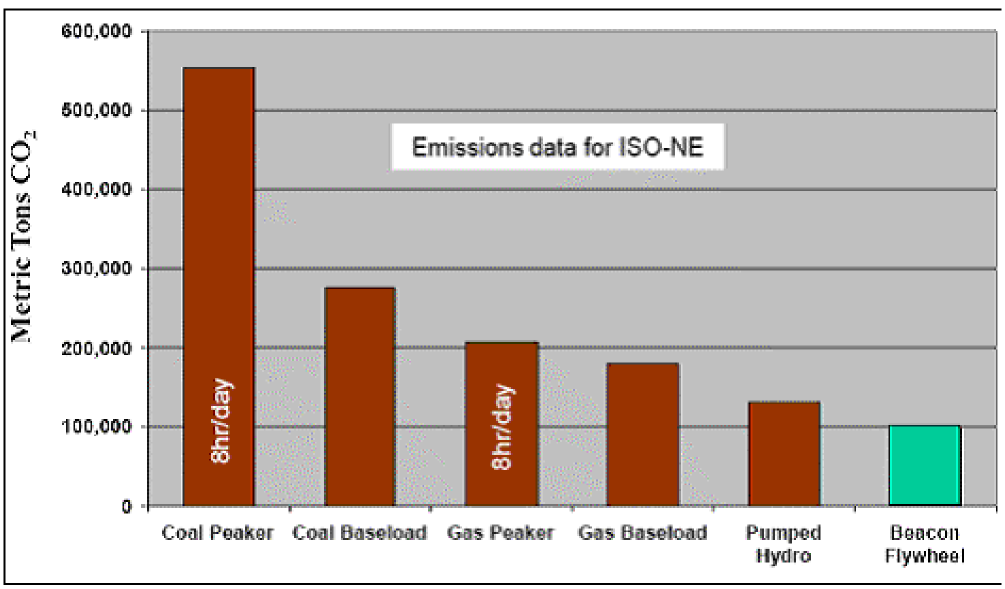
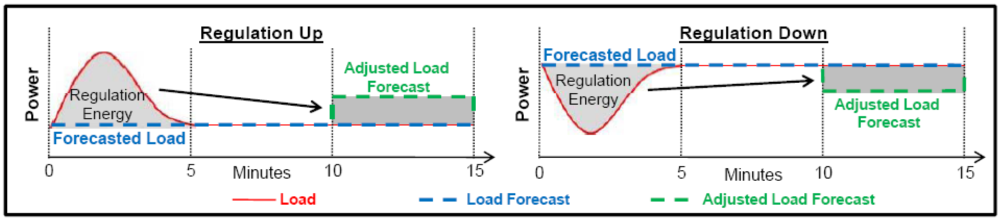


Figure 5-16. CO2 emissions with different regulation systems [12].

New York ISO is utilizing 5-minute energy market that allows 15-minute energy storage to manage its energy. Utilizing a 5-minute correction (purchase or sale of energy) dramatically reduces the amount of energy storage capacity required to provide regulation. Fast response storage instantaneously responds to imbalance; energy used to restore storage to its preferred state-of-charge can be economically scheduled (Figure 5-17). Energy management results in sending the right energy market price signal.



	Interval 1	Interval 2	Interval 3
Regulation Up	Storage injects energy	If storage nearing empty, ISO schedules storage to "charge" and adjusts Interval 3 load forecast	ISO procures the energy necessary to meet new forecast in energy market on most economic resource
Regulation Down	Storage withdraws energy	If storage filling up, ISO schedules storage to "discharge" in interval 3	Storage injects recycled energy as price taker, displacing deployment on marginal unit in energy market

Figure 5-17. NYISO/MISO Energy management – smart energy following in 15 minutes periods [55].

European transmission grid 42 European TSO (Transmission System Operator) companies founded in 2008 a new organization European Network of Transmission System Operators for Electricity (ENTSO-E). ENTSO-E association incorporates the European Transmission System Operators association (ETSO) and the five TSO organisations: UCTE, NORDEL, UKTSOA, BALTSO and ATSOI. ENTSO-E launched Requirements for Grid Connection Applicable to all Generators Working Draft (20.10.2010). [13]

In the following picture (Figure 5-18) it is presented ENTSO-e secondary control requirements and shown flywheel energy storage system ability to fulfil them.

Secondary Control Requirements	Beacon Smart Energy Matrix Capability
Secondary controller must be of proportional-integral (PI) type (closed-loop feedback)	Yes
Controller cycle time between 1 to 5 seconds	Less than 4 seconds
In the case of malfunction of automatic secondary control, manual control must be possible	Yes, manual control possible
No minimum duration for the capability of delivery for secondary control	Continuous frequency regulation with managed state of charge
Deployment ○ Activated within 30 seconds of incident ○ 100% deployment must be achieved within 15 minutes of incident	Deployment ○ 100% in less than 4 seconds

Figure 5-18. Flywheel storage system capability to fulfil ENTSO-e secondary control requirements [Source: Peacon Power].

The first utility-scale battery storage system in the U.S. started in the beginning of 2011. The system is an 8 MW lithium ion battery (Figure 5-19) located in Johnson City, NY. The system is a first part of total 20 MW battery systems. The project, which is operated by AES Energy Storage, is operating simultaneously as a provider of frequency regulation services and load following, as well as customer electricity demand.

Figure 5-19. 8 MW Lithium-ion battery system in Johnson City, N.Y. [Source: AES Energy storage].

Another technology being tested for frequency regulation is flywheels supplied by Beacon Power, which is developing a frequency regulation service in Stephentown, N.Y

5.4.4 Electric Supply Reserve Capacity

There are three generic types (USA) of reserve capacity [8]:

- Spinning Reserve – Generation capacity that is online but unloaded and that can respond within 10 minutes to compensate for generation or transmission outages. 'Frequency responsive' spinning reserve responds within 10 seconds to maintain system frequency. Spinning reserves are the first type used when a shortfall occurs.
- Supplemental Reserve – Generation capacity that may be offline, or that comprises a block of curtailable and/or interruptible loads, and that can be available within 10 minutes. Unlike spinning reserve capacity, supplemental reserve capacity is not synchronized with the grid (frequency). Supplemental reserves are used after all spinning reserves are online.
- Backup Supply – Generation that can pick up load within one hour. Its role is, essentially, a backup for spinning and supplemental reserves. Backup supply may also be used as backup for commercial energy sales.'

Within the inter-Nordic power system, it has been agreed that the Nordel countries maintain continuously a total frequency controlled normal operation reserve of 600 MW for frequency control in a normal state. The joint reserve is shared annually between the countries involved in the inter-Nordic system in proportion to the annual energies used by them. Fingrid's current reserves in 2011 are:

Table 5-3. Fingrid's reserves in 2011 [Source: www.fingrid.fi].

Reserve	Available capacity	Need
Frequency controlled normal operation reserve (50,1-49,9 Hz)	- Annually contracted, power plants 71 MW - Hourly market, power plants 50 MW - Vyborg DC-link 100 MW - Estonia DC-link 50 MW	136 MW *)
Frequency controlled disturbance reserve (49,9-49,5 Hz)	- Annually contracted, power plants 244 MW - Hourly market, power plants 298 MW - Disconnectable loads 40 MW	220-240 MW **)
Fast disturbance reserve (manually activated)	- Fingrid's own gas turbines 615 MW - Contracted capacity, gas turbines 203 MW - Disconnectable loads 395 MW	880 MW ***)

*) In the Nordic system total 600 MW, which is divided between the Nordic countries annually in proportion to the annual consumption.
**) The volume corresponding the largest dimensioning fault in the Nordic system is divided between the Nordic countries weekly in proportion to the dimensioning faults.
***) Volume corresponding to a dimensioning fault.

The U.S. Department of Energy (DOE) estimates that for every gigawatt (GW) of wind capacity added, for example, 17 megawatts (MW) of spinning reserves must also be built to account for the system's variability.

Some energy storage systems can be used as a spinning reserve. Because storage system must be available to discharge when needed the self-discharge should be very low to avoid extra cost for charging. Typical discharge time is couple hours. Storage systems like new type of lithium-ion batteries as well as NaS batteries can work by partial loads when their cyclic lifetime is remarkable higher with partial cyclic functions. Redox-flow batteries have very small or non-existing self-discharge and enough response-time to be suitable for reserve capacity.

As an example of the energy storage installations for spinning reserve A123 officialized in February 2011 a 20 megawatt project from Chile's AES Energy Storage. This is an expansion to in 2009 started a 12 MW spinning reserve project. That was the first energy storage system deployed in Chile.

Figure 5-20. 20 MW Lithium-ion battery system for spinning reserve in Chile [Source: A123 systems].

5.4.5 Voltage Support

Voltage support is typically maintained by generators providing reactive power that offsets reactance in the grid. Voltage support can be done also by energy storages (Figure 5-21) that are necessary in the islanded grid where are no generators as power source. For example the reactance from motors can pose a significant voltage-related challenge because the starting motors draw high currents. Storage system used for voltage support system must be available in few seconds and should be able to discharge from few minutes to an hour. Some battery systems like lithium-ion batteries have these features. Also capacitor–battery hybrid system can be used. Then the capacitor provides power during first seconds and after that battery system starts to discharge. In this hybrid case same battery systems can partly be also for regulation services in other case not. Also flywheel systems have been used for local voltage support purposes.

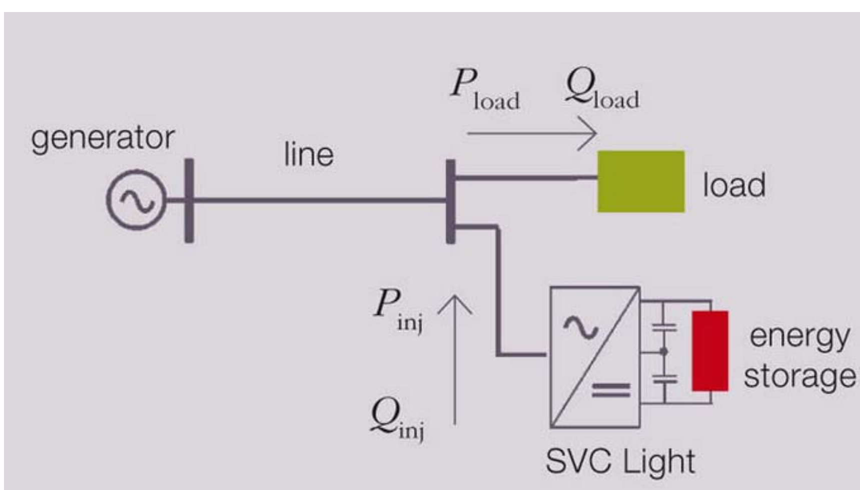


Figure 5-21. SVC with energy storages, basic scheme [Source: ABB].

The need for reactive power support is continuously increasing. In the following picture (Figure 5-22) is presented the growth rate of installed Static Var Compensators until 2020.

