

458

Electric Energy Storage Systems

Working Group

C6.15

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Definitions

Useful capacity (Net capacity)

Net energy output of a storage system which is necessary to fulfil a defined task.

Design capacity (Gross capacity)

Gross energy content that a storage system needs to be designed for in order to be able to deliver the useful capacity. The design capacity includes the losses in the discharge mode as well as the non-usable capacity (to be considered for technical or economical reasons). The design capacity is relevant for the construction costs of the storage.

Storage Duration

Period of time for which the energy is intended to be kept in the storage

Discharge Duration

Period of time for which (constant) power has to be delivered

Charging Duration

Period of time which is intended to fully charge an empty storage at a given power

Charging Losses

Energy losses occurring during the charging mode

Discharge Losses

Energy losses occurring during the discharge mode

Standby Losses

Energy losses occurring during the storage mode; in some applications the standby losses may be compensated by a low additional charging (trickle charging)

Storage Efficiency, Cycle Efficiency

For a given cycle: the sum of charging losses, discharge losses and standby losses related to the total input energy

Frequency of Use

Number of full cycles per time unit

Access Time

Time needed between request of power and full power output

Control Speed

Load following capability

Cycle Lifetime

Number of full cycles to which a storage system is designed

Calendar Lifetime

Lifetime of a storage system on standby (without cycling)

CHAPTER 1 - INTRODUCTION AND MOTIVATION FOR THE WORKING GROUP C6.15

1.1 INTRODUCTION

(Zbigniew A. Styczynski)

The world wide development plans of renewable generation in the coming years (e.g. European SET Plan) underline the high number of problems that the integration of such new resources produce in the power delivery system. One such problem is the full integration of generation from renewable sources during the low load conditions. As can be seen in Figure 1-1, during some hours of the day, there is an overproduction of electricity (negative values in the y axis), which is mainly produced by generators based on renewable sources.

To prevent such a “waste”, electric energy storage systems must be incorporated within power systems. The energy storage can be additionally used for energy shifting either for peak looping or arbitrage as well as for providing ancillary services (e.g. power reserve). This multi-functionality can significantly improve the economical performance of these still expensive technologies. Based on storage technology, a methodological framework to manage the energy surplus coming from renewables and CHP during low load and other operationally constrained conditions will be proposed.

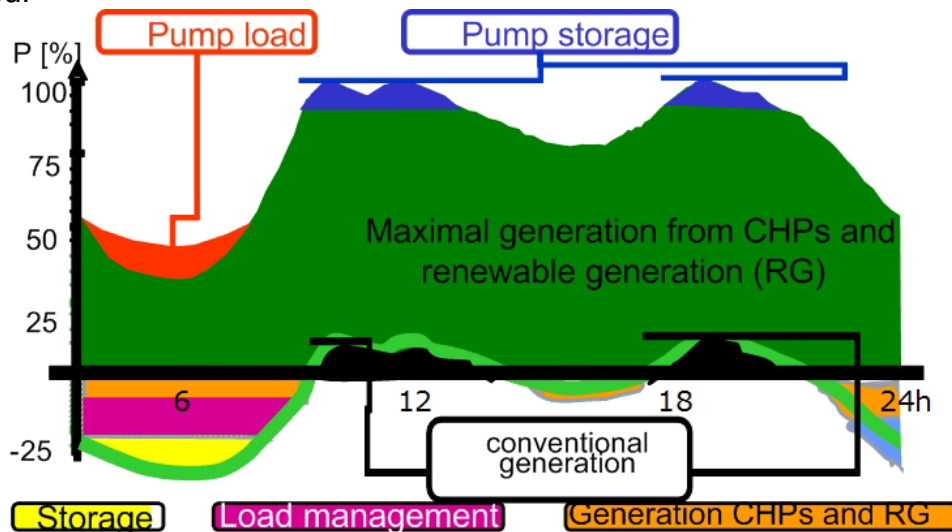


Figure 1-1 Daily load profile in Europe 2020. SET – Plan for Europe – 2020 – 635-GW in RG+CHP

This report first presents the development of the future power system with a high penetration of intermittent generation (chapter 2), while in chapters 3, 4 and 5 it describes an overview of the existing storage technologies taking into account technical and economical aspects as well as the results of different national studies. The focus will be on new technologies like Na-S and Ni-Ca batteries, compressed air storage systems (CAES) and the “vehicle-to-grid” concept. (V2G) The advantages and disadvantages of these technologies will be presented in detail by taking into account international experiences. Moreover in chapter 2, additional scenarios for renewable generation in 2020 and beyond, used in the WG C6.15, will be shown and discussed. The scenarios will focus on a few characteristic regions like Europe, North and South America, Russia, Japan, developing countries and islands and will take

into account published national and international plans (e.g. SET Plan for Europe and information from the W.G. members). Based on these scenarios a methodology for determining the optimal storage capacity, necessary for 100% green energy integration, will be introduced. This methodology uses a reservoir model for electric storage, the specific parameters of which (e.g. charge or discharge time, depth of discharge, efficiency, cycling capability, life time, etc) will be set depending on the technology analysed.

In chapter 6, by taking into account international experiences from pilot installations, the technical and economical validation of the results will be discussed and some initial recommendations will be given.

CHAPTER 2 - STORAGE AS A NECESSARY PART OF THE FUTURE POWER SYSTEM

2.1 STATE OF THE ART AND FUTURE DEVELOPMENT OF THE POWER SYSTEM

(Zbigniew A. Styczynski, Geza Joos, Ravi Seethapathy, Bartosz Wojszczyk)

2.1.1 State of the art

The power system structure is mainly composed of: generation, transmission and distribution. Thus is also due to the unbundling process which takes in many countries. Many power networks are commercially unbundled, with a separation of generation from the operation of the network.

In a traditional power system, the power is produced by few large power plants, which are located in the vicinity of primary energy source is (e.g. coal mine, water). The power is then transmitted at very high or high voltage for long distances (e.g. 500 km) and finally it is distributed to the end users.

Generation

The generation is the main part of the power system. More than 50% of the total costs of the power system are related to generation, which is also responsible for the majority of the pollution emissions. For this reason, in this chapter, the investigation is focused on this part of the power system.

The general structure of the primary energy sources has not changed significantly during the last 30 years (see Figure 2-1). Fossil energy dominates the sources structure with a share of about 80%. From an environmental point of view this is unsatisfactory.

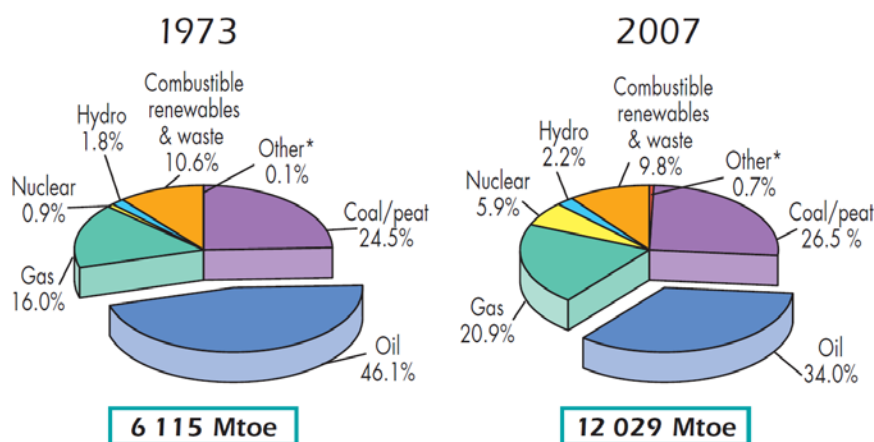


Figure 2-1 1973 and 2007 fuel shares of total primary energy supply [1]

In the year 2007 the Net Electricity Generation (NEG) amount reached the value of 18780 Billion kWh and is concentrated in about 50 of the more than 200 listed countries [2]. The forecasted electricity generation from renewable energy sources is displayed in Figure 2-2, while Figure 2-3 shows only the wind generation forecast.

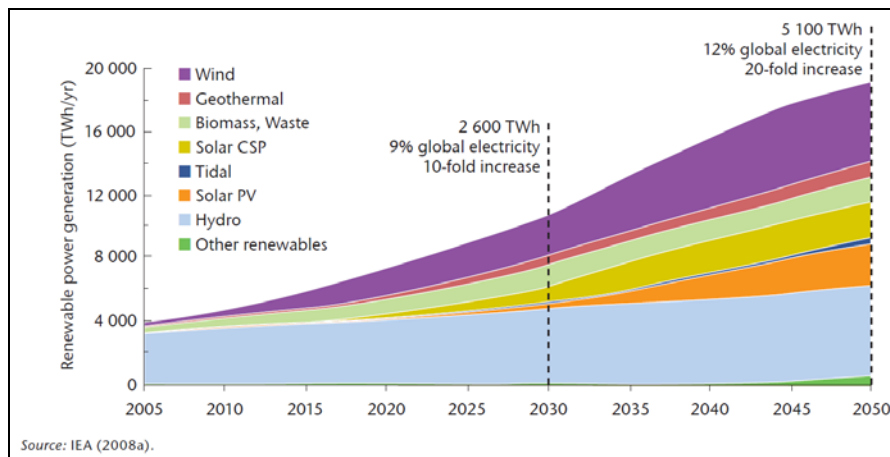


Figure 2-2 : Electricity from renewable energy sources up to 2050 in the ETP 2008 BLUE Map scenario [3]

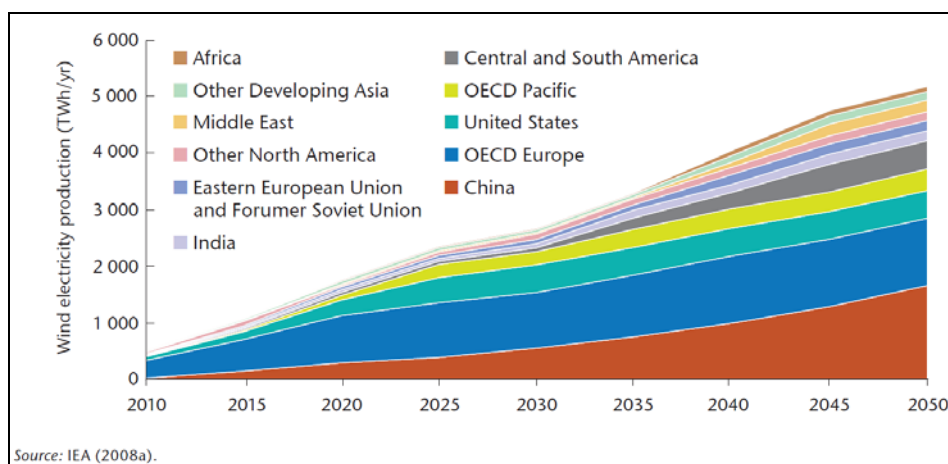


Figure 2-3 Regional production of wind electricity in the ETP 2008 [3]

Currently, among the technologies which use renewable sources, the highest proportion of generation is provided by hydro power plants (see Figure 2-2), nevertheless it is not any expected that there will be a significant increase of hydro electricity generation in the coming years, since hydro power stations, especially large plants, are geographically limited and there are not so many new sites available. The main contribution to an increase in the share of the renewable energy will be given from both solar (e.g. PV and CSP) and wind based technology (Figure 2-2). European and Chinese targets aim to increase by 10-fold the generation from the wind by 2050 (Figure 2-3). In 2050 the forecasted photovoltaic electricity generation should reach about 10% share of the global electricity generation and this contribution is 50 times higher than today's status.. The basic need for generation from renewable sources is a direct consequence of the limited supply of fossil energy sources. In Figure 2-4 the production and reserve of different individual non-renewable energy sources is presented. The estimated energetic reserve is around 38946 EJ, while the current production is about 450 EJ. This means that at the current energy consumption rates there will be enough reserve for around 80 years. The knowledge of this time limit is the main incentive for investment in new technologies able to generate electricity and thermal energy from renewable sources.