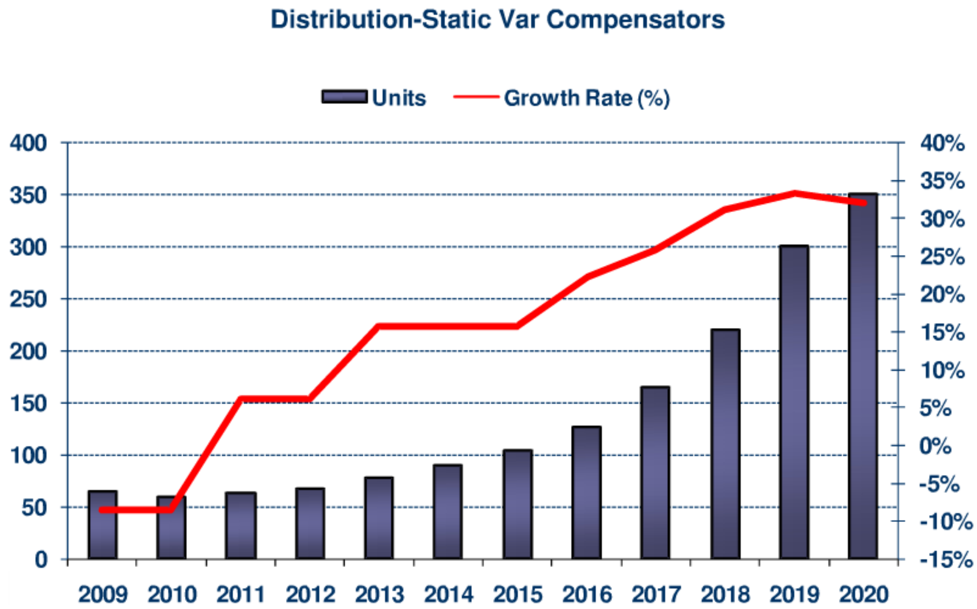


Figure 5-22. Growth rate of static VAR compensators [Source: Frost & Sullivan].

5.5 Grid System

5.5.1 Transmission Support

The goal of the transmission support is more stable T&D performance including compensating for voltage sags, unstable voltage and sub-synchronous resonance. Energy storages can reduce voltage dips and the need of load shedding. Energy storage system can provide both real and reactive power.

The most used energy storage system for transmission support is pumped hydroelectrical storage. Since the 1920s, pumped-storage hydroelectric plants have provided valuable storage capacity, transmission grid ancillary benefits, and renewable energy in the U.S. and Europe. Today, the 40 pumped-storage projects operating in the U.S. provide more than 20 000 MW, or nearly 2 percent, of our nation's energy capacity. Pumped-storage plants account for about 16 percent of renewable capacity in the U.S. PHS plant provide stability services. The hydro industry proposes to more than double the pumped storage capacity in the near future.

Denmark is depended on the interconnections with Germany and Norway for grid stabilizing services. And these two countries are rich in pumped storage and conventional hydro, respectively. [52]

5.5.2 Transmission Congestion Relief

Transmission congestion appears when it is limitations to transfer desired amount of power across a transmission interface. Energy storages can used to avoid congestion-related costs and charges e.g. cost of building new transmission lines. Energy storages e.g. with FACTS / Flexible AC Transmission System) can be charged when there is no transmission congestion and discharged during peak periods.

The philosophy behind corrective control applied to FACTS is similar as in Figure 5-23. After clearance of network fault follows typical first swing stability, power oscillation damping (POD), voltage stability/recovery and frequency control. After 10 to 20 seconds starts post-disturbance phase and slower actions like thermal limitations, voltage support (to avoid slow voltage collapse) and frequency support are needed. [17]

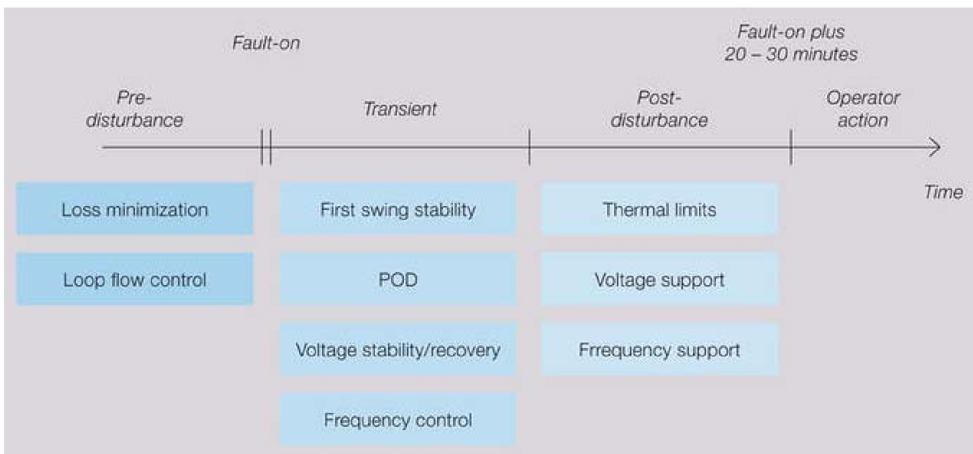


Figure 5-23. The philosophy behind corrective control [17].

5.5.3 Upgrade Deferral

Energy storage system can be used at locations where T&D assets are at the limits of their capability, and where future expansion is not clearly viable. In such cases, storage system can cover peak loads while alternative power supplies are developed if necessary.

The case example presents 5 years forecast of an utility load. The utility load carrying capacity is 12 MW and the first year peak demand (that goes over 12 MW with 63 kW) will be covered by150 kW energy storage that the utility can defer the upgrade. [53]

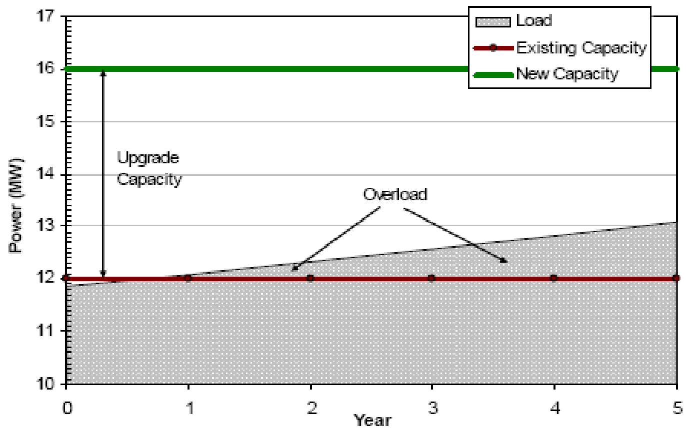


Figure 5-24. An example of the upgrade deferral [53].

An example of this type of energy storage use is a San Francisco project where Pacific Gas and Electric Co have four 500 kWh transportable Zn-Br BESS modules with a total capacity of 2 MW output and 2 MWh capacity.

Figure 5-25. 500 kWh transportable Zn-Br storage system [Source: ESA/ZBB].

5.5.4 Substation On-Site Power

Energy storages provide power to switching components and to substation communication and control equipment when the grid is not energized. An emerging need in this application is the ability to serve the on-site DC load.

The duty cycle imposed on switchgear batteries usually consists of momentary high ampere loading during charging of the respective tripping or closing springs, in addition to the small continuous load of powering protective relays and lights.

There are at least 100 000 battery storage systems at utility substations in the U.S. They provide power to switching components and to substation communication and control equipment when the grid is not energized. The vast majority of these systems use lead-acid batteries, mostly vented and to a lesser extent valve-regulated, with 5% of systems being powered by NiCd batteries. [2]

IEEE Standard 485, which addresses sizing of battery systems for substation DC loads, groups substation DC loads into three categories: 1) continuous loads, 2) non-continuous loads, and 3) momentary loads. Based on results from a survey of systems, locations serving voltages of about 69 kV are rated at 1.6 kVA; locations serving the grid at 69 kV to 169 kV have storage rated at about 2.9 kVA; and substations serving the grid at voltages exceeding 169 kV have storage systems rated at 8.5 kVA. The standard value assumed is 2.5 kW. The standard discharge duration is assumed to range from 8 to 16 hours. [2]

If it is very roughly calculated approximated energy storage capacity in Finnish substations according to the figures mentioned above, we have at least 100 substations in transmission grid (of which 57 in 400 kV grid) and 740 substations in distribution grid [51] meaning around 1.8 MVA and 14.3 MWh energy storage capacity installed in the substations. Most of this could be assumed to be covered either by lead acid batteries or by nickel batteries.

5.6 End User/Utility Customer

5.6.1 Utility Benefits vs. End-User Benefits

Energy storage benefits for utilities can be same time benefits for utility customer-AEP (American Electric Power) has defined benefits as [58]

- Strategic benefits
- Service benefits and
- Market Benefits.

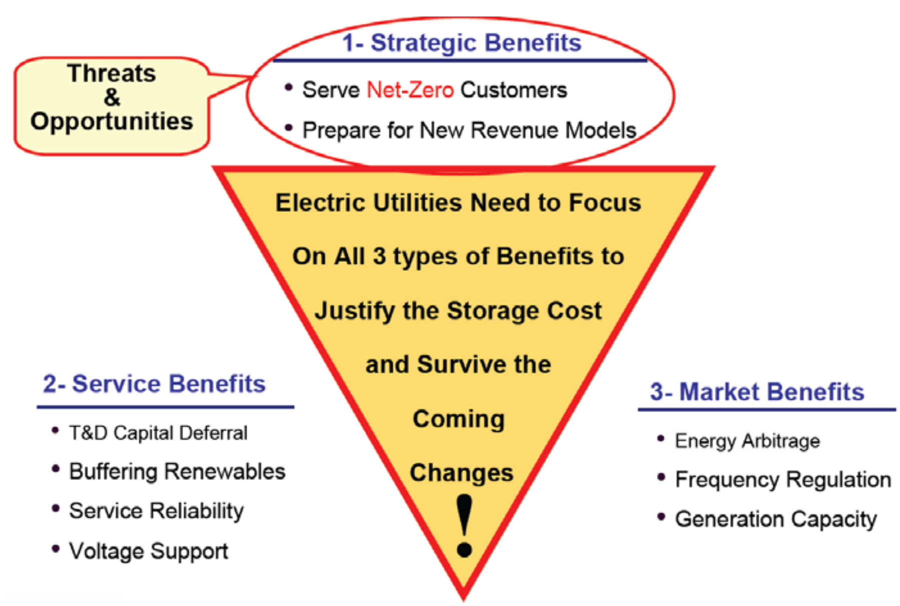


Figure 5-26. Utility benefits of energy storage [58].

Migratory Path of Utility Energy Storage starts from large central unit and ends to the community energy storages at grid edge.

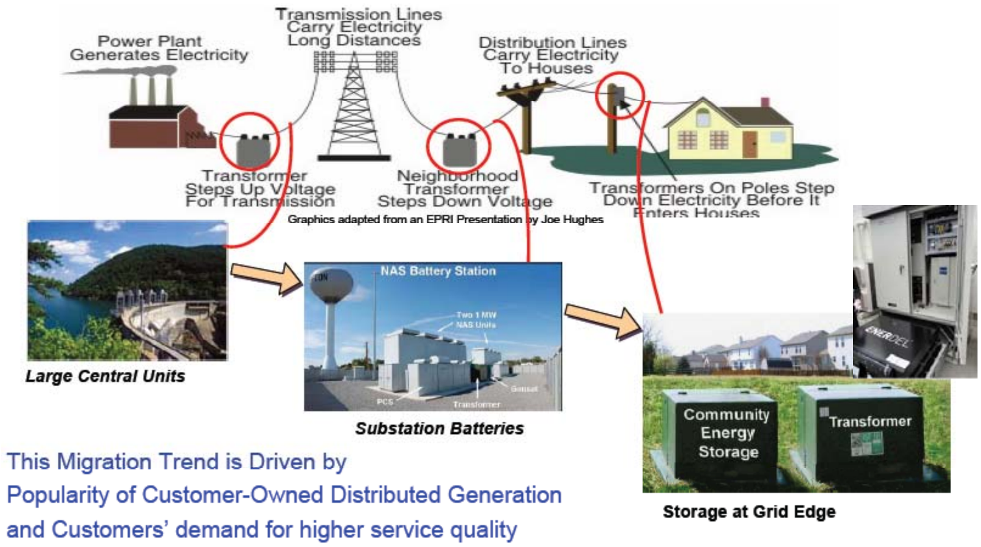


Figure 5-27. Migratory path of utility energy storage [58].

AEP see highest energy storage value in the community energy storages (CES) (Figure 5-28). CES is seen a small-distributed energy storage unit connected to the secondary of transformers serving a few houses or small commercial loads (Figure 5-29). CES can perform local benefits as backup power, voltage correction and renewable integration and grid benefits as load levelling at substation level, power factor correction and ancillary services. [58]

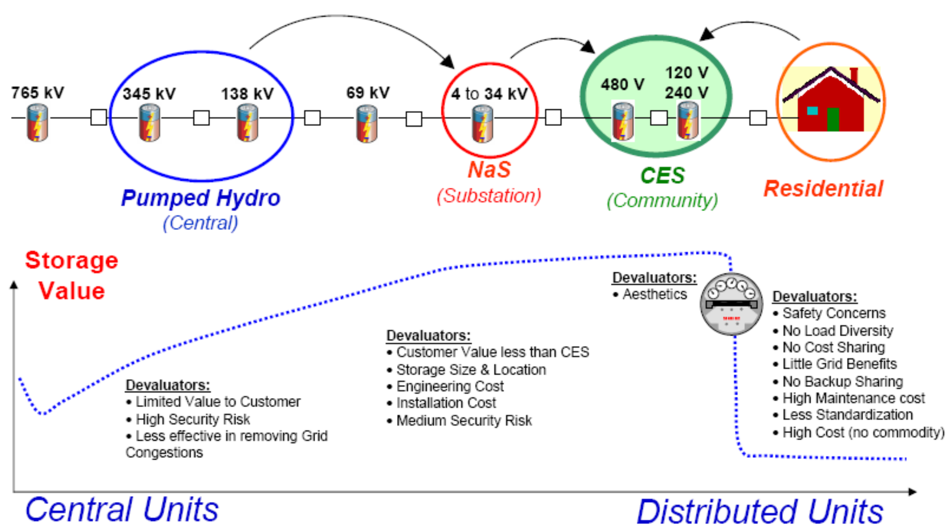


Figure 5-28. AEP's view of energy storage value [58].

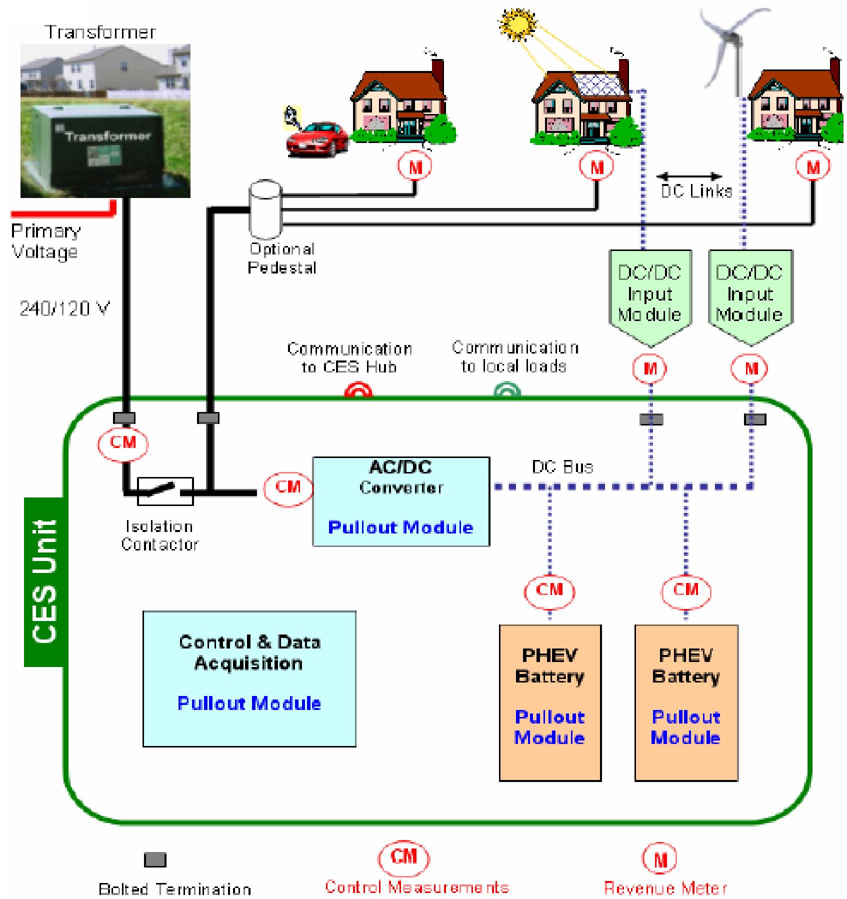


Figure 5-29. Community energy storage (CES) layout [58].

CES batteries would have benefits in Finnish communities especially in communities with high PV penetration or in communities in the end of a long open-wire distribution line.

5.6.2 Time-of-use (TOU) Energy Cost Management (to Shift High Peak Usage to Low Cost Time)

For time-of-use cost management energy storages are used to reduce overall energy cost by charging energy storage during low price hours and discharging during high price hours.

Now as hourly metering is introduced, also hourly energy pricing can be implemented. Consumer can save money if some loads can be shifted to cheaper time period. Use of some appliances like washing machines can be shifted to nighttime with simple timers, but computers, TV and many others are not convenient to be shifted around the clock. Energy storages enable consumer to use cheaper energy during the day when energy storages are charged from the grid during cheaper time periods. In most cases energy price differences do not cover storage costs. Figure 5-30 displays energy price in 9th of January in 2010 in Nord Pool Spot electricity market.

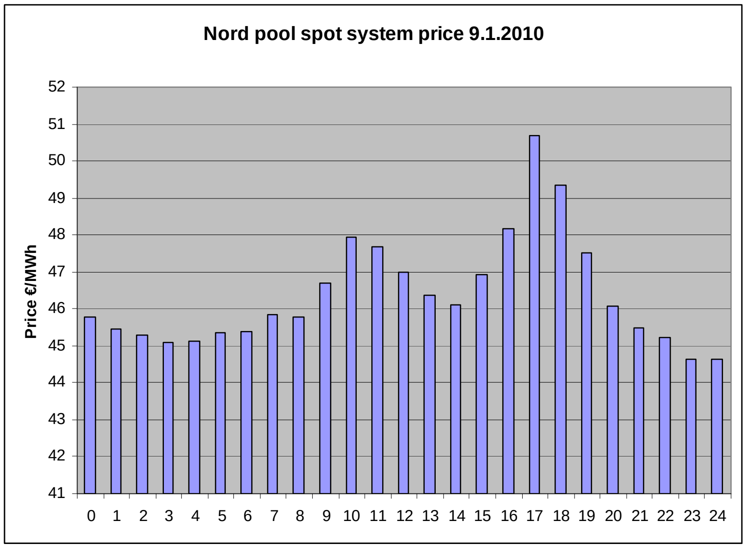


Figure 5-30. Nord pool spot system price in 9.1.2010.

When data from the previous figure is converted to €/kWh and transmission costs of 0.0307 €/kWh and taxes of 0.01703 €/kWh and VAT of 23% are added, hourly price differences are smaller [1]. This is presented in Figure 5-31 together with energy storage charge cost if 80% cycle efficiency is assumed.

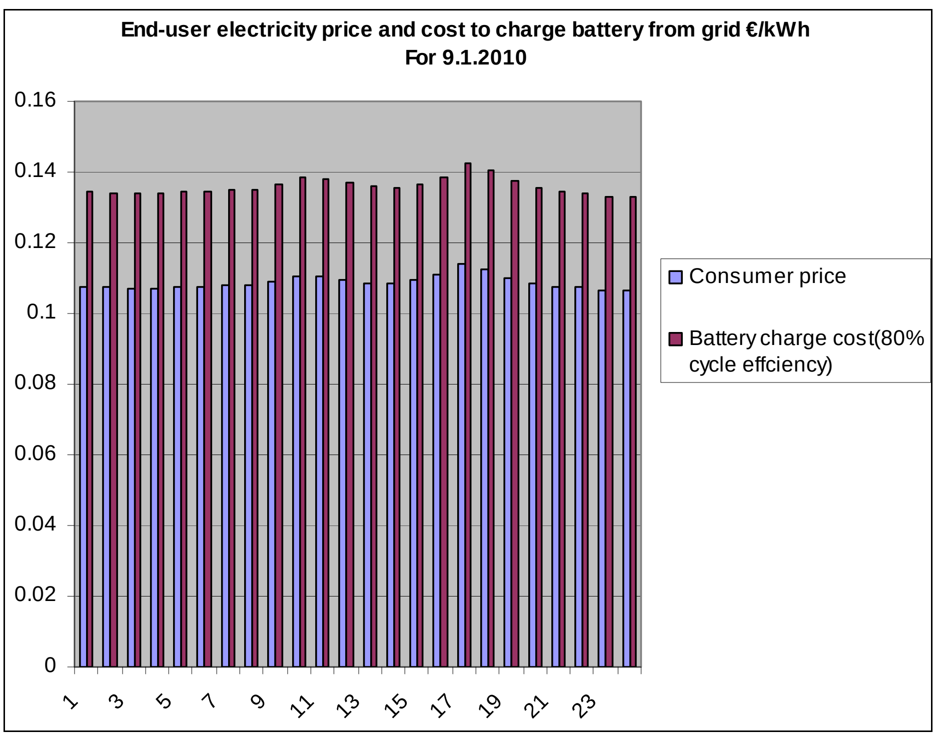


Figure 5-31. End-user electricity price and cost to charge battery from grid c/kWh.

It can be seen in the figure that use of energy storage device in this time period is not economical, because there is not a single hour when charge costs of the storage are cheaper that any single hour of grid supply. Calculated rule for minimum price difference is,

$$\frac{(\text{lower spot price} + \text{electricity tax}) \cdot \text{VAT} + \text{transmission costs with VAT}}{\text{storage efficiency}}$$

$$\leq$$

$$(\text{higher spot price} + \text{electricity tax}) \cdot \text{VAT} + \text{transmission costs with VAT}$$

If pricing presented in [1] and storage cycle efficiency of 80% is used, following simplification can be calculated from the rule:

$$\text{higher spot price} \geq 1.25 \cdot \text{lower spot price} + 1.046\ \text{c / kWh}$$

Table 5-4 presents how high the peak hour price has to be at least to make storage system making profit daily.

Table 5-4. Price difference requirements in different price levels.

Spot price of lower time period c/kWh	Required price of higher time period c/kWh	Difference as percentage
4.5	6.67098	48.244
6	8.54598	42.433
7	9.79598	39.9425
10	13.54598	35.4598
15	19.79598	31.9732
20	26.04598	30.2299

In 2010, there was 153 days when it would have been cheaper to charge energy storage at cheapest time of day to spare on electricity costs later, when system price of Nord Pool Spot system price and same transmission costs and taxes as in figure 7.2 are used. Following calculation presents an approximation of savings that could have been achieved during 2010 in TOU-management of energy storage system.

Approximation of yearly savings using 2010 price data:

Detached House

Peak hour time as defined by Nord Pool Spot 8 am to 8 pm: 12 h
Average demand during high priced hours: 0.7 kW
Average consumer price in cheapest hour of those days was 11.82 c/kWh
Average consumer price during peak hours was 12.46 c/kWh
Approximated savings: 8.22 €/year which is negligible compared to costs of storage system.

Apartment House

Peak hour time as defined by Nord Pool Spot 8 am to 8 pm: 12 h
Average demand during high priced hours: 0.4 kW
Average consumer price in cheapest hour of those 153 days: 11.82 c/kWh
Average consumer price during peak hours: 12.46 c/kWh
Approximated savings: 4.7 €/year which is negligible compared to costs of storage system.