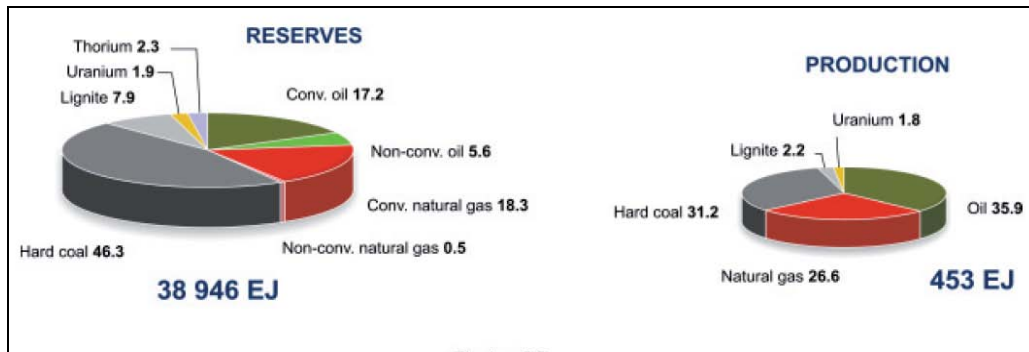


Figure 2-4 Annual production and reserves of the individual non-renewable fuels in 2008 (given in percent of the total) [5]

The massive use of renewable based generators will change the power system structure as well. The current power structure is characterized by large centralized electricity generators that then transmit the electricity at high voltage and distribute it to the end user at medium and low voltage. Renewable sources, on the other hand, will be mainly provided from decentralised generators at the distributed level, so the distribution system will have more importance than today. To get information and to control so many decentralized generators, distributed in different areas of the power network, it will be necessary to use more and more information and communication systems (ICT). Those changes will lead to a new, intelligent (smart) grid structure. Energy storage systems, as well as other measures like load adjustment, will be necessary to compensate for the stochastic generation from wind and PV plants. This report analysed in detail the possibility of using different storage technologies for 100% integration of renewable generation.

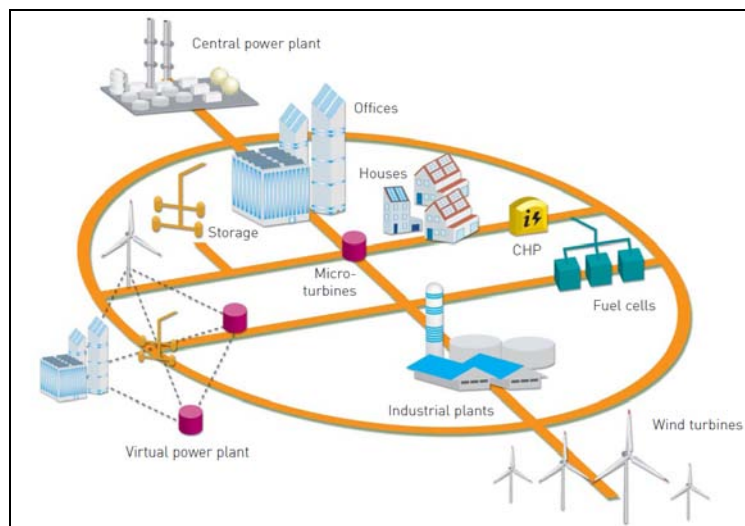


Figure 2-5 Power System – Structure.
Source – European Smart Grids Technology Platform

2.1.2 Smart Grid concept for the future grid

The concept of a smart grid has many definitions and interpretations depending on the drivers and the desirable outcomes of the specific country or industrial stakeholders. Smart grid refers to the entire power grid from generation through transmission and distribution infrastructure all the way down to a wide array of consumers. It is often described in terms of elements of traditional and cutting-edge

power engineering, employed technologies/solutions/applications (e.g. distributed energy resources, microprocessor protection, advanced automation, sensing and monitoring, energy management, etc.), enabled functionalities and capabilities, robust communications, cyber security and data/information management (e.g. data mining and architecture, data analytics, etc.) to provide better grid observability, performance and asset utilization.

Although the details of employed technologies/solutions/applications may differ from one stakeholder to another, the general characteristics of a smart grid are typically similar.. Furthermore, many smart grid stakeholders define a smart grid not only by what technologies or functionalities it incorporates, but also by what value it brings to all smart grid participants. Energy storage plays an important role in the realization of the smart grid concept. Key smart grid applications that benefit from the integration of energy storage include:

- **Microgrid and Island Concept:** energy sustainable communities, grids and islands effectively operating based on the mix of renewable energy generation, energy storage and well-defined protection, automation, monitoring and control design and engineering standards/principles.
- **Demand Response:** demand response enabled through the Virtual Power Plant (VPP) concept. Effective and optimum dispatchability and controllability of distributed energy resources (distributed generation and energy storage) in order to reduce energy peak demand, minimize distribution grid losses, and improve overall system efficiency and asset utilization.
- **Management of intermittent renewable energy generation:** integration and management of embedded energy storage within the grid, such as various battery-based technologies, flywheels, compressed air, capacitor banks, etc., to enable intermittent renewable generation dispatchability and controllability.
- **Ancillary services support:** support of primary and secondary frequency control provided by traditional power plants.

2.2 REPRESENTATIVE SCENARIOS FOR INTERMITTENT RENEWABLE ENERGY SOURCES

2.2.1 EUROPEAN SCENARIOS

(Franziska Adamek, Zita Maria Almeida do Vale, Joao Peças Lopes, Pio Lombardi
Henrik Vikelgaard)

2.2.1.1 Current situation

In Europe, renewable energy production is becoming more and more important, and its market share is increasing continuously. In particular, wind and solar power contribute significantly to the growing ecological energy production. In 2008, about 66 GW of wind power and more than 9 -GW of solar power were installed in Europe [1]-[8]. Figure 2-6 shows the installed wind and PV power for several European countries in the years 2007 and 2008. It can be seen that wind is dominant, but PV is also widely used throughout the European countries.

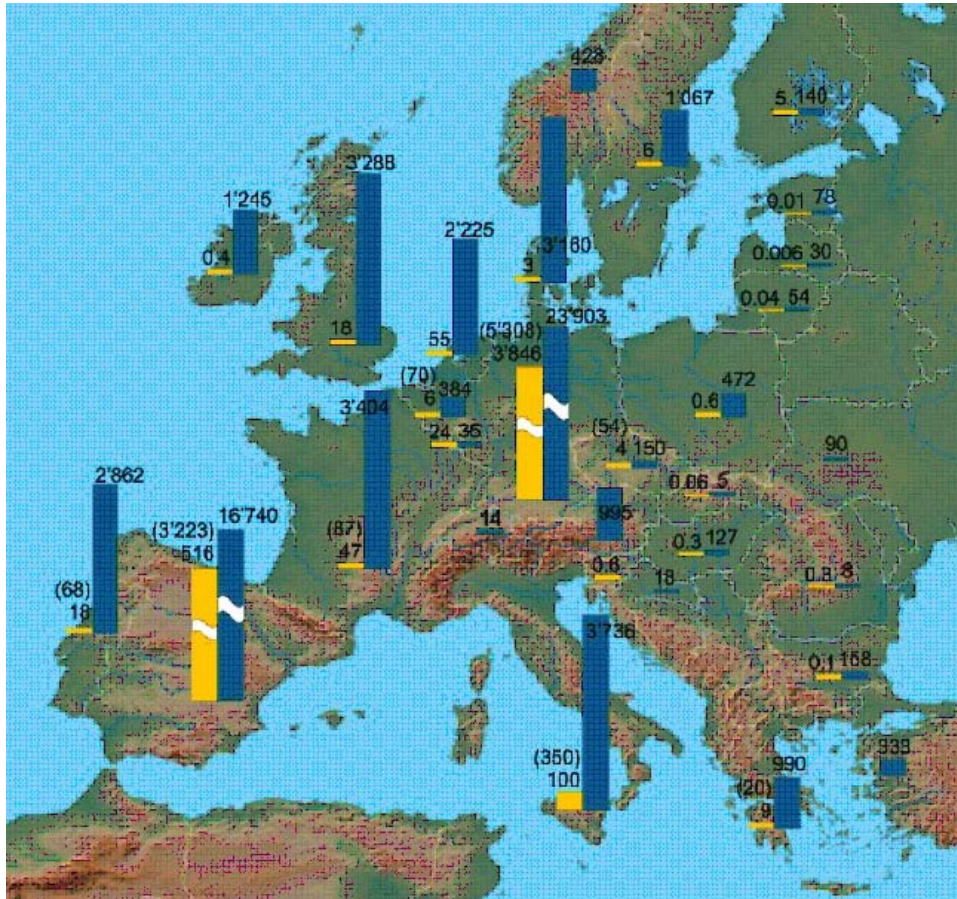


Figure 2-6 Installed wind (blue) and PV (yellow) power in Europe in 2007 and 2008
Wind data is from the end of 2008, PV data is from 2007 and, where available, from 2008
(in brackets) [1]-[3].

2.2.1.2 Future development

Renewable energy use is broadly supported within Europe [9]. Besides encouraging the installation of renewable power, the European Union also aims to take the leadership in research and development of green technologies, in order to stay competitive in a global market and to fulfill the two major EU goals [10]:

1. 2020 target: Reduce greenhouse gas emissions by 20% and ensure 20% of renewable energy sources in the EU energy mix by 2020
2. 2050 vision: Complete decarbonisation

However, currently member states are mostly working on their own, without any coordination of research and development projects. Consequently, synergies cannot be used and there is a multiplication of efforts. To bundle research and development efforts and to coordinate activities, the European Strategic Energy Technology Plan (SET-PLAN [10]) was developed. It proposes a *Steering Group on Strategic Energy Technologies*, an increase in research resources, international cooperation, and an open-access information and knowledge management system, among others. Summarizing, the EU SET-Plan aims to bundle up research and development projects within the European Union to stay globally competitive and to reach market leadership in sustainable technologies.

2.2.1.3 European Scenarios

The European Union supports the use of renewable energy resources, and it is likely that they will dominate the future energy supply. Scenarios range from cases with nearly no renewable energy use to pure renewable energy use [11]-[15].

The business-as-usual scenario established by the European Union in 2007 (*European Energy and Transport – Trends to 2030* [17]) is frequently cited as a reference case and will be presented in the following assessment. In the context of storage operation, the case of a high penetration of (intermittent) renewable generation is of interest. Consequently, a scenario favorable for renewable energy use is presented as well.

Business as usual scenario

The business-as-usual or baseline scenario for 2030 is presented in detail in [17]. This section describes the forecasts regarding renewable energy penetration, as the intermittent nature of most renewables strongly motivates the use of storage.