Other question is, whether it is economical to have hourly pricing for consumer. In theory, hourly pricing should result in savings on average, because fixed prices should include risk-based addition over market prices. Problem is however that fixed monthly fees in markets based pricing products can be large. Also if house uses electricity for heating using straight radiator heating or heat pumps, most of the power is consumed in wintertime when electricity is more expensive. Straight radiator heating and heat pumps are more common detached houses than in apartment houses, which are mostly connected to district heating systems. Electricity consumption increases also in wintertime because it is darker and people tend to spend more time indoors. As a conclusion TOU-management seems not to be profitable in due to small approximated yearly savings and fixed fees of pricing included in hourly market based energy products.

5.6.3 Demand Charge Management

Demand charge is the power and energy based costs that grid operator charges from new connections and monthly fee from existing connections. Examples of power and energy based pricing are presented in following tables 5-5–5-6 [18].

Table 5-5. New connections [18].

Main fuse	**Zone 1**	**Zone2**	**Zone 3**
3 X 25 A	1 059 €	1 589 €	2 119 €
3 X 35 A	1 377 €	2 065 €	2 754 €
3 X 50 A	1 854 €	2 780 €	*
3 X 63 A	2 267 €	*	*
3 X 80 A	2 807 €	*	*

¨*Case-specific pricing

Larger new: 265 € + 31,77 € x A

Table 5-6. Existing connections (transmission costs) [18].

Main fuse		
1x16 A...35 A		3.31 €/month
3x16 A...25 A		5.59 €/month
3x35 A		8.27 €/month
3x50 A...63 A		13.24 €/month
3x80 A...100 A	25.65 €/month	
3x125 A...160 A	41.37 €/month	
3x200 A		70.75 €/month

Energy based transmission cost 0.03 €/kWh

Example of Reducing Demand Charge with Energy Storage System

The smallest connection size offered by the first table is 3 x 25A, which means 17.250 kW peak consumption. 17.25 kW is quite large power limit and usually small house does not need any more capacity and this leads to no possibilities to reduce demand charge by lowering connection size. Let's take an example where connection has to selected to 3 x 35A, which equals 24.15 kW because rare use of pressure washer together with some other large loads which would compromise the 25A fuse on one phase. As an alternative pressure washer is driven with battery which last about half an hour; duration washing car etc.

Following list presents the case details:

- Time: 15 years
- Imputed rate of interest: 4%
- Connection cost savings: 1 377 € – 1 059 € = 318 €
- Monthly savings = 8.27 € – 5.59 € = 2.68 € which makes 31.16 €/year
- Needed additional power capacity on one phase: 3 kW (power of pressure washer)
- Energy capacity = 1.5 kWh (washing with pressure washer takes about 0.5 hours)
- Inverter price: 385 € [19]
- Battery system with 160Ah capacity = 259 € [20]
- Battery charger price = 30 € [21]
- Charger + battery + inverter with usual discount of 5% = 640 €

Total savings for using smaller connection for 15 years calculated with net present value method [22] is 675.5 €. Battery system costs were lower at 640 €. There are some more costs from efficiency loss in charger and inverter, but these are more or less cancelled by cheaper power price for charging battery at night. System can also have some resell value from inverter and battery. Savings of 35 € are clearly not worth the trouble in this example but additional benefit could be found e.g. using battery supply backup power during blackouts. Also the benefit will be larger if we can skip many fuse sizes with the energy storage system.

Energy storage as way to use high power machines in small connections
Use of energy storage in demand charge management can be also seen as a way to use high power devices that would be impossible with lower main fuse without energy storage system. One example of this kind of appliance is a wood cutting device with induction motor. Each log causes induction motor to draw a high current, which causes voltage to sag momentarily. Also every client connection has a power limit, which can make use of some devices impossible. Energy storage can offer a solution to these problems by balancing the load from the device.

Energy Storages Enabling Technology to Live Off the Grid

Off grid living means that house is not connected to power grid and all power is generated locally. These small independent electric systems are called microgrids. Microgrids need own power generation, energy management system and usually energy storages. Usually power in microgrid is generated by unpredictable renewable power sources like PV-cells and wind power. For this reason, an energy storage system is needed to balance out the periods of low wind speed and natural cycle of sun irradiation. Example of small microgrid system for a house is presented in Figure 5-32 [24]

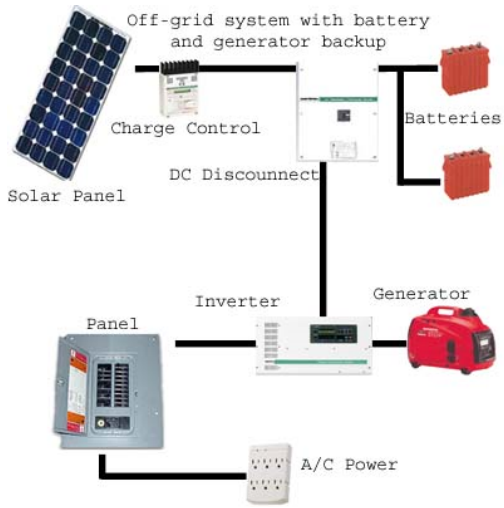


Figure 5-32. Example of small microgrid system [24].

5.6.4 Electric Service Reliability

Energy storage system can provide energy to ride through outages of extended duration and decrease on-site generators start-ups.

Summer 2010 was very harsh on the power lines in Finland when power lines were cut by storms all around the country. Energy storages help to ease the problems caused interruptions by supplying energy to critical loads when line power is down. Following Table 5-7 presents interruption cost estimation for Finland given in [23]. Table 5-8 presents same values with yearly average inflation correction of 1.7% to year 2011.

Table 5-7. Interruption costs to different sectors (2005) [23].

	Unexpected		**Planned**		**Fast reclosing**	**Timed reclosing**
Sector	€/kW	€/kWh	€/kW	€/kWh	€/kW	€/kW
Residential	0.36	4.29	0.19	2.21	0.11	0.48
Agricultural	0.45	9.38	0.23	4.8	0.2	0.62
Industrial	3.52	24.45	1.38	11.47	2.19	2.87
Public	1.89	15.08	1.33	7.35	1.49	2.34
Service	2.65	29.89	0.22	22.82	1.31	2.44

Table 5-8. Interruptions costs from [23] with inflation correction to year 2011 (1.7%/a avg.).

	Unexpected		**Planned**		**Fast reclosing**	**Timed reclosing**
Sector	€/kW	€/kWh	€/kW	€/kWh	€/kW	€/kW
Residential	0.405088	4.827296	0.213796	2.486789	0.123777	0.540117
Agricultural	0.50636	10.55479	0.258806	5.401171	0.225049	0.697651
Industrial	3.960859	27.51221	1.552837	12.90655	2.464284	3.22945
Public	2.126711	16.96868	1.496574	8.270543	1.676613	2.633071
Service	2.981896	33.63354	0.247554	25.67807	1.47407	2.745595

Tables give rough estimates for interruption costs and actual costs should be calculated case by case to make right decisions on backup power investments. If interruptions last long time, energy storages should be switched to generators because to cover long interruptions with energy storage systems is expensive in most cases. A one household application of energy storage could be run refrigerator trough an UPS device so that food won't go bad even if power is down. Value of the food inside refrigerator can be high if all the costs from collecting berries and game hunting etc. are added, and can make UPS price seem to be fairly small in comparison.

5.6.5 Electric Service Power Quality

Energy storages can be used to control voltage and frequency, improve power factor, decrease harmonics and interruptions.

Power quality (PQ) describes how well electricity fulfils the quality standard EN 50160. Power quality standard is needed so that devices will work properly and users do not experience problems like light flicker caused by fluctuating voltage level.

Standard sets limits on:

- Voltage frequency
- Voltage level
- Voltage deviations
- Quick voltage deviations: Magnitude, flicker index
- Voltage dips
- Short interruptions
- Long interruptions
- Temporary over voltages between conductor and ground at base frequency 50 Hz)
- Transient over voltages between conductor and ground
- Voltage asymmetry
- Harmonic voltage amplitudes
- Unharmonic voltage amplitudes
- Grid signal voltages (if electric lines are used for data transmission).

As there are also limits for interruptions, EN 50160 also defines requirements for reliability. It is quite rare for household customers to experience and notice problems with electric quality other than interruptions in service, but it can happen. Flicker is most noticeable human eye can detect fluctuations in voltages with lighting going brighter and dimmer. Flicker is more common in weak grid conditions like rural areas, where use of large machinery is a usual cause. Machines can be heat pumps, log cutters, and all other sort of power tools. Other reason to cause flicker is fluctuating power generation which can be e.g. a wind turbine in gusty wind. [25], [26]

Power quality is however a major issue for European industry with estimated 150 billion € losses per year estimated by a survey done in 2007 [27]. Figure 5-33 represents some of the results revealed by the survey.

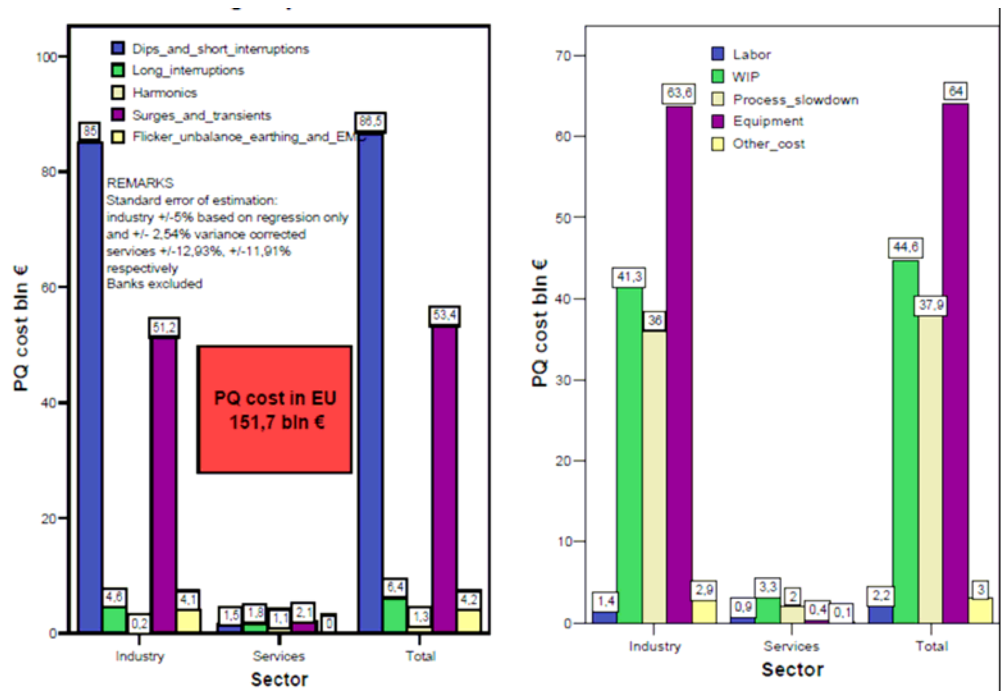


Figure 5-33. Results of power quality survey done in 2007 [27].

Poor power quality can cause process slow down, additional labour costs, equipment break down and wear, process resetting, energy loss, quality problems in finished products, and possible costs in fees and penalties. Survey reveals that most of the monetary PQ losses are a result of voltage dips and short interruptions. Other major factor is power surges and transients. [27]

Use of energy storages together with harmonic filtering can ease the problems with power quality. Survey revealed the potential of energy storages to solve these problems because most of the monetary losses resulted from short voltage sags and interruptions. Also active harmonic filtering capability can be integrated to energy storage inverter control so that additional active compensators are not needed.

One way is to use energy storage is set it to guard the voltage quality in parallel to normal electricity supply. In interruption or voltage quality problem, the storage system would start to operate and control power quality by adjusting reactive and active power supply or intake of the storage. Storage has to be fairly quick so that it can pick up before there is a problem caused by poor PQ. Other way is to drive the whole process through an energy storage device always in series. This results in much faster response time and can also supply process specific power (voltage and frequency are not needed to be standard). Figure 5-34 displays the connection of energy storage using series and parallel connection.

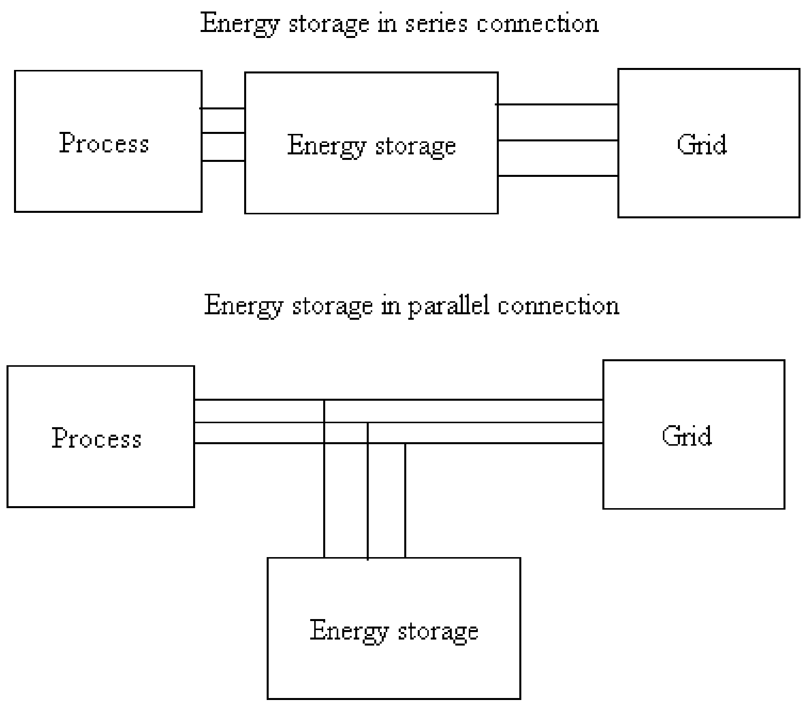


Figure 5-34. Series and parallel connection of energy storage to industrial process.

Series connection can reduce overall electrical efficiency of the system and be more expensive because power electronic costs are bit higher because system needs a frequency converter opposed to possibly just an inverter in parallel connection. Series connection however can be more efficient to filter out harmonic disturbance from the voltages. Usually harmonic filtering is done by separate filters installed to power lines.

5.7 Renewables Integration

5.7.1 General

Renewable energy based energy production is fast increasing. According to Frost & Sullivan growth rate of wind power is 15.2% and other renewables 7.7% until 2020 compared to the growth rate of other fuels e.g. gas 2.4% and nuclear 1.8% (Figure 5-35).

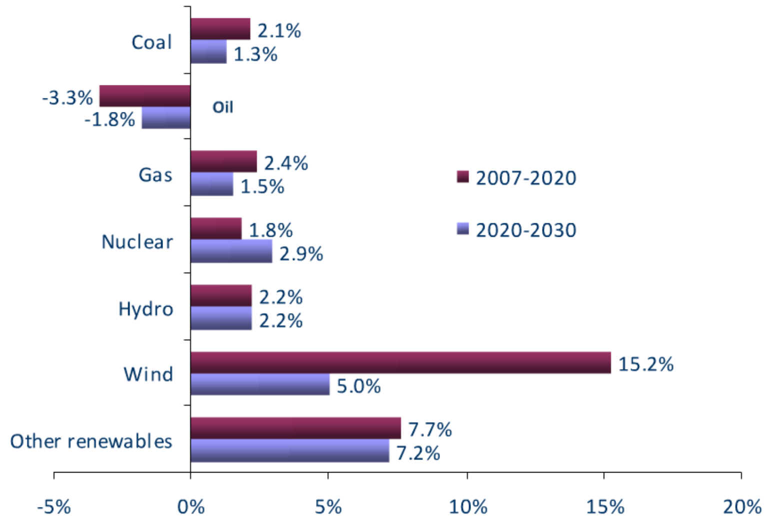


Figure 5-35. Compound annual growth rate of key fuels [Source: Frost & Sullivan].

According to Blackburn & Cunningham estimation solar power start to be cheaper that nuclear power in 2010 (Figure 5-36).

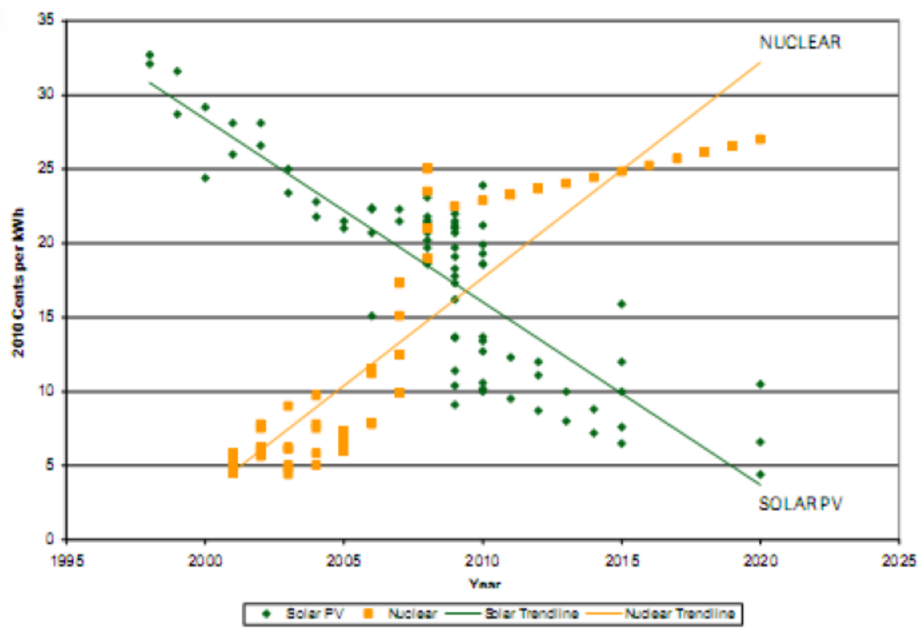


Figure 5-36. Solar and nuclear cost development [Source: Blackburn & Cunningham].

The typical feature for the renewable energy generation is an irregular output with stochastic power variations and breaks. These variations are not usually detectable above normal variations in supply and demand, but when the amount of irregularly varied power generation exceeds the performance limits of local network it can influence on power quality and system reliability. The output power smoothing and limitation may be needed if a turbine is running on a weak, low voltage electrical grid but may also be needed in regions, where wind power generation is very high. [4]

Stochastic power variations are typical for the wind power production. Both reactive and effective output includes large amount of variations in different frequency (from tower shadow effect (> 0.1 Hz) to long period wind speed variations and breaks) and amplitude and numerous interruptions of different lengths. Requirements for energy storages in solar wind power management are described in Table 5-9. [4]

Table 5-9. Requirements for energy storages in wind and solar power management [4].

Time scale	**Target**	**Driving force**	**Storage requirements**	**Energy storage type**
Very fast (ms)	Power quality control, smoothing	Power quality standards, regulations, recommendations	Very fast, very high cycle life, power demand varies	Electrostatic/ electro-chemical (super) capacitors, SMES
Fast (s)	Power quality control, smoothing	Power quality standards, regulations, recommendations	Very fast, very high cycle life, power demand varies	Electro-chemical (super) capacitors, SMES, flywheels
Medium fast (min)	Power quality control, smoothing	Power quality standards, regulations, recommendations	Fast, high cycle life, power demand varies	Super-capacitors, flywheels, batteries
Slow (h)	Power smoothing, management of peak power, breaks etc.	Power production reliability, economical aspects	High power, high energy, proper cycle life	Batteries, flow batteries, fuelcell+ electrolysator, CAES, pumped hydro
Very slow (d, m)	Energy management	Power production reliability, economical aspects	High energy and power	Batteries, flow batteries, fuelcell+ electrolysator, CAES, pumped hydro

CAES (Compressed Air Energy Storage), SMES (Superconducting Magnetic Energy Storage)

According to the study of Frost € Sullivan (2009) renewable energy storage market are segmented in Europe to two main groups centralised and decentralised systems. Long discharge-time storages are mainly usable in the centralised storage applications and fast short-term storages and traditional batteries for decentralised systems.

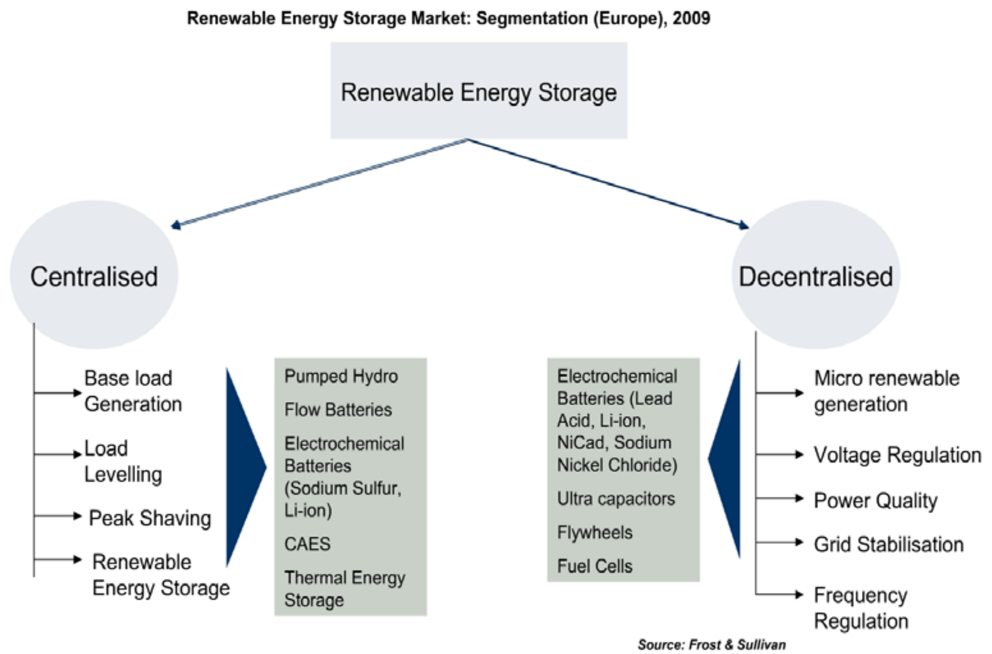


Figure 5-37. Renewable energy storage market segmentation (Europe 2009) [5].

In the following picture (Figure 5-38) it is presented the main challenges of the renewable energy storage industry e.g. lack of suitable energy storage technology, cost, recycling issues and lack of visibility on who will bear the charges.