General framework

The baseline scenario (Table 2-I) assumes an economic growth of 2.2% per year from 2005 to 2030. The gross domestic product (GDP) increases by 71% compared to 2005. Tax rates stay constant, but prices for CO₂ and fossil fuels rise. The oil price increases from 55\$/bbl¹ (2005) to 63\$/bbl (2030). Gas prices increase by 38%, oil prices by 15%. Coal prices stay more or less constant, while the CO₂ price also increases by 20%.

Table 2-I Baseline Scenario Prices for Fuels and CO₂ [17]

Year	Oil price [\$/bbl]	Gas price [\$/boe] ²	Coal price [\$/boe]	CO ₂ price [€/t]
2005	54.5	34.6	14.8	20
2030	62.8	47.6	14.9	24

Energy

Primary energy consumption increases by about 200 Mtoe between 2005 and 2030. The majority (about 115 Mtoe, or nearly 60%) of this increase is supplied by renewables. In total, the contribution of renewable energy to meeting the increase in primary energy consumption rises to almost 12% in 2030 (Table 2-II).

Table 2-II Share of Energy Sources in Total Primary Energy [%] [17]

Year	Solid fuels	Oil	Gas	Nuclear	Renewables
2005	17.7	36.7	24.6	14.2	6.8
2030	16.7	35.3	25.7	10.3	11.8

The share of renewable energy in gross power generation amounts to 23% in 2030. A major part is generated by wind (Figure 2-7). Wind produces about 15 times the

¹ bbl: oil barrel

² boe: barrel of oil equivalent (roughly 7.2 boe = 1 toe)

amount of energy it produced in 2000. Thus, almost as much electricity as produced from hydro will be generated from wind. Hydro power only increases a little because of potential limitations and environmental restrictions. Biomass and solar PV rise considerably.

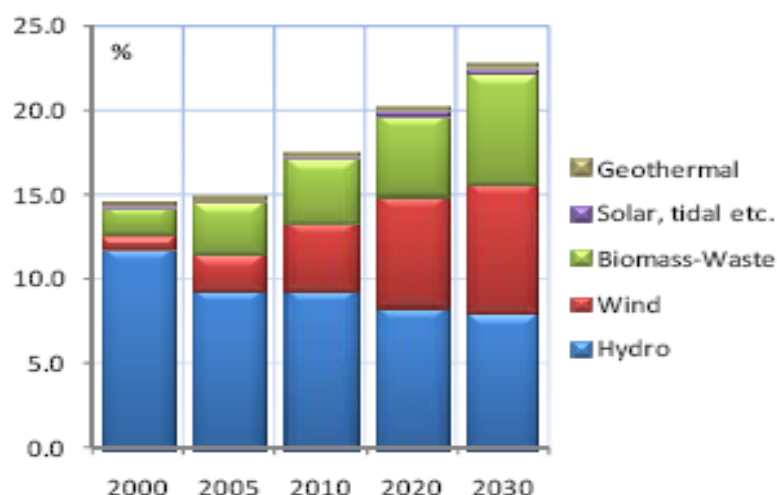


Figure 2-7 Renewables share in electricity generation (gross) [17]

Increasing electricity demand, as well as the higher penetration of intermittent renewable energy sources, requires a substantially higher power generation capacity than is needed currently. The net capacity increases by 31%, and is mainly generated by renewables and natural gas (Table 2-III). The installed capacity of renewables increases by more than 1.5 times from the year 2005 to 2030. The capacity of about 325 -GW of renewables is mainly provided by onshore wind (39%) and hydro (34.5%) (Table 2-IV).

Table 2-III Net Power Generation Capacity by Type of Main Fuel Used [%]

Year	Nuclear	Solids	Gas	Oil	Biomass/ Waste	Hydro	Wind	Solar	Geoth./ tidal
2030	10.9	19.0	36.0	3.2	5.0	10.9	14.5	0.33	0.17

Table 2-IV Installed Capacity of Renewables

Year	Hydro	Wind onshore	Wind offshore	Solar and Others	Biomass
2030	34.5% 112.1-GW	39.0% 126.8-GW	4.5% 14.6-GW	7.0% 22.7-GW	15.0% 48.8-GW

High Renewables Scenario

The high renewables scenario [18] (EU-25³) makes the same assumptions about the general framework as the business-as-usual scenario. However, renewables are supported in a much stronger way than in the baseline scenario. The high

³ In comparison to the baseline scenario, the high renewables scenario examines the EU-25. The European Commission published the updated baseline case in 2007. The baseline case of 2005, which is the basis for the high renewables case, is no longer accessible so the figures may slightly be different. However, the expected trends and changes are visible.

renewables scenario includes a significant contribution of biomass and waste, as well as a remarkable penetration of solar water heating in households and in the tertiary sector. Also, electricity production from renewables, and the use of biofuels are strongly supported. The share of renewables in gross energy consumption increases to about 24.0% in 2030, in contrast to 11.8% in the baseline scenario (Table 2-V). In electricity generation, the share of renewable energy forms (including waste) reaches about 45% in 2030 (around 23% in the baseline case). In particular, solar energy and geothermal heat increase significantly compared to the baseline scenario (9.4 times, and 4.0 times higher, respectively). The net power generation capacity increases to about 38% in the high renewables case compared to about 28% in the baseline scenario. The total installed capacity of renewables increases by about 85%, with significant gains in biomass, solar and wind.

Table 2-V Shares of Renewables in the Baseline and the High Renewables Scenario [18]

<i>Scenario</i>	<i>Gross energy consumption</i>	<i>Electricity generation</i>	<i>Net power generation capacity</i>
Baseline	11.8%	23%	28%
High Renewables	24.0%	45%	38%
Increase	+12.2%	+22%	+10%

2.2.1.4 Renewable energy development in the Iberian Peninsula

Renewable energies have always played a key role in the electricity generation mix in the Iberian Peninsula. The volume of renewable generation has soared in the last few years, mainly with the increase of wind generation, and it is foreseen that this trend will continue in the coming years. Portugal, in particular, has one of the highest levels of sun radiation, wind resource and hydro resources among all the EU member-states. As a result, the renewable energy investments have recently boomed and, consequently, have become a crucial area for the Portuguese economy. Specifically, by the end of 2007, Portugal had installed 7,409 MW of renewable-based power plants, thus, the renewable energy share is 36.4% of the total electricity demand (one of the highest percentages in Europe) [21]. The goals defined by governmental institutions for renewable participation in electricity demand for 2010 and 2013, corresponds to 39% and 45%, respectively. Taking into account that in Portugal there are presently 4,945 MW of hydropower capacity, the accomplishment of the 2020 targets requires the installation of another 2,055 MW, to a total of 7,000 MW. Concerning wind generation, it is very likely that the defined goals for that sector will be reached, by assuming a yearly development rate of the installed capacity around 20% through 2010 (and grid capacity schedule for wind power enhancement) [22]. This will lead to an installed capacity of about 8000 MW by 2020. Regarding Spain, their 2010 targets pledged - in the Plan of Renewable Energies (PER) - for renewable generation to increase, with the aim of reaching at least 12% of total energy use from renewable sources by that year. Additionally, the PER aspires to reach 29.4% of electricity generated from renewable sources by 2020 [23]. Concerning wind energy, the objective of the PER rests on attaining 20,155 MW of capacity by the end of 2010, as it is depicted in the above figure. Additionally, it is unanimously agreed that in 2020, about 40,000 MW ought to be installed. Concerning the contribution to demand, in 2006 wind generation fulfilled 10% of the electricity load, ahead of beating hydropower (9% of the load). In 2007, 3,522 MW of new wind power capacity was installed, (double the amount registered in 2006) and,

therefore, Spain has demonstrated the second largest wind power growth world-wide. According to the Wind Power Observatory, in January 2008 the wind power total installed capacity was 15,145 MW [22], [24]. Finally, it is possible to foresee that the wind generation on the Iberian Peninsula will rise roughly 192% between 2005 and 2015.

2.2.1.5 The Danish Scenario

Since the first oil crises in the 1970s Denmark has been a world leader in power generation from wind turbines. Today more than 20 % of the total annual electricity consumption in Denmark is covered by its Wind Turbine Generators. In the EU the average is less than 4%, while Spain as the second best is at around 12%.

The goal of the Danes is to have more than 50% of their electricity consumption generated by wind in 2025. Part of the explanation of how this can be achieved is the location of Denmark, and its strong electrical connections to its neighbours. In total, they have an exchange capacity of up to 5,3 GW, which should be compared to a peak load of 7,3 GW, and an average load of 4,1 GW. Denmark plans to add an extra 2,5 GW of exchange capacity before 2017. Denmark copes with the fluctuation of the wind power by using its transmission lines to Norway and Sweden in the north and Germany in the south, using their neighbours as an storage option. In Norway they have a large amount of hydroelectric power, some of it reversible, and since Germany is so large compared to Denmark, the excess production or need, can relatively easily be absorbed. This is no longer possible due to the large number of wind power plants which have been installed during the last years especially in Northern Germany. Every exchange of power is based on solid commercial ground, operated and controlled by the “Nordpool” energy marketplace. The grid, together with the “Nordpool” results in an electricity market, where prices shift on an hourly basis, depending on demand, production capacity e.g. high wind in Denmark, or lots of rain (which equals fuel for the hydroelectric power plants) in Norway. The prices can fluctuate greatly, making electricity one of the most volatile “raw materials” in the world. If a problem occurs in the transmission grid, it can have a very big influence on the price of electricity (see Figure 2-9). For this reason an on line picture of the actual grid situation can be found on www.nordpoolspot.com (see Figure 2-8),

In 2007 electricity production in Denmark from wind turbines was a little over 7 GWh. The export to its neighbours was around 11 GWh, and the import around 10 GWh.

The lesson to be learned from the Danish case is that a strong transmission grid, securing the possibility to export electricity in high wind periods, and import in low wind periods, makes a high penetration of renewables, e.g. wind power, possible. The grid and the surrounding countries act like large scale energy storage. This will no longer be possible if the neighbouring countries are situated in the same climatic zone.



Figure 2-8 The actual situation of the critical exchange points. Blue indicates normal operating conditions; orange indicates reduced transfer capacity [25]

Prices at Nord Pool Spot (EUR/MWh)



Figure 2-9 Prices [€/MWh] can have a huge variation from hour to hour on the spot market [26]

2.2.1.6 Conclusion

As can be seen from the information presented above, Europe strongly supports the increase of renewable energy production and aims to reduce drastically the greenhouse gas emissions. The example of the Iberian Peninsula shows that available resources are already used, but still offer a great potential for growth; therefore increasing technical impact on grid security and its reliable performance.

2.2.2 NORTH AMERICAN SCENARIOS

(Matthew L. Lazarewicz, Brad Roberts, Reza Iravani, Bartosz Wojszczyk)

2.2.2.1 Overview

In North America aggressive programs are in place to incentivise the growth of renewable energy sources with a primary focus on wind followed by solar and biomass. Inclusion of storage programs to support these recourses is still early stages, but support from the federal government in the US has commenced.

2.2.2.2 United States of America

The need for storage in the US utility grid came to the forefront in 2007 with the passage by the US Congress of the Energy Independence and Security Act (EISA) of 2007. The law calls for a significant increase in funding to support R&D and storage demonstration programs for grid power and transportation. In response to the growing interest in this area the US Department of Energy formed the National Electricity Advisory Committee and elevated energy storage to one of the top three issues along with Smart Grid technology and generation adequacy⁴.