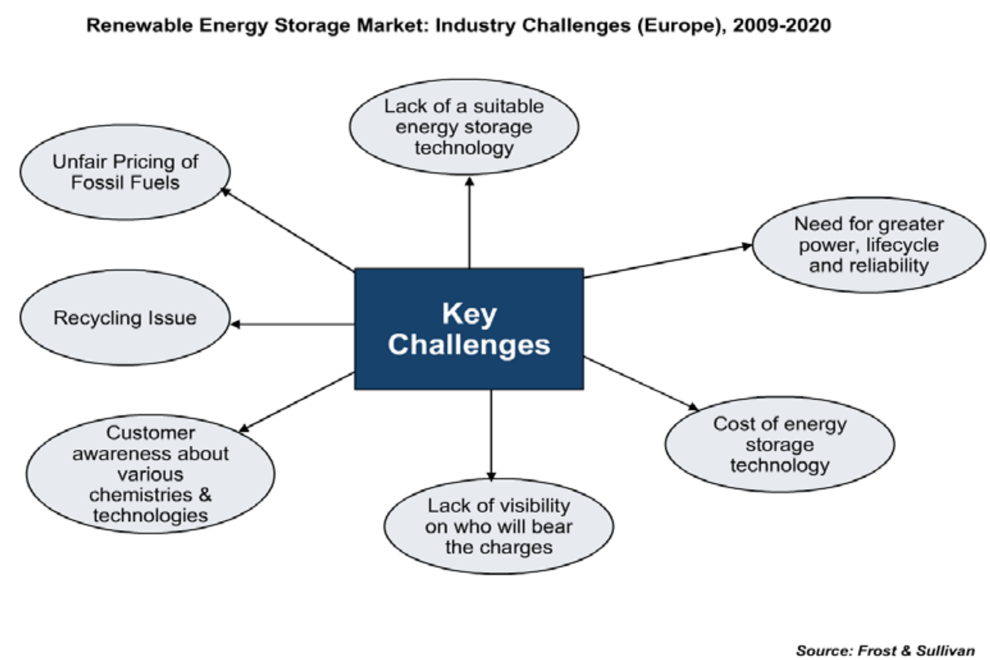


Figure 5-38. Renewable energy storage market: Industry challenges (Europe), 2009–2020 [5].

Molten salt, Flow batteries, CAES are the currently used storage systems, NaS, ultracapacitors, flywheels and fuel cells are considered as a near future emerging renewable energy storage technologies in the Frost & Sullivan's analysis (Figure 5-9).

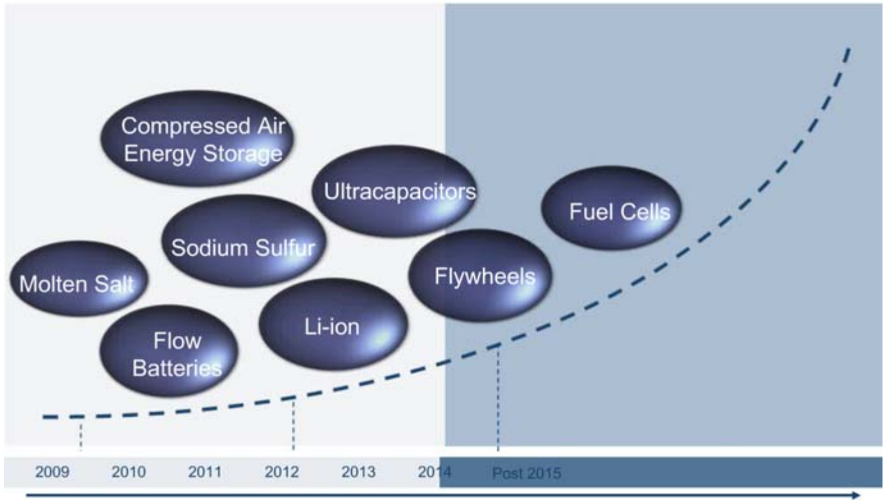


Figure 5-39. Renewable energy storage market: Emerging technology roadmap (Europe), 2009–2020 [5].

In addition to the technologies described in the Figure 5-39 also pumped hydro storages have a remarkable potential for wind power balancing. Iberdrola that is the largest producer of the wind in the world with installed wind capacity worldwide of 9 302 MW, is building the 852 MW La Muela 2 pumped-storage plant for this purpose and is investigating construction of three additional pumped-storage plants with a total capacity of 1 640 MW to help firm the variability of its wind capacity. The UK, Spain and Italy are countries that would greatly benefit from storage technologies in order to support higher renewable penetration [3].

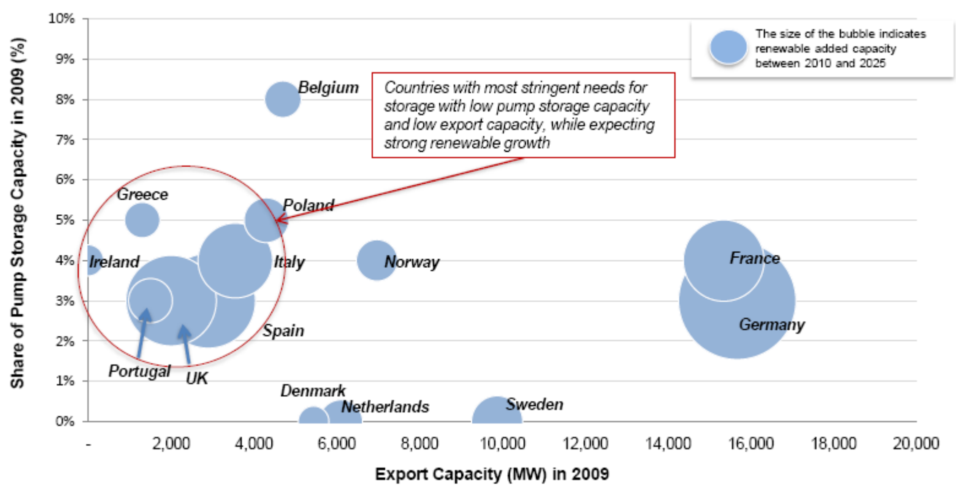


Figure 5-40. Storage Needs by Country based on Export Capacity and Storage Capacity [3].

5.7.2 Smart Grid and PV-Systems

Smart Grid systems support better communications and control between distributed resources such as PV-system and the utility distribution system (Figure 5-41).

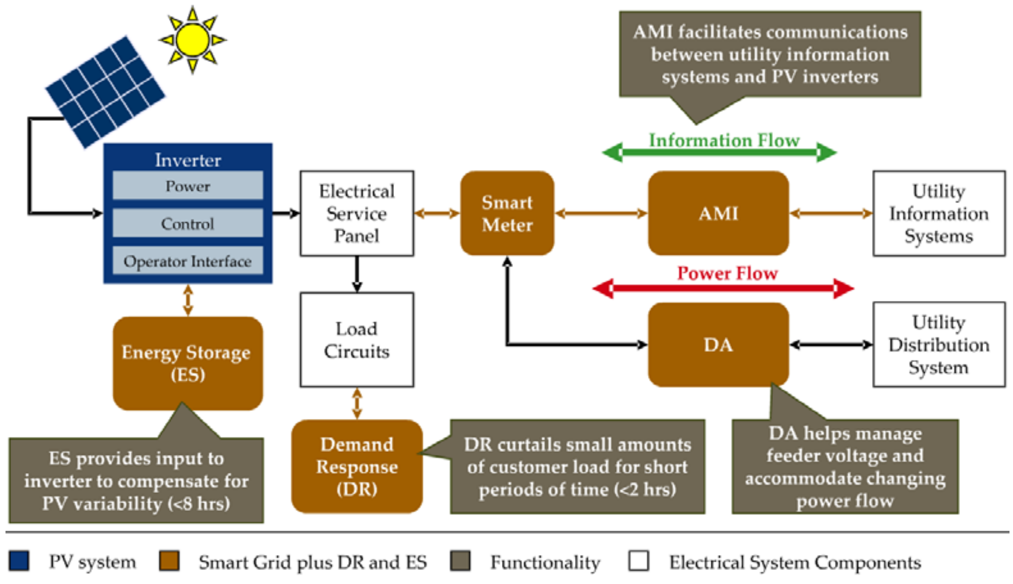


Figure 5-41. Smart Grid – PV framework [Source: Navigant Consulting Inc. 2009] [6].

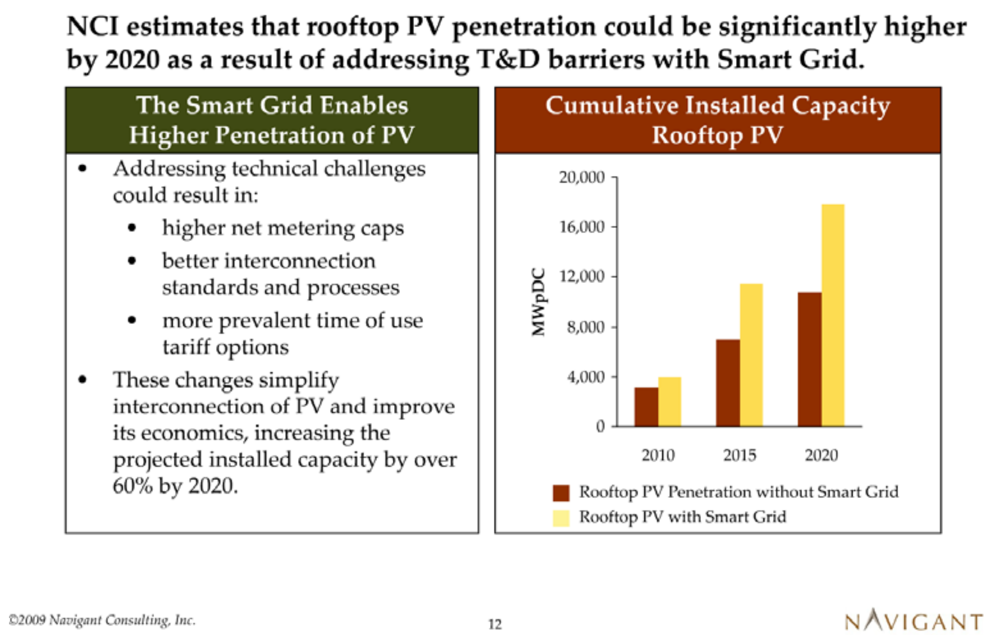


Figure 5-42. Smart grid influence to PV rooftop penetration [6].

According to Navicant Consulting the most promising areas of PV system business opportunity in Smart Grid are in smart capacity firming, grid optimisation and DG PV power plants.

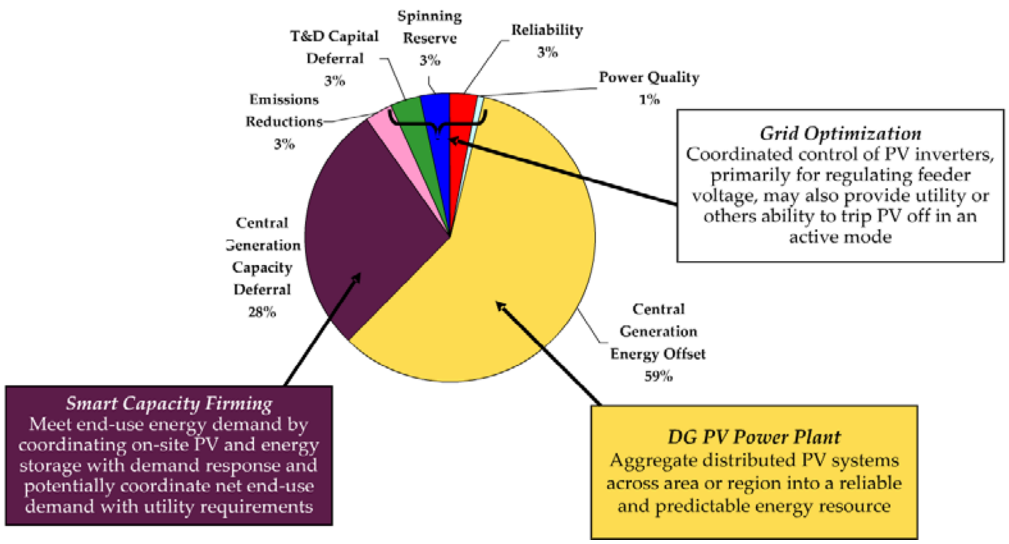


Figure 5-43. The role of PV-systems in Smart Grids [Source: Navigant Consulting Inc. 2009] [6].