The USA has a fairly large base of storage in the form of pumped hydro with 21 - GWs currently installed, which represents a little more than 2% of the current (2008) total generation capacity in the US. One of the world's two CAES systems is installed in the US with a capacity of 110 MWs. Other battery storage systems in the US totalled just over 32 MWs by the end of 2008. Virtually all of these projects support utility projects not focused on renewables. Smaller pilot programs for adding storage to solar systems are underway but limited information is currently available.

In October 2008, the US Congress passed the Financial Bail-out Bill, which included renewal of the Production Tax Credit (PTC) for renewable sources and a 30% tax credit for adding storage to a solar power system. The impact of these incentives has yet to be assessed. In 2008 approval to proceed with test well drilling was given for the Iowa Municipal Utilities CAES project. The 268 MW plant will be built in conjunction with a 200 MW wind farm. The project is being jointly funded by municipal utilities in Iowa plus others in adjacent states. This region of the US has rapid growth in wind farms and will have wind penetration levels at or above 30% in the next decade. The largest area of growth of storage systems in the US is for ancillary services. Lithium-Ion batteries and larger flywheels appear to be cost competitive with natural gas plants to provide ancillary services (mainly frequency). Two major studies conducted during 2008 show that as renewable energy penetration increases, the need for fast response systems in the 5-15 minute timeframe will increase. This 15 minute "non-spin" option is ideal for energy storage systems like batteries and flywheels. This market will develop the fastest in the USA. One of the key drivers to facilitate storage use in the US grid at every level from utility substation scale down to residential sizes is Smart Grid Technology developments. At least one utility project is underway to test grid automation coupled with storage to demonstrate system reliability and "islanding" of large sections of a distribution grid.

⁴ The DOE Energy Storage Committee Report to the US Congress will be issued on December 11, 2008. Excerpts and recommendations regarding renewable energy storage will be made available for inclusion in the WG6.15 report

The Hawaiian Islands are a unique test bed for storage on the islands with very high levels of wind penetration. The very high cost of delivery of fossil fuels provides the incentives to add storage. At least one of the smaller islands has indicated a commitment to 100% renewable power in the near future. The largest storage activity in the US is the development of batteries for transportation. The batteries for PHEVs and EVs will help stimulate fixed battery opportunities, and one potential use offered for used PHEV batteries is a residential application to work with PV arrays. One possible scenario is that PHEV battery packs will be replaced in automobiles at about a 60% capacity point resulting in a “second life” as battery packs in homes to support PV systems that power the load during peak periods.

2.2.2.3 Canada

The overall power generation market in Canada has a unique mix of generation. The provinces of Quebec and Manitoba both have over 90% of their production provided by hydro power. Plus, both provinces are ideal locations for wind farms as well. Because of the large expanse of Canada, the distances between the wind/hydro power generation plants and the loads can be quite long. For Canadian grid operations, the control of nodal voltages will be a growing issue as the penetrations of renewables increases. One approach to a solution is adding storage to the generator “fuel mix” with appropriate incentives.

2.2.3 JAPANESE SCENARIOS

(Suresh Chand Verma)

Japan's energy supply-and-demand structure and CO₂ emissions have been forecasted for 2030 taking into account the progress of energy technologies and their applications on the assumption that the Japanese economy would achieve a stable growth despite high energy prices. In this forecast, the yearly economic growth rate is assumed to be 2.1% in 2005-2010, 1.9 % in 2010-2020, and 1.2% in 2020-2030, while crude oil prices are estimated to be \$90 per barrel in 2020 and \$100 per barrel in 2030 [118]. On 24 May 2007, the Japanese Prime Minister released “Cool Earth 50” a new initiative on the climate change issue that proposed to set up a world-wide initiative to halve the emissions of global gases by 2050 [119]. It is difficult to address such a long-term objective with only conventional technologies, and so the development of innovative technologies is considered essential. In order to achieve the long term target to reduce CO₂ emissions by 2050, “Innovative Photovoltaic Power Generation” has been identified as one of the prioritized technological areas under the “Cool Earth-Innovative Energy Technology Program” by the Japanese government. For Japan, many energy related organizations have modelled the future energy system and some reports are available on their web sites. However, the “Outlook for Resources and Energy Supply and Demand” report issued by the Agency for Natural Resources and Energy, Japan, in May 2008, is considered here for the energy forecasts, also called scenarios. In this report, the energy scenarios for the time frame up to 2030 have been divided into three types depending upon how efforts to improve the energy efficiency are made and implemented [118]:

1. The reference scenario is based on “business as usual” where no new efforts and/or technologies are implemented.

2. The continued promotional effort scenario considers the efforts to improve the efficiency of equipment continuously based on the trajectory of existing technologies.
3. The maximum introduction scenario takes into account the deployment of equipment with a significant improvement of energy efficiency performance by using cutting-edge technologies.

The main features of the individual scenarios are discussed in the following sections.

2.2.3.1 Reference Scenario with business as usual

This chapter describes the forecasts regarding energy scenarios with some renewable energy penetration, with the usual efficiency improving measures and where no new major technologies are adopted

General conditions

The reference scenario assumes a yearly economic growth rate of 2.1% in 2005-2010, 1.9% in 2010-2020, and 1.2% in 2020-2030, while the population is projected to decrease by about 10% compared to 2005. All the scenarios seek a decrease in the dependency level of the oil based primary energy share to the extent of about 20% by 2030 compared to 2005 by using the other energy sources like renewables, etc. The forecast data pertaining to 2020 is also included for each scenario.

Energy

The share of energy sources in the total primary energy is shown in Table 2-VI. The primary energy consumption increases by about 98 Mkl between 2005 and 2030. The renewable share increases to 40 Mkl by 2030 from 34 Mkl in 2005, and the primary energy consumption rises to almost 7% in 2030. Out of this 7%, the share of each renewable type is shown in Table 2-VII. The renewables share including hydro in gross power generation amounts to 9% in 2030. A major part about 7% is generated by hydro.

Table 2-VI Share of Energy Sources in Total Primary Energy [%]

Year	Coal	Oil	Gas	Nuclear	Renewables
2005	21	43	18	12	6
2020	21	38	19.5	15	6.5
2030	21	36	21.5	14.5	7

Table 2-VII Renewables Share in Total Primary Energy [%]

Year	Hydro	Wind	Solar	Biomass, Waste, Geothermal etc	Total
2030	41	5	15	39	100

2.2.3.2 Continued Promotional Effort Scenario

This scenario focuses on the reduction of CO₂ emissions by the continued promotional efforts like shifting coal power plants to other type of generation such as building additional nuclear power plants, increasing the renewables share, and introducing high efficiency energy utilization technology. By taking into account the above measures, the CO₂ emission can be reduced by 5% by 2030 compared with 2005. With regard to the renewable share in 2030, there is about a 1% increase in primary energy and 2% increase in power generation. This is despite the fact that there is a decrease (about 12%) in primary energy consumption in 2030 as compared to the reference scenario due to the introduction of high efficiency technologies. However, the primary energy consumption shows a rise of about 2.5% as compared to that in 2005.

2.2.3.3 Maximum Introduction Scenario

The share of energy sources in the total primary energy is shown in Table 2-VIII. The primary energy consumption decreases by about 61 Mkl from 587 Mkl in 2005 to 526 Mkl in 2030 due to the efficiency measures assumed to be applied to both the energy supply and demand side. The renewable share increases from 34 Mkl (6%) in 2005 to 58 Mkl (11%) in 2005, the solar type of renewable sources shows a significant increase of about 35 times as compared to 2005. Out of this 11% increase, the share of each renewable type is shown in Table 2-IX.

Table 2-VIII Share of Energy Sources in Total Primary Energy [%]

Year	Coal	Oil	Gas	Nuclear	Renewables
2005	21	43	18	12	6
2020	20	37	17	18	8
2030	18	35	17	19	11

Table 2-IX Renewables Share in Total Primary Energy [%]

Year	Hydro	Wind	Solar	Biomass, Waste, Geothermal etc	Total
2030	33	5	22	40	100

In gross power generation, this scenario exhibits about 49% share with an increase of 18% as compared to 2005. The renewables share shows a four-fold increase as compared 2005 scenario. This is mainly due to the significant increase of about 37 times in solar energy systems as compared to 2005. There is a sharp increase in the share of Solar (PV) type renewables envisaged by NEDO, the Agency for Natural Resources and Energy under the Ministry of Economy, Trade and Industry. NEDO has provided PV technology development targets.

2.2.3.4 Conclusion

The chapter above considers three scenarios but elaborates only two main possible situations for the energy system in the year 2030. The last scenario “Maximum Introduction Scenario” shows a significant growth in renewable energy use compared to 2005. Solar energy, in particular, gains importance and as such the increase of renewables strongly motivates the use of storage technologies to bridge the gap between production and consumption of intermittent energy.

2.2.4 SOUTH AMERICA SCENARIO: Argentina

(Pedro Enrique Mercado)

2.2.4.1 Wind Power Potential:

Because of its vast territory, Argentina has a rich variety of climates. Geographic factors influence the climate directly, determining the climatic characteristics of different regions, and the broad range of latitudes covered has a particular influence on climate. Argentina lies almost entirely within the temperate zone of the Southern Hemisphere, unlike the rest of the continent to the north, which lies within the tropics. Tropical air masses only occasionally invade the north-eastern provinces. The southern extremes of Argentina also have predominantly temperate conditions, rather than the cold continental climate of comparable latitudes in North America. The South American landmass narrows so markedly toward the southern tip that the climate is moderated by the Pacific and Atlantic oceans, and average monthly temperatures remain above freezing in the winter. The temperate climate is interrupted by a long, narrow north-south band of semiarid to arid conditions and by tundra and polar conditions in the high Andes and in southeast. The Andes Mountains that extend from north to south along the west of the country constitute a relief factor that facilitates the circulation of air masses in the east, thus determining various types of winds. Three winds influence the climate in a permanent way, which originate beyond the Argentine boundaries; these are the warm and humid winds coming from the Atlantic anticyclone and affecting the regions located to the north of Patagonia: the west winds coming from the Pacific anticyclone, and cold winds from the Antarctic anticyclone. Among the most noticeable characteristics of such winds are the prevailing strong winds from the west in Patagonia, which blow all year round and reaches an average 8 m/s on a yearly mean basis (at heights of 30 m above ground). In some regions of Patagonia, the wind speed exceeds an average 10 m/s. Thus, having this wind power, there is the potential capacity to produce the same or even higher energy annually than offshore installations, at much less costs.

Four major local winds in Argentina influence the climate in such a way that restricted areas with specific wind potential are formed. These include: The Zonda, which is warm and dry, generally blowing between May and October and originating to the west of Cuyo area; The Sudestada, which originates in the Pampa littoral and is characterized by its high humidity content; The Pampero, coming from the south-west, is cold and dry, and blows mainly in summer, after several days of constant increase of temperature and humidity; and Tornadoes, which consist in an air mass in the form of a vertical funnel reaching a rotating movement of about 500 km/h (310 mph), originate between October and March in the Plata Basin.

In order to assess the potential of wind energy sources in Argentina, a map of annual average wind resource estimates at heights of 30 m above ground has been developed employing a geographical information system (GIS).