5.7.3 Renewables Energy Time-Shift

Many renewable energy generation resources produce a significant portion of electric energy when that energy has a low financial value (i.e., when demand is low and supply is adequate). Energy storage used in conjunction with renewable energy generation could be charged using this low-value energy and discharged when the energy is more valuable (i.e., when demand is high and supply is tight). The energy that is discharged from the storage could be used by the owner, sold via the wholesale or 'spot' market, or sold under terms of an energy purchase contract. [Source: ESA]

In the following picture its is an example of ES installation for solar farm integration in Hokkaido, Japan (Figure 5-44). The installation includes 5 MW solar panels and 1,5 MW NaS battery system. Energy storage absorbs output fluctuation and do peak shifting.

Figure 5-44. An example of ES installation for solar farm integration [Source: NGK].

5.7.4 Renewables Capacity Firming

The objective of renewables capacity firming with energy storages is to use storage to ‘fill in’ so that the combined output from renewable energy generation plus storage is somewhat-to-very constant. The resulting firmed capacity offsets the need to purchase or ‘rent’ additional capacity. Depending on location, firmed renewable energy output may also offset the need for transmission and/or distribution equipment. Renewables capacity firming is especially valuable during peak demand periods. [Source: ESA]

Using storage to fill the dips and gaps in supply, storage predictably firms solar capacity, eliminating the need for spinning reserve to offset the intermittent and fluctuating nature of photovoltaic generation.

Energy storages in capacity firming can be seen also as a benefit-increasing tool (Figure 5-45). E.g. when compared 4 kW PV system (Cost 30 k$) 40% utility benefit with 2 kW PV system (15 k$) and 5 kWh storage system (15 k$) 100% utility benefit.

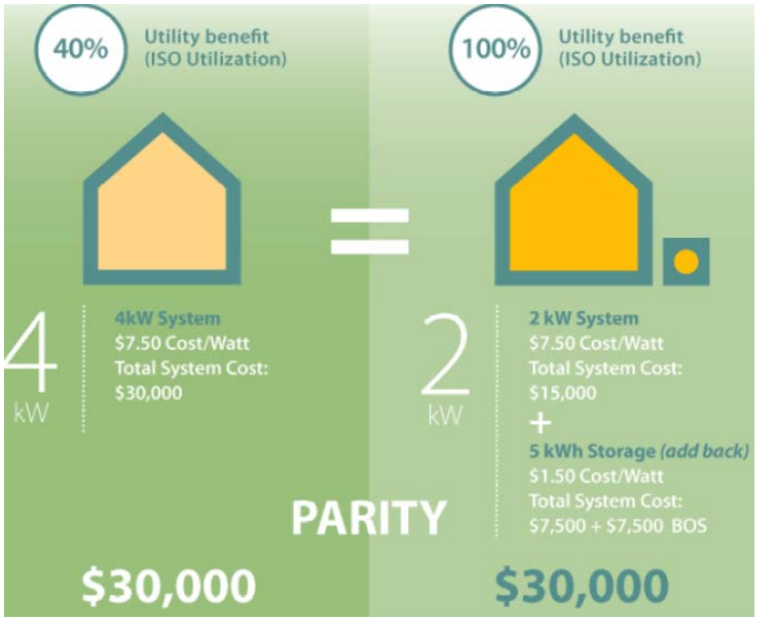


Figure 5-45. PV cost optimising and firming [Source: Sunverge].

5.7.5 Wind Generation Grid Integration

The need of regulation with wind integration depends on highly of wind penetration level (Figure 5-46) and grid ability to accept fluctuating power input. The U.S. Department of Energy (DOE) estimates that for every gigawatt (GW) of wind capacity added, for example, 17 megawatts (MW) of spinning reserves must also be built to account for the system's variability. In addition, utilities are building capacity to meet peaks in electricity usage that could occur for as few as two hours in a given time period.

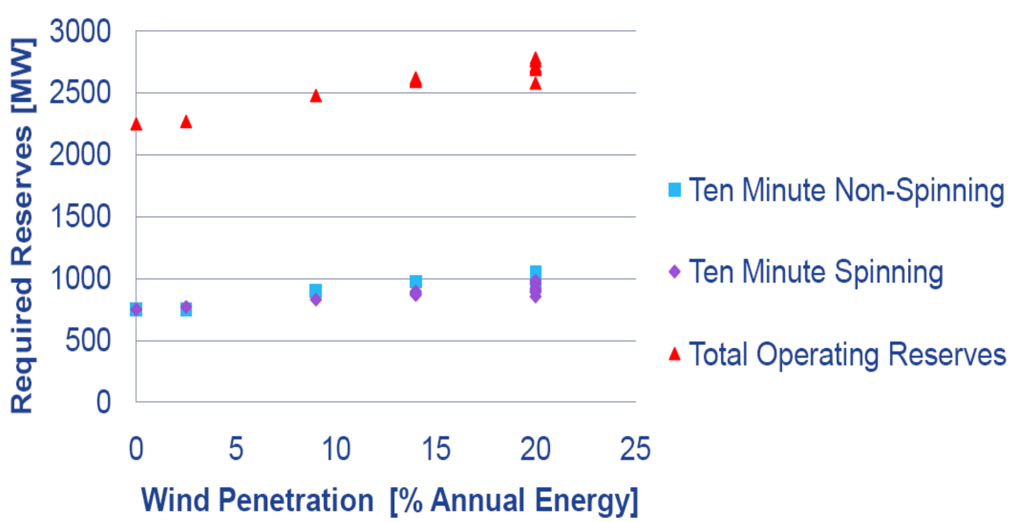


Figure 5-46. Reserves as function of wind integration in New England, USA [54].

In the US, many states are setting renewable portfolio standards to ensure they stimulate growth of renewable energy. With some states expected to have portfolio standards as much as 30 percent. With such high levels of penetration, this renewable or “variable” generation has the potential to create problems with maintaining grid operations. Impacts are expected in areas of frequency regulation, voltage regulation, and balancing. California ISO estimates that storages would be helpful from 20% of renewables and essential for 33% of renewables. Two 1 MW storage devices based on Altairnano’s Lithium Titanate material battery cells successfully demonstrates potential for utility applications. Fast response and over 90% roundtrip efficiency were verified in 1998.

According to studies DERlab and VTT ([56] and [4]) the storage plant would need to have a power rating of at least 0.34 kW per kW of renewable energy generation output for some minutes (Figure 5-47).

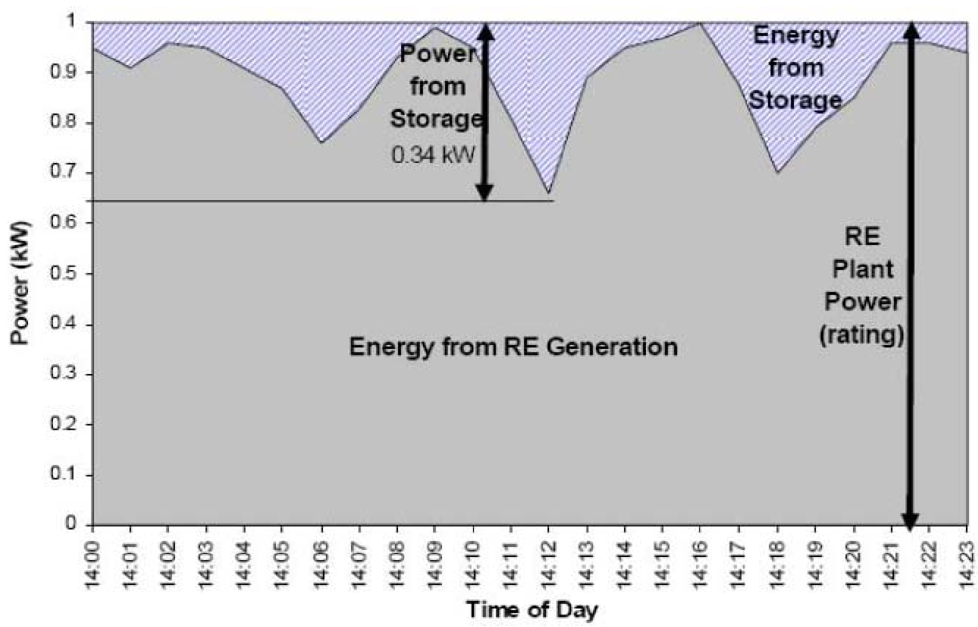


Figure 5-47. Storage power vs. renewable energy generation rated output [56].

Wind Power Capacity vs. Storage Needs in Finland

According to this information we can calculate theoretic potential of needed energy storage power to firm the Finnish wind power production short-term fluctuation

- Current installed wind capacity is around 147 MW
  - 35% storage firming capacity means 51 MW storage capacity for some minutes e.g. 2 MWh
- Planned capacity together around 9 000 MW starting before year 2017
  - 35% storage firming capacity means 3 150 MW storage power 105 MWh (2 min 3,15 GW peak).

9 147 MW installed wind power capacity would mean around 35% of total power capacity (14 700 MW) and practical active capacity 17% in 2017.

Current penetration level < 1% (147 MW vs. 13 500 MW) is not a problem to the grid, all wind power production can be sold on the market and new feed-in tariff makes wind energy storing economically unprofitable for wind power producer. Future penetration might be high enough to require new balancing power that could be partly based also on the energy storage capacity. According to Fingrid they are going to prepare the grid for 2 500 MW wind energy and are planning 300 MW new fast regulation power.

An Example of the Future Storage Installation in Wind Farm in USA

In the following picture describes 8 MW 4 hr lithium ion battery system project for Tehachapi 660 MW wind farm in California. Project is planned to be ready in 2014. Project cost is $54.9 M. The battery system the will have various tasks:

- Transmission
  - Provide Voltage Support/Grid Stabilization
  - Decrease Transmission Losses
  - Diminish Congestion
  - Increased System Reliability
  - Provide Future T&D Investment Opportunity
  - Enhance Value and Effectiveness of Renewable Energy-related Transmission
- System
  - Provide System Capacity/Resource Adequacy
  - Integrated Renewable Energy (smoothing)
  - Shift Wind Generation Output

Figure 5-48. An example of the currently started project 8 MW, 4hr li-ion batterysystem in 660 MW wind power farm in California [Source: A123 Systems].

5.8 Rules and Guidelines for ES Grid Integration

Grid-connected energy storage implementation presupposes approved energy-storage market rules, rules for so-called non-generation resources. An example of this type market rules is the Federal Energy Regulatory Commission (FERC) approved energy-storage-based market rules for the New York Independent System Operator (NYISO) power grid on May 15, 2009 [55].

The California Independent System Operator Corporation (ISO) Board of Governors enables now new types of storage resources, such as batteries and flywheels, to provide reserves for the power grid. An estimated 5–10 megawatts of storage is expected to begin bidding into the ISO market once the Federal Energy Regulatory Commission approves the required tariff changes and software modifications are made.

Energy storages and grid integration are handled also in IEEE guides. IEEE P2030 project, “Guide for Smart Grid Interoperability of Energy Technology and Information Technology Operation With the Electric Power System (EPS), and End-Use Applications and Loads,” and IEEE P2030.1, “Guide for Electric-Sourced Transportation Infrastructure”. The project, IEEE P2032.2, “Guide for the Interoperability of Energy Storage Systems Integrated with the Electric Power Infrastructure,” is being developed by the IEEE Standards Association Standards Board and its SCC21 – Fuel Cells, Photovoltaics, Dispersed Generation, and Energy Storage Committee.

5.9 Summary

Energy storages can serve various grid and especially Smart Grid applications and Smart Grid applications give different kind of requirements for energy storages (Table 5-10):

Table 5-10. Requirements for energy storage characters in Smart Grid applications.