The Argentinean installed capacity of grid-connected wind power generation did not exceed 29.8 MW in late 2008 [96], and the total amount of power installed in the country in secure operation was 18 GW, mainly composed of hydraulic, thermal, and nuclear generation. Thus, wind power represents only an insignificant fraction of the total power installed, having slightly more than 40 wind generators in the entire territory. The onshore energy potential from wind generation is exceptional. The potential capacity of wind power in Argentina is estimated at about 2.1 GW, with a penetration not higher than 12 % in order to not perturb the adequate operation of the existing Argentinean high voltage interconnected system (SADI) [97], [98] Most of this onshore power capacity is in the southern sections and particularly in the Patagonian region, and would correspond to an investment of approximately US\$ 2000000000. In this way, the development of the wind industry in Argentina would constitute an additional important factor for reactivating the national economy, beginning with base industries and ending with service areas. Presently, there exist two Argentinean enterprises developing their own technology for large wind power generators.

2.2.4.2 Solar Photovoltaic Power Potential:

Argentina has a significant natural potential for solar energy use. The central region of the country has an insolation of about 1600 kWh/m²/year, an excellent resource compared with most regions of Europe. Additionally, some western largely mountainous provinces such as Jujuy in the north and San Juan near the centre enclose areas that mostly exceed 2200 kWh/m²/year, undoubtedly making them among the sunniest places in the world. A map of annually averaged daily global insolation estimates on horizontal surface has been developed employing a geographical information system (GIS). So far, photovoltaic (PV) solar power applications in Argentina have been in isolated areas mainly through the rural electrification program called PERMER (Renewable Energies Program for Rural Markets) launched by the Energy Department in 1995 and funded by the World Bank and by subsidies from the Global Environment Facility (GEF) [101]. The installed capacity of isolated solar power generation exceeded 9 MWh in late 2008 [102], and there is a potential capacity estimated at about 1.45 GW considering restrictions. As is clear, this potential remains largely untapped. There has been no experience of PV installations connected to the grid in Argentina. Regulatory obstacles and the lack of specific incentives to promote solar power have so far inhibited this development. Nevertheless, at present there exist some pioneer projects aimed at spreading this technology with connections to the grid, although it is clear that a national support program is needed.

2.2.5 RUSSIA SCENARIO

(Nicolai Voropai)

A project of VPP with Smart Grid technologies is also supported by the Russian Federal Grid Company (FGC UES) [103]. The Smart Grid concept is especially important for Russia, because there are many power supply problems in the energy sector, such as the ever more unreliable electric power grids. Energy resources in Russia are frequently wasted. Different authorities show that losses during energy distribution in Russia are significantly higher than in the European countries [104]. Russia is the fourth largest electricity producer in the world after the USA, China and Japan with the total electric generation capacity of about 228.7 GW, and in 2008 it produced about 1,036 TWh of electric power. It has a unique interconnected power system that joints 70 local energy systems and provides the energy transfer across 8 time zones. The Russian electricity generation capacity consists of 68 % of thermal plant power generation, 21% of hydropower generation, 10% of nuclear, and about 1% of renewables (geothermal, wind and waste heat). The vast area of the Russian Federation with different landscapes has a huge development potential for renewable energy sources. There is large wind energy potential in Russia especially along the seacoasts, in the steppes and in the mountains of about 700 GW [105]. The total technical potential for biomass is about 15,000 MWe. The operational reorganization of paper plants and the utilization of wood waste are becoming more popular. The geothermal potential is also significant, about 3,000 MWe. The solar potential depends on the location, with the most favourable regions situated in southern Russia (Caucasus, Tuva, Astrakhan region, Chita region). Russia has a huge hydro potential, about 9% of the global hydro resources. Thus, the hydropower stations are the most popular of the renewable sources. The hydropower energy generation is currently 21% of total energy production (in Germany it is about 1%) [105]. Very promising in Russia is the usage of combined heat and power systems (CHP). This is due to the predicted increase of tariffs for electricity (the CHP-systems are paid off quite rapidly, and if the tariffs are increased 10-15% the payback period would be significantly reduced). Today the application of natural gas CHP into the local heating systems is popular. Russia has huge natural gas resources and needs power supply in remote regions, so it has a good ability to solve the power supply problem by using small scale CHP-units (up to 30 MW). The advantages of CHP are the cheapness of heat and electric energy, short distances to the consumers, absence of expensive power lines and substations, environment friendliness and simple installation.

In Germany the usage of renewable energy sources is encouraged by governmental support. For example, the energy from renewables is sold at higher prices (e.g. app. 0,06-0,1 €/kWh for wind energy and 0,24-0,31 €/kWh for solar energy [106]).

The Russian Government Order from January 8, 2009, determined the main values of energy generation from the renewable sources up to the year 2020 (excluding the hydropower stations with installed power of more than 25 MW) as follows: in 2010 1,5 %, 2015 – 2,5 %, 2020 – 4,5 %, [107]. Therefore, the renewable energy sector in Russia is expected to rise in the coming years.

2.2.6 CHINA SCENARIO

(Cheng)

China is in a period of fast economic growth. From 2003 to 2006, the annual growth rates of its GDP remained above 10%. Rapid economic development in China is accompanied with a large level of energy consumption. China is becoming the world's largest coal production and consumption country, and at the same time it is also the second largest energy production and consumption country, and the second largest oil consumption country. Since 2000, the average annual energy consumption increase rate in China has reached approx. 10%. In 2006, the total energy consumption of China was up to 2.46 billion tons of the standard coal equivalent. China aims to achieve the goal of quadrupling its GDP from 2000 levels by 2020. Facing the new round of growth in the chemical industry, transferring the international manufacturing industries and the acceleration of the urbanization process, economic growth in China will increasingly depend upon energy consumption.

In the past 20 years, the GDP of China quadrupled and energy consumption doubled. In 2004, the economic growth rate of China reached 9.5%, however, the annual output of coal exceeded 1.9 billion tons in this scenario. Additionally, China's dependency on imported oil has raised in recent years. It increased drastically up to 50% in 2007 compared to 30% in 2000. The coal-dominated energy consumption in China results in huge CO₂ emissions, which has put increasing pressure on the Chinese government. Although the per capita emissions of CO₂ in China are still far less than that of the developed countries, the total gas emissions have already surpassed the United States, which makes China the largest emitting country among the developing countries. The main reason for this is the low efficiency utilization of the energy. Electricity generation per kWh results in 418 grams of CO₂ emissions in Japan and 625 grams in the United States. However, this amount reaches 752 grams in most of the top ten power generation companies in China. According to China's strong economic growth and the heavy reliance on coal for its power generation and other energy consumption industries, IEA predicts that China's CO₂ emission will be double in the period from 2004 to 2030. Accordingly, the following countermeasures have been taken in China to solve the above mentioned problems. In the last three and a half years, China has decommissioned some of the lowest-efficient coal-fired power plants with a total power generation capacity of 54.07 GWh, which exceeds the total installed capacity of electricity in Australia. The Chinese government has requested that the power generation companies phase out all the inefficient coal-fired electrical power generation units with a capacity lower than 100 megawatts before 2012. By taking these measures, China will be able to reduce 90 million tons of coal consumption and 220 million tons of CO₂ emissions every year. In view of the constraints of the increasing energy production capacity and the environmental protection capacity of China, as well as the effect of the implementation of energy conservation, a large gap will appear between China's traditional fossil energy supply and the energy demand. According to the estimation of the Energy Research Institute, National Development and Reform Commission (NDRC) of China, this gap will reach 18%, 20% and 30% in 2020, 2030 and 2050, respectively. Renewable energy will bear the responsibility of bridging the gap between energy supply and demand, ensuring energy security, optimizing the energy structure and protecting the environment. Energy development in China will follow one of the development strategies and programs listed here:

- Conventional development program: This is a normal energy development program. In this program the pressure of greenhouse gas emissions is basically not taken into account.
- Intermediate development program: In this program, the total energy supply will be partially shared by the increasing renewable energy supply, while the energy-saving emission reduction of traditional energy will be continuously carried out.
- Affirmative development program: In this program, China will increase the R&D and marketing efforts in the renewable energy, such as wind, solar and bio-liquid fuel. Much effort will be placed on the development of new energy and renewable energy sources.

The following gives a description of the three kinds of development programs in accordance with the development feature of energy systems.

2.2.6.1 Conventional development program

General conditions

This is a conservative program in which the pressure to reduce emissions of greenhouse gases is not take into account. In accordance with the conventional development, China may learn from the experience of developed countries in renewable energy policy in order to save investment.

Energy

In this program, the demand of oil, natural gas and electricity will maintain a rapid growth into future. In accordance with the conventional development, the proportion of the renewable energy accounting for the total energy requirement is shown in Table 2-X.

Table 2-X Proportion of renewable energy accounting for the total energy requirement in accordance with the conventional development

	2006	2020	2030	2050
Total energy (tons of standard coil equivalent)	24.6	35	42	50
Proportion of renewable energy: with hydro	7.6	15.5	20.5	26.4
Proportion of renewable energy: without hydro	1.2	5.3	9.5	17.7

In the case of the statistics without taking hydropower power generation into account, the proportion of renewable energy accounting for the total energy requirement increases from 1.2% in the base year (2006) to 17.7% in 2050. Taking hydropower generation into account, the portion of renewable energy will increase from 7.6% in the base year up to 26.4% in 2050. A fast growth trend can be seen

from this statistical result. In the conventional development program, the prediction of the installed power generation capacity of all kinds of renewable energy is shown in Table 2-XI.

Table 2-XI Prediction of the installed power generation capacity of all kinds of renewable energy in accordance with the conventional development program

	2006	2020	2030	2050
Installed power generation capacity [GW]	132.9	347	570.0	1250.0
Wind	2.6	30.0	120.0	300.0
Solar	0.1	2.0	20.0	500.0
Biomass	2.3	15.0	30.0	50.0
Hydro	128.0	300.0	400.0	400.0
Generation capacity [TWh]	472.2	1280.4	2042.0	3240.0
Wind	3.4	63.0	264.0	690.0
Solar	0.1	2.4	28.0	700.0
Biomass	7.9	75.0	150.0	250.0
Hydro	460.8	1140.0	1600.0	1600.0
Generation capacity proportion [%]	100.0	100.0	100.0	100.0
Wind	0.7	4.9	12.9	21.3
Solar	0.0	0.2	1.4	21.6
Biomass	1.7	5.9	7.3	7.7
Hydro	97.6	89.0	78.4	49.4

2.2.6.2 Intermediate development program

General condition

In this program, both the possibility of development and practical demands are taken into account. It represents a of compromise proposal between the conventional development program ("business as usual") and the affirmative development program

Energy

According to this program, the national average coal consumption of electricity will drop from 397 grams standard coal equivalent per kilowatt-hour in 2000 to 360 grams standard coal equivalent in 2010 and even lower to 330 grams standard coal equivalent in 2020. Compared with the year of 2000, 350 million tons of coal can be saved correspondingly. Before the mid-1990's, in addition to the factor of scientific and technological progress, the motivation of the rapid decline in energy consumption per unit output mainly rests with the efficiency released by the phased adjustment of the economic structure with respect to the process of institutional transformation, which means the system adjustment from planned economy to market economy and the transition towards the law of the industrialized economies. It seems that the energy saving space obtained from the economic restructuring in

China will be very limited in the next 10 years, and that the product structure is highly dependent on the policy-orientation. The space of energy saving in China is shown in Table 2-XII. An estimate, over the next 20 years, of space of energy saving obtained from the technology progress is unlikely to exceed 20%. Therefore, it is necessary for China to develop different kinds of renewable energy to bridge the gap of the energy demand.

Table 2-XII Space of energy saving

Industry	The space of energy saving		
	1980	1990	2002
Agriculture	28.2%	27.1%	14.5%
Industry	48.1%	41.6%	51.8%
Tertiary industry	23.7%	31.3%	33.7%

According to this development program, in 2020 the total utilization of renewable energy in China will be up to 620 million tons standard coal equivalent, of which hydropower accounts for 58%, biomass accounts for 19%, solar energy accounts for 14%, wind energy accounts for 8% and others accounts for 1%. In 2030, the total utilization of renewable energy in China will reach 1 billion tons standard coal equivalent, of which hydropower accounts for 45%, biomass accounts for 23%, solar energy accounts for 19%, wind power accounts for 11%, other for 2%. In 2050, the total utilization of renewable energy in China will reach 1.7 billion tons standard coal equivalent, of which hydropower accounts for 26%, biomass accounts for 20%, solar energy accounts for 34%, wind power accounts for 18% and others accounts for 2%. In accordance with the intermediate development program, Table 2-XIII shows the proportion of renewable energy accounting for the total energy in China. In the case of the statistics, without taking hydropower power generation into account, the proportion of renewable energy accounting for the total energy requirement increases from 1.2% in the base year (2006) to 25.4% in 2050. Taking hydropower power generation into account, the proportion of renewable energy accounting for the total energy increases from 7.6% in the base year to 34.1% in 2050, which is obviously increasing faster than that obtained from the conventional development program.

Table 2-XIII Prediction of the Installed power generation capacity for all kinds of renewable energy in accordance with the Intermediate development program

	2006	2020	2030	2050
Total energy (tons of standard coil equivalent)	24.6	35	42	50
Proportion of renewable energy: with hydro	7.6	17.6	24.5	34.1
Proportion of renewable energy: without hydro	1.2	7.5	13.5	25.4

For the purpose of comparison with the conventional program, the prediction of the installed power generation capacity for all kinds of renewable energy in the intermediate development program is shown in Table 2-XIV

Table 2-XIV Prediction of the Installed power generation capacity for all kinds of renewable energy in accordance with the intermediate development program

	2006	2020	2030	2050
Installed power generation capacity [GW]	132.9	405	720	1750.0
Wind	2.6	80.0	180.0	500.0
Solar	0.1	5.0	100.0	800.0
Biomass	2.3	20.0	40.0	50.0
Hydro	128.0	300.0	400.0	400.0
Generation capacity [TWh]	472.2	1414.4	2336.0	4120.0
Wind	3.4	168.0	396.0	1150.0
Solar	0.1	6.0	140.0	1120.0
Biomass	7.9	100.0	200.0	250.0
Hydro	460.8	1140.0	1600.0	1600.0
Generation capacity proportion [%]	100.0	100.0	100.0	100.0
Wind	0.7	11.9	17.0	27.9
Solar	0.0	0.4	6.0	27.2
Biomass	1.7	7.1	8.6	6.1
Hydro	97.6	80.6	68.5	38.8

2.2.6.3 Affirmative development program

General condition

As a result of strong environmental pressure, China will greatly increase its R & D efforts. A significant amount of investment will be put in the R & D and market to promote the solar and bio-liquid fuel technology in this program. The proportion of solar power and bio-liquid fuel in the energy structure will grow rapidly.

Energy

China has very rich renewable energy resources, which could make renewable energy the mainstream of the energy supply, or even enable the renewable energy to dominant the energy requirement in the future in China. In general, the renewable energy market of China is just beginning to enter its rapid development period. The investment in the development of renewable energy increases drastically and is accompanied by the rapid development of the manufacturing industry. Significant effort is placed on the large scale utilization of renewable energy.

China is currently launching a variety of projects supporting affirmative development of new energy power generation, focusing on wind power, solar power generation, as well as biomass power generation. To promote the new energy power generation, it is planned that there will be 10000 MW of power generation by 2010, of which wind

power makes up 4000 MW. The capacity of the renewable power generation will be 40000 MW, including 20000 MW of wind power. It is anticipated that the annual average growth rate of the wind power generation will be between 15% and 20%, which means that the installed capacity of wind power connected to the state grid will reach about 8000 MW by 2020. Developing new energy resources affirmatively becomes an important alternative measure to solve the problem of the energy supply shortage in China. Since the 1990s, utilization of solar energy has been growing faster than all other kinds of renewable energy in China. PV power generation represents the development trend of the solar energy utilization. By 2020, the photovoltaic power generation capacity will increase from 4000 MW to 8000 MW.

2.2.6.4 Conclusion

Three development patterns for the future of China are presented in this section. Considering the fact that coal is still the main sources of energy consumption patterns, it is necessary for China to build a strong, efficient, diverse, safe, and flexible clean energy mix of power generation. The main effort for the renewable energy utilization in China will be focus on the development of wind, solar photovoltaic and solar thermal. Meanwhile, it is necessary in China to develop biomass power generation, waste power generation, geothermal power, tidal power and other kinds of renewable energy to meet the increasing demand for energy.

2.2.7 AUSTRALIAN SCENARIO

(Marian Piekutowski)

Australia has access to vast renewable energy sources and Figure 2-10 shows spatial distribution of renewable energy. At present renewable energy supplies 5% of total energy consumption demand and this includes about 6.5% of power generation needs. Most of this energy is delivered by hydroelectric and wind generation. Biomass and solar energy are also used for power generation however this constitutes a small portion of overall demand. Other energy sources (geothermal and marine) are being investigated and tested in pilot projects.

The significant deployment of these technologies would substantially mitigate Australia's greenhouse gas emissions, as electricity generation accounts for the largest part of the country's carbon emissions.

Australian governments have developed policies and initiatives to encourage investment in renewable or environmentally friendly forms of generation infrastructure to reduce carbon. Introduced in 2006, a Mandatory Renewable Energy Target (MRET) scheme offered incentives for up to 9,500 GWh of new renewable generation annually by 2010 and continuing through to 2020.

In 2008, State and Federal Governments partially funded a few more renewable energy projects, which were funded mostly by private companies: a solar thermal energy plant and several wind farms, now operational and contributing to the grid supply. Legislation was proposed for a national feed-in tariff, however the bill has not been enacted by government yet. The Federal Government has announced that an Emissions Trading Scheme (called the Carbon Pollution Reduction Scheme CPRS) will be implemented in 2010 to further stimulate the industry and viability, induce cost parity, reduce greenhouse gas emissions and act against climate change. A new design for a national Renewable Energy Target (RET) scheme that expands on the Mandatory Renewable Energy Target (MRET) scheme has been agreed.

In developing the non-scheduled generation projections, it [145] has been assumed that the national Renewable Energy Target (RET) scheme will support meeting the expanded target of 45,000 GWh nationally by 2020. To meet the emissions targets stemming from these initiatives, future projections used by AEMO [146] assume that apart from traditional large plant (wind farm) there will be a considerable increase in installations of less than 1 MW, including small renewable energy generating units (photovoltaics), small-scale solar hot water systems and non-scheduled renewable generating units with a capacity of 1 MW or more, exporting into a local network. The non-scheduled energy projections do not include new generation from wind farms and other large scale intermittent generating systems. New intermittent generation, including wind farms with a capacity of at least 30 MW is to be classified as semi-scheduled. This results in lower projections of energy supplied by significant non-scheduled generation.

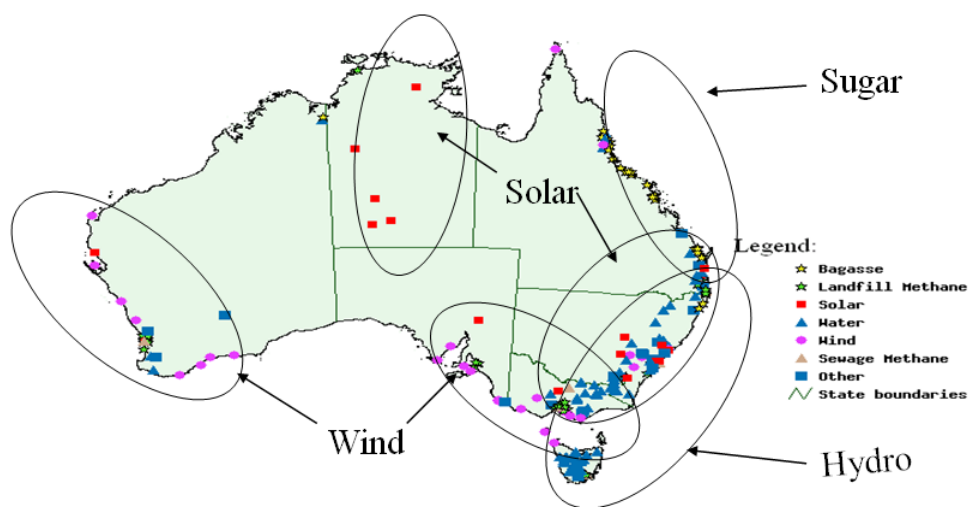


Figure 2-10 Australian locations of renewable energy resources (source: Office of Renewable Energy Regulator, ORER).

Table 2-XV and Table 2-XVI present projections of semi-scheduled, non-scheduled and exempt generation [147], which will contribute to achieving renewable energy targets (RET). Current assumptions indicate that wind farm generation will be a dominant technology up to the year 2020. There are very limited opportunities to develop new hydro and there are also concerns about the impact of the ongoing drought on the output of the existing hydro plant. The other renewable category includes commercial sized solar thermal generation, solar water heaters, solar photovoltaic, biomass/bagasse electricity generation, wave and tidal generation and geothermal generation. Geothermal sources based on hot fractured rock (HFR) technologies have attracted high interest particularly in South Australia. The technology is still largely unproven and potential sites are located remotely from the grid contributing to high access costs. The projections include small scale non renewable schemes that are based on the gas fired generation, predominantly open cycle (OCGT), which operates during peak loads and has an annual capacity factor below 20%. Also included are small scale other non-renewables such as waste energy recovery and cogeneration.

New power and energy projections (Table 2-XV and Table 2-XVI [147]) represent the NEM system only and exclude Western Australia and Northern Territory systems.

These projections have been used in preparation of AEMO's 2009 statement of opportunity.

Table 2-XV Projections of the capacity (MW) of semi-scheduled, non-scheduled and exempted generators in the NEM and Jurisdictions, 2008/09 to 2018/19 [147]

	2008/09	2009/10	2010/11	2014/15	2018/19
Hydro	441	461	461	466	466
Wind	1209	1762	3268	7321	7388
Other renewables	755	755	912	1226	1298
Other non-renewables	535	535	541	562	562
TOTAL	2940	3513	5182	9575	9714

Table 2-XVI Projections of the energy (GWh) generated by semi-scheduled, non-scheduled and exempted generators in the NEM and Jurisdictions, 2008/09 to 2018/19 [147]

	2008/09	2009/10	2010/11	2014/15	2018/19
Hydro	1203	1253	1253	1266	1266
Wind	3522	5054	9227	20561	20733
Other renewables	1322	1322	2059	2853	3156
Other non-renewables	1243	1243	1268	1333	1333
TOTAL	7290	8872	13807	26013	26488

Intermittency of wind and solar generation poses significant integration difficulties, however these are managed by AEMO through the generator registration process requiring power stations larger than 30MW to be registered as semi-scheduled and therefore actively participating in the central dispatch through the use of 'Unconstrained Intermittent Generation Forecast' (UIGF).

Figure 2-10 shows that renewable energy resources tend to be located in specific areas. Some of these areas may have complementary resources allowing management of intermittency such as wind and hydro or wind/solar and open cycle gas generation or actively managed interconnections. Hydro support for other intermittent generation is provided either through management of water storage or using pump storage stations. However, in most locations there is a shortage of natural water storage capability and other support options will need to be considered. Considering that in 2006/07 the Australian electric energy demand was supplied in 83.8% by black and brown coal, 83.8% and the next 11.6% came from gas, the increase of renewable energy contribution from 3.5% to 11% is substantial. Based on current technologies wind generation can provide a significant contribution in some parts of Australia. New hydro development opportunities are limited and a significant change in environmental policy is required to open new options. Other renewables are still largely in the pilot stage of development.

2.3 ALTERNATIVE SOLUTIONS TO STORAGE

(Anthony Price)

2.3.1 Traditional generation

Peaking generation/responsive generating plants such as open cycle gas turbines, fast synchronising diesel generation or responsive hydroelectric plants can be used to match demand with generation. The plants may be either held in a synchronised mode - able to respond to rapid changes in supply or demand - or in standby mode.

2.3.2 Advanced generation

New technologies such as the next generation of nuclear plants or supercritical coal plants with carbon capture and storage may be able to respond to system changes more rapidly than existing plants. A CCS plant separates the generation of electricity from the process of capturing carbon dioxide, pumping and storing it, it will be possible to use the carbon capture cycle as a responsive load able to support the system with frequency response and short term reserve.

2.3.3 STRONGER TRANSMISSION INTERCONNECTS and LOAD MANAGEMENT

(Raquel Ferret, Pio Lombardi)

2.3.3.1 Introduction

The most significant barriers that slacken a high penetration of renewable energy sources are both the limited transfer capacities of the grid and the problems due to the energy congestion. New transmission interconnections and/or load management represent suitable solutions for increasing the production of energy based on renewable energy sources. Interconnected electric power systems exist in different parts of the world. They differ in size, as well as in total generation capacity and geographical area covered. The liberalization of the power industry supports interconnections to enable the exchange of power between the regions or countries and to transport energy over long distances to the load centres. However there are technical and economical limitations, due to a lack of public acceptance of new overhead lines, in the interconnections if the energy has to be transmitted over extremely long distances [72]. Moreover, nowadays, it is well known that the interconnections approach must consider the required integration of significant quantities of renewable energy into the electricity grid. Among others, the advantages of the interconnection is the ability to balance load between different areas with differing consumption patterns, as well as the ability to share reserve capacities and to reduce required levels of both spinning and non-spinning reserves. Interconnection gives system security because of the interconnected systems providing mutual support for each other in times of emergency [73]. There is a shortfall of investment in the interconnection capacity all around the world. Consequently, new investment is needed, yet existing capacity is not allocated on market basis. Data monitor research

shows a very weak relationship between power prices, interconnection capacity prices and the volume of booked capacity on most interconnections [74].

The final objective must be to reach an efficient, secure, resilient, adaptable and economic electric power infrastructure, which is able to support the continuous increase of global energy demand. The term “load management” refers to the changes both to the usage time and the volume of the demanded electricity by the customers. Customers are offered, directly or/and indirectly, the possibility to reduce the use of electricity during the peak load times. Load management programs are mainly based on technologies able to inform the customers, in real time, of the electricity price. Consequently, in reaction to the electricity price, appliances and equipment are activated manually, semi-automatically or automatically. However, the benefits of load management do not only concern the customers, but also the utilities, which avoid investing capital in network and generation capacities [75]. Together with economic aspects the environment can also benefit from the load management programs, since less efficient power generators are usually used for producing electricity during the peak loads. Energy storage systems, both electrical and thermal, can efficiently contribute to change the behaviour of the energy demand. They can be charged during the off peak times and discharged during the peak times.

2.3.3.2 Stronger transmission interconnections: challenges

The new means of generation that have recently entered the established utilities transmission and distribution networks are changing the existing rules of network management, adding new challenges to global network stability and a new variable to be considered, namely the unpredictability and non-continuous availability. Even though new high power and high energy storage solutions will probably come to facilitate the predictability of intermittent renewable energies, the growing need of stronger interconnections together with the enormous growth of new sources of distributed generation with new energy management rules, will influence the developed new concept of networks and therefore bring about a totally new concept of energy management. Aging grid infrastructure, constraints associated with new infrastructure build-out, , and requirements for higher reliability are prompting many utilities to consider distributed generation and energy storage options for capital deferral, grid support, optimum distribution planning and effective end-user energy management. An efficient coordination of regulation and technology will be required to avoid ever growing network power quality degradation and inefficient network development investments.

2.3.3.3 Solutions

In the transmission grid, energy storage can be used to improve power quality by correcting voltage sags, flicker and surges. It can also provide line stability and Power Oscillation Damping (POD) [77]. During the last decade, coinciding with renewable energy growth, different energy storage technologies have reached maturity and have been installed to improve supply quality and to boost renewable energy integration. However, these efforts have been not enough. Most studies have shown that in order to reduce transmission bottlenecks and to decrease the generation costs, new transmissions, interconnection capacities and load management programs are needed. Interconnections are mostly realized by

synchronous links where such solutions are technically feasible and economically justified. On the other hand, High Voltage Direct Current (HVDC) links often offer a technically better solution. Even, in many situations, hybrid solutions for interconnections are more advantageous [78]. HVDC systems remain the best economical and environmentally friendly option for conventional applications. However, three different dynamics - technology development, deregulation of electricity industry around the world, and a quantum leap in efforts to conserve the environment - are demanding a change in thinking that could make HVDC systems the preferred alternative to high voltage AC systems in many other situations as well. New transmission technologies are needed to develop a sustainable energy infrastructure, as presented recently by the California Energy Commission [79]. Traditional “Build” solutions (investments in wires, towers and power plants), can’t meet current energy system needs (provide physical access for each new power plant; reliably accommodate any unique renewable generator behaviours, and increase its power carrying capacity to handle the additional electric power flows). According to California Energy Commission, new technologies are identified to improve transmission lines and provide a better renewable energies integration:

- Underground transmission
- High voltage direct current
- Advanced transmission line conductors
- Engineered compact designs
- Web-based interactive stakeholder sitting tools
- Cost allocation and strategic benefit analysis tools
- Distributed renewables

Likewise, other technologies have been identified to accommodate unique renewable generator behaviour through a more flexible grid:

- Energy Storage & Intelligent Agent
- Solar & Wind forecasting tools
- Synchrophasor measurement
- Power Flow Control (Spatial)
- Demand Response
- Distributed Generation
- Generator and Load Modelling
- Statistical and Probabilistic Forecasting Tools
- Advanced Intelligent Protection Systems

2.3.3.4 Load management

The electricity production costs of power plants are highly dependent on the investment costs, amount and type of fired fuel (for the thermal units only), and on the quantity of electricity produced during their life time.

Based on the generation costs and on the typology of the power unit, three categories of power plants can be defined:

- Base load power plants, such as coal fired thermal plants, nuclear and run on the river hydroelectric plants. Such power units are characterized to have low marginal operation costs and high conversion efficiency. Due to their high inertia (thermal and mechanical) they are not able to quickly react to changes

in demand. For this reason such plants should operate at a fixed level of output close their maximal rate.

- Intermediate load plants, such as hydroelectric and more flexible thermal plants. Their output level can change within specific limits.
- Peak load plants, such as gas turbine and daily hydroelectric plants. Such plants have the flexibility to rapidly react to the changes in demand. Due to their lower conversion efficiency and to their high marginal operation costs, the peak load plants operate for limited periods.

The Figure 2-11 shows a typical load duration curve. The higher amount of electricity is covered by base plants. During the peak load the less efficient, but more flexible, power plants are switched on. As a consequence, the generation costs are higher during the peak periods than during the off-peak periods.

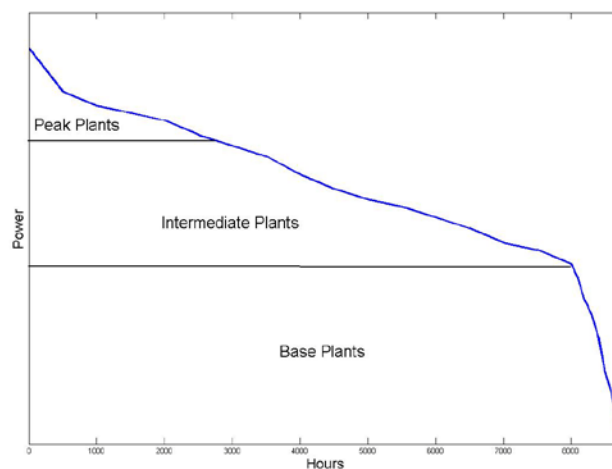


Figure 2-11 Load duration curve

The aim of Load Management (LM) is to control and modify the behaviour of demands of different consumers of a power utility in order to constantly meet the supply in the most economic manner. Secondly, LM strives to make the best use of the available generating capacity, in order to avoid building new power plants and thereby produce more pollution. Three main techniques are adopted in order to manage the loads:

1. Peak clipping
2. Valley filling
3. Load shifting

The goal of peak clipping is to reduce the load during peak periods in order to get a desirable load profile. In order to achieve such an aim Demand Side Management (DSM) programs are generally used. By means of DSM the end users are encouraged to modify their pattern and level of electricity usage. The peak clipping can be a useful technique especially for the utilities that do not possess enough generating capabilities during the peak hours.

Through valley filling, the off-peak loads are built up in order to smooth out the load. Such technique is generally used when the incremental generation costs for producing more electricity are less than the average costs. Then, adding load can decrease the average costs. As an example, during the night electric energy storage systems (pumped storage or electrical vehicles) can be charged in an economical way.

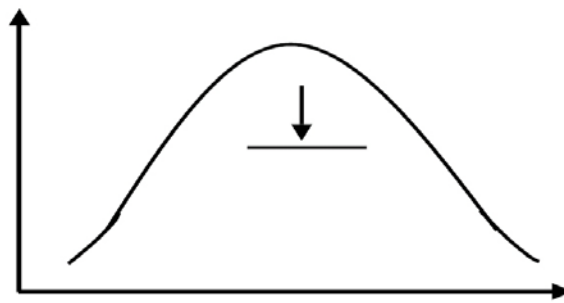


Figure 2-12 Peak clipping

Load shifting consists in moving the energy use from peak time periods to off peak time periods without changing the overall consumption. A practical method for shifting the load is to charge thermal storage or batteries of electrical vehicles during the night, when the overall electricity consumption is low, and to use the stored energy as needed during peak times.

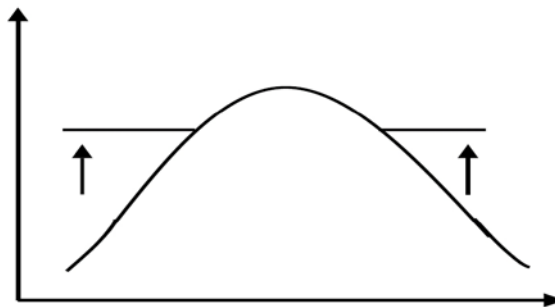


Figure 2-13 Valley filling

Nowadays, one of the most promising strategies to accomplish the LM is the Time of Use Tariff (TOU). The costs of electricity depend on the hour of the day and the season in which it is consumed. As aforementioned, the costs of electricity, and thereby the price, is higher during the peak load periods and lower at off-peak time. Related to the price signals, the end users change their consumption pattern in order to minimize the electricity costs. The end users, especially the industrial users, can plan their activities according to the electricity price. Through TOU the utilities and consumers work together in order to maximize the benefits from the energy use and minimize the electricity costs. Moreover, through TOU the three techniques aforementioned are encouraged. In addition to TOU, the Interruptible Load Tariff (ILT) has also been adopted as a strategy for managing the load. Consumers receive incentives if the supplied power is reduced or interrupted. In some cases the utilities have direct control over the user's load for switching off the consumer appliances.

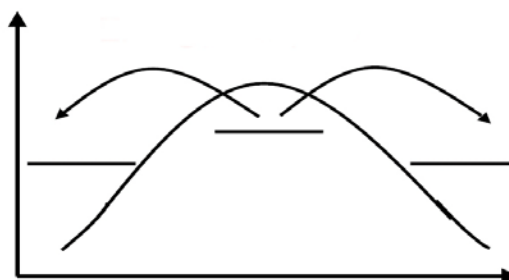


Figure 2-14 Load shifting

2.3.3.5 Conclusions

The generation based on renewable energy sources will play a significant role in the energetic scenarios of the future. This role can become even more significant if the solutions to the problems due to energy congestion are adopted. New transmission lines and load management programs together with energy storage systems can definitely encourage the usage of renewable energy sources.

2.4 STORAGE CAPABILITIES FOR THE FUTURE POWER SYSTEM

2.4.1 REQUESTED SERVICES FROM STORAGE SYSTEMS -TIME

(Pedro Enrique Mercado)

Energy storage is needed to store electricity, which is produced at times of low demand and low generation cost and from intermittent energy sources such as wind and solar power generation. It is released at times of high demand and high generation cost or when there is limited base generation capacity available.

Reliable and affordable energy storage is a prerequisite for using renewable energy in remote locations, for integration into the energy system and the development in a future decentralised energy supply system. Moreover, these concepts straightforwardly extend to the use of traditional fossil fuel-based generation. Energy storage therefore has a pivotal role to play in the effort to combine a future, sustainable energy supply with the standard of technical services and products that we are accustomed to and need. In this way, energy storage is the most promising technology currently available to reduce fuel consumption, and supports the new paradigm of electrical microgrids operation by permitting distributed generation to seamlessly operate as a dispatchable unit and autonomously isolated from the main power system. Storage capacity is defined in terms of the time that the nominal energy capacity can cover the load at rated power. Storage capacity can be then categorized in terms of power density requirements (for short- and very short-term needs), as shown in Table 2-XVII or in terms of energy density requirements (for medium- and long-term needs), as depicted in Table 2-XVIII.

Table 2-XVII Short- and very short-term storage capability

Storage application	Discharge Duration
Spinning Reserve	20s-10min
Primary Frequency Control	<15s
Flicker Compensation	<60s
Voltage Sag/Swell Mitigation	10ms-60s
Uninterruptible Power Supply (UPS)	1s-30s
Integration of Intermittent Renewable Energy Sources	5min-20min
Islanded Microgrid	20s-hours

The operating reserve is the generating capacity available to the system operator within a short interval of time to meet demand in case a generator is lost or there is another disruption to the supply. The operating reserve can be divided into two kinds of reserve power: the spinning reserve and the non-spinning reserve.

The spinning reserve is the extra generating capacity that is available by increasing the power output of generators that are already connected to the power system. For most generators, this increase in power output is achieved by increasing the torque

applied to the turbine rotor. This service can be effectively carried out through energy storage with excellent activation times when compared to traditional approaches. Moreover, the primary frequency control with discharge durations of up to 15 min. can be also performed. (PQ) problems are caused by brief momentary power variations lasting less than a few seconds, and long-term outage. Instantaneous response from an energy storage device can provide sufficient energy to 'ride through' short-term power delivery anomalies and provide bridge power to standby power generation. With the increased use of nonlinear loads in the industry, customer owned computers and other sensitive electronic circuitry, power quality (PQ) has become crucially significant. In particular, harmonic distortion of voltages and currents such as voltage sags/swells and flickers can be generated either externally or internally to an industrial or commercial facility and means of eliminating them or minimizing their effects have assumed greater importance. Despite the fact that various PQ problems can be solved with only reactive power compensation, energy storage can be used to greatly improve the PQ of the electric system.

An uninterruptible power supply (UPS), also known as a continuous power supply or a storage backup is a device which maintains a continuous supply of electric power to connected equipment by supplying power from a separate source when utility power is not available. It differs from an auxiliary power supply or standby generator, which does not provide instant protection from a momentary power interruption. A UPS, however, can be used to provide uninterrupted power to equipment for a limited duration (usually in the range of up to a few hours) until utility power is restored. Sometimes the storage device is backed-up by a generator which can be turned on in due time in order to take over the supply also for longer durations.

An intermittent power source is a source of electric power generation that can be uncontrollably variable or more intermittent than conventional power sources, and therefore non-dispatchable, and it is usually used to refer to renewable energy sources (RES) such as wind and solar. When the utility integration of these intermittent renewable technologies reaches a high penetration level, technical adaptations such as additional back-up capacity or transmission capacity is required. In this sense, energy storage technological solutions are able to deal with this intermittency with a discharge duration in the range of minutes up to hours in order to override the intermittent generation or until other generation units have taken over the supply. The realization of active distribution network technologies will allow radically new system concepts to be implemented; perhaps the most promising novel network structure is the microgrids paradigm. Microgrids comprise low voltage distribution systems with distributed energy resources (DERs) such as microturbines, fuel cells, photovoltaic (PV) arrays, wind power generators, etc., together with storage devices and controllable loads, offering considerable control capabilities over the network operation. These systems are interconnected to the medium voltage distribution network, but they can be also operated isolated from the main grid in case of faults in the upstream network. This implies that reserve plays an important role in the distribution level as it has traditionally done in the transmission level, requiring discharge durations in the range of minutes up to hours in order to balance generation and load during islanded operation of the microgrid or until dispatchable generation units within the microgrid have followed the demand.

Table 2-XVIII Medium- and long-term storage capability.

Storage application	Discharge Duration
Peak Shaving	4h-8h
Load Levelling	4h-12h
Blackstart Capability	2h-10h
Non-spinning Reserve	10min-2h

Peak shaving allows reducing the effect of peak electric demand by providing energy to the electric grid when demand is high; this is the energy stored during off-peak times when demand as well generation cost is low. This practice avoids the need to build new power plants to meet growing demand. Utilities could also idle dirty and expensive "peaking plants", which are only turned on during times of high demand, such as very hot summer days. The discharge duration required for this service is in the order of up to 8 hours. In the same way, load levelling is any load control technique that dampens the cyclical daily load flows and increases base load generation, by employing a higher discharge duration than the previous practice but reducing the power requirement.

A black start is the process of restoring a power station to operation without relying on external energy sources. Normally, the electric power used within the plant is provided from the station's own generators. Frequently a transmission line will be installed to provide this station service power if all the main generators are shut down. However, during a wide-area outage, this off-site power supply will not be available. In the absence of grid power, a so-called black start needs to be performed to bootstrap the power grid into operation. Energy storage units have the capability to provide this ancillary service with discharge duration requirements of up to 10 hours. Non-spinning or supplemental reserve service is the generating capacity which is capable of being brought online within 10 minutes if it is offline, or interrupted within 10 minutes if it is online, and which is capable of either being operated or interrupted for at least 2 hours.

2.4.2 APPLICATION OF STORAGE CAPACITY IN THE DISTRIBUTION SYSTEM (EXAMPLES AND CONCEPTS)

(Pedro Enrique Mercado, Zbigniew A. Styczynski)

In general, a large percentage of the electric power produced is generated by centralized generation plants located far from the consumers and delivered by transmission and distribution systems, with different levels of efficiency; therefore different levels of technical losses. This problem has been increased in the recent years due to the significant growth of electric energy demand and because of the vulnerability of weakly meshed networks, with faults which cause severe transient and dynamic problems, leading to a reduction in system security [108]. Many large blackouts that have happened worldwide in the last decade are a clear example of the consequences of this model of electric power. These problems, far from finding effective solutions, are continuously increasing, compounded by even supply factors (oil crisis), ecological aspects (climatic change) and by financial and regulatory restrictions of wholesale markets. These factors require technical alternatives to assure, on one hand the appropriate supply and quality of the electric power and on the other the conservation and the efficient use of natural resources to preserve the environment. An alternative technical solution to this problem is using small generation units and integration into the distribution network as near to the

consumption site as possible. This solution diminishes the dependence of the local electrical demand on the energy transmission power system. This solution is known as in-situ, distributed, embedded or dispersed generation (DG) and represents a change in the paradigm of the traditional centralized electric power generation [109] [110]. In this way, the usually passive distribution grid is transformed into an active grid, in the sense that decision making and control is distributed and the power flows bi-directionally. Here the idea of using clean non-conventional technologies of generation that use renewable energy sources that do not cause environmental pollution is consolidated [111]. At present, perhaps the most promising novel network structure that would allow obtaining a better use of the distributed generation resources is the electrical microgrid [112]. This new paradigm tackles the distributed generation as a subsystem formed by distributed energy resources, and controllable demand response (DR), also offering significant control capacities on its operation. This grid can be managed as a group with a predictable unit of generation and demand, and can be operated as interconnected to the main power system or as isolated. In this way, the coordinated control of DER and DR would allow maximisation of the benefits for the owners of the microgrid, giving an attractive remuneration, as well as for the users, providing the thermal and electric demands with lesser energy costs and meeting the local requirements of security and dependability [113] [114]. The progress in development of new power electronics based technologies [115], e.g. named flexible AC transmission systems (FACTS), is presently leading the use of advanced energy storage systems (ESS) in order to enhance the electrical grid performance, providing enough flexibility to adapt to the specific conditions of the microgrid and operating in an autonomous fashion. There are many advanced technologies available on the market for energy storage with high potential of being applied in electrical microgrids, including the following:

- Batteries (Li-Ion, NaS, NaNiCl, NiCd, NiMH and Redox Flow).
- Flywheels.
- Ultra-Capacitors (or Electric Double Layer Capacitors – EDLC/DLC) [116].
- Superconducting Magnetic Energy Storage (SMES) [117].

Vanadium redox-flow batteries (VRB) and Sodium Sulphur Batteries (NAS) hold a great promise for storing electric energy on a large scale in the future. They present many attractive features including modular design, long lifetime, high efficiency and fast response. They also show the potential of relatively low investment as well as operational costs. VRB and NAS can be used for a variety of applications such as power quality control, energy management, emergency power, back-up power, load leveling, stabilization of renewable energy, as well as for multiple other applications.

Just as flexible FACTS controllers permit improvement in the reliability and quality of transmission systems, these devices can be used in the distribution level with comparable benefits for bringing solutions to a wide range of problems. In this sense, FACTS-based power electronic controllers for distribution systems, namely custom power (CP) devices, are able to enhance the reliability and the quality of power delivered to customers. A DSTATCOM is a fast response, solid-state power controller that provides flexible voltage control at the point of common coupling (PCC) to the utility distribution feeder for PQ and stability improvements. It can exchange both active and reactive power with the distribution system by varying the amplitude and phase angle of the inverter voltage with respect to the PCC voltage, if an energy storage system is included into the DC bus. The effect is a controlled current flow through the tie reactance between the DSTATCOM and the distribution network, which enables