Character	Requirement
Cost (investment and maintenance)	Low
Reliability	High
Safety	High
Maintenance needs	Low
Energy output duration	Depends on the case
Depth of Discharge	High
Roundtrip efficiency	High
Cyclic life, operating life	High
Plant footprint	Small
Charge rate	Depends on the case, generally high
Ramp rate	Depends on the case, generally high
Self-discharge rate	Low, 0
Energy and power density	High
Short duration power capability	Depends on the case, generally high
Power quality	Output power high quality
Recyclability	Good, 100%
Modularity	High
Transportability	Depends on the case
Plug and Play	Important in smaller systems

In principle these applications can be divided power applications and energy applications, which describes also an important issue, a discharge time.

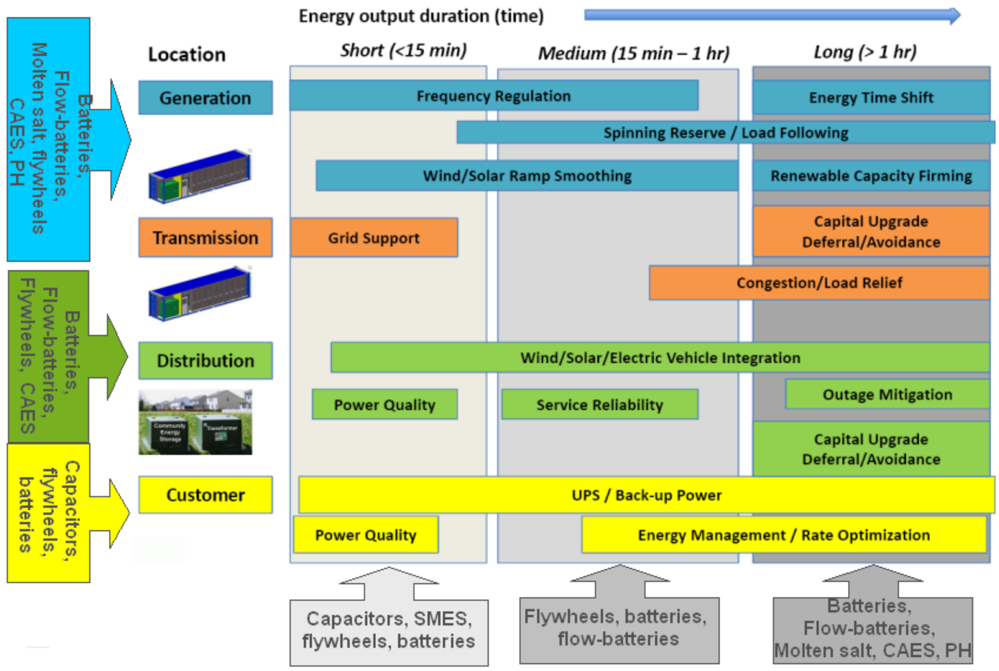


Figure 5-49. Energy storages vs. energy duration time of smart grid. Based on ENER1 [57].

Is the energy storage use in Smart Grid management profitable today depends on many issues. For example according to the Danish study [41] there are three ways for an electricity storage facility to make profit in the Danish power system

1) the system can profit from arbitrage (buying and selling power) on the spot market
2) the system can profit on the regulating market which maintain energy supply and demand balance in real time. Demand (and wind power supply) forecasts are not perfect and the imbalances are handled by the regulating market
3) an energy storage system can sell ancillary services to the transmission system operator (TSO)

According to the study [41] the highest annual revenues (€/kW) can be made on the market for fast reserves and it is likely that large battery systems can make profits on this market today in Denmark (Figure 5-50).

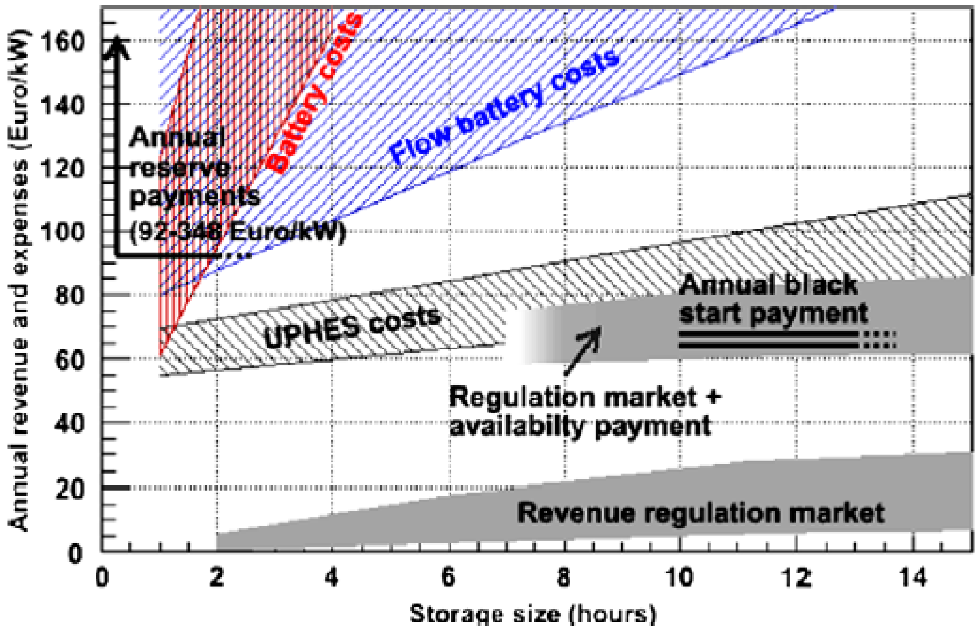


Figure 5-50. Danish study of the possible annual revenues on the regulating market and the market for ancillary services together with annual expenses of having electricity storage systems [41]. (UPHES is underground pumped hydro).

In which amount of energy storages will be implemented in smart grid applications in future depends on many things not least the cost issue. However the choice of a relevant solution for a certain grid application is not only depending on investment cost but also other cost issues and other avoided costs. As an example of the study where storages and natural gas peaker plant is compared taking care of different cost issues – also avoided costs: peaker substitution cost, grid level cost and societal costs (Figure 5-51). Avoided cost realized in

1. Societal level
   - GHG (greenhouse gas) and air quality
   - renewables integration
   - smart grid implementation
   - streamlined permitting
2. Grid system level
   - electric energy time-shift
   - voltage support
   - electric supply reserve capacity
   - transmission congestion relief
   - frequency regulation
3. Peaker level
   - peaker plant substitution.

According to the cost comparison most energy storages are competitive with natural gas peakers. [59]

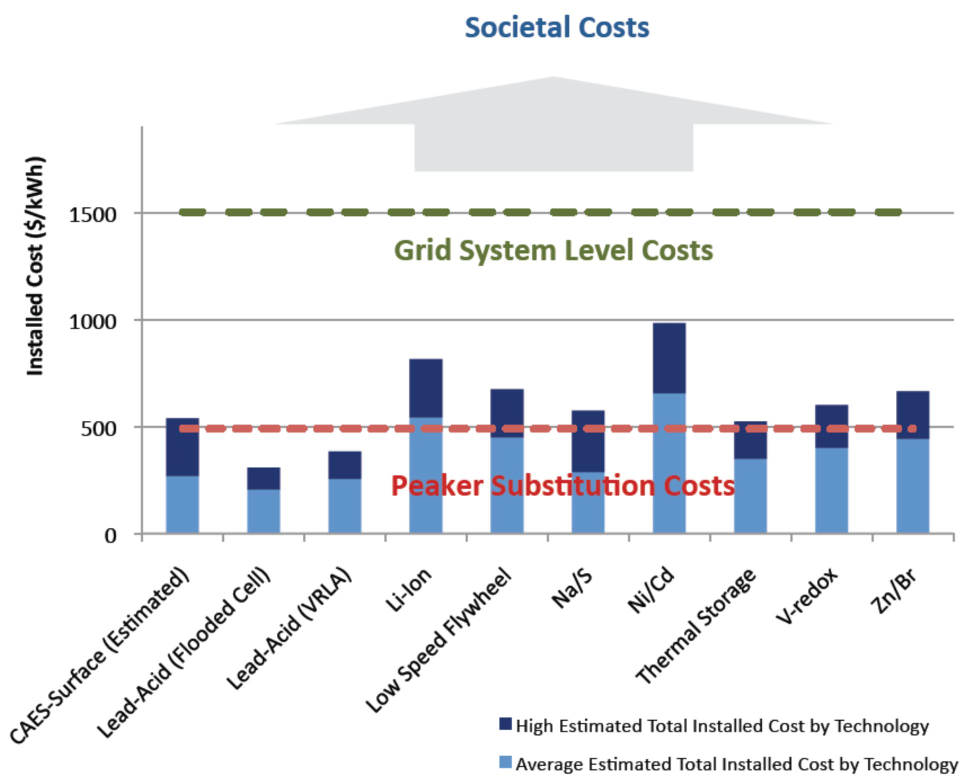


Figure 5-51. Fossil Fuel Societal, Grid, and Peaking Costs vs. Energy Storage Costs [59].

When all benefits are taking into account energy storages can be cost effective solution providing numerous benefits to many stakeholders such as a customer, utility, system operator and society (Figure 5-52).

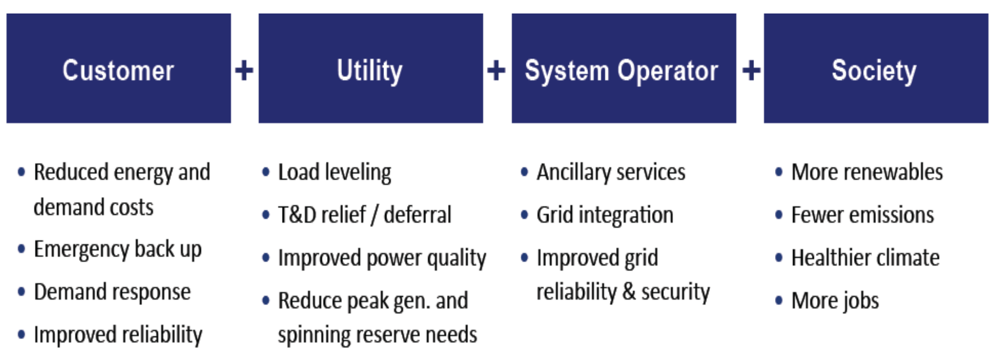


Figure 5-52. Energy storage gives benefits for different stakeholders [9].

6 Conclusions and Summary

In this study it is made a wide review of latest available energy storage techniques that could be potential in Smart Grid applications. It is also characterized energy storage application areas, possible applications and usability in the Smart Grid management. Energy storage technology is fast developing area at the moment when large funding is targeted for energy storage development for mainly because of electric vehicle needs. Also large grid connected battery systems are more important because of larger penetration of renewables, increased reliability requirements of customers and grid operators as well as higher requirements of intelligent, Smart Grid performance. The main activities currently happen in USA where most evaluations and large demonstration systems have been started or planned. For example first commercial 8 MW lithium battery system started up currently working connected in NY grid being first part of total 20 MW storage system. Similar situation as in USA grid might be already in near future in some European countries where renewables penetration is already remarkable high. Most important utility scale energy storage type considered widely in Europe is pumped hydroelectric storage that capacity is already high. Currently PHS systems are built to balance fluctuating wind power instant of peaking nuclear power. New PHS systems are currently installed in Switzerland and planned to install in many countries e.g. in Austria and Portugal. Also new large NaS battery installations are planned in Europe by EDF Energy.

In this first project year study it is included only few minor evaluation of energy storages benefits in Finland where it is not yet easy to find economic benefits for the commercial use of energy storages. However, energy storages are essential in some applications or application areas such as in islanded systems and UPS-systems. If all benefits like high reliability of the grid, environmental factors, GHG emissions and comfort factors are taken into account the use of energy storages can be reasonable e.g. in community area electricity distribution grid, with domestic PV-systems, as a peaking power system and with weak distribution grids in rural areas. Future larger renewables penetration level, higher electricity price and lower storage prices can change the storage economics remarkable.

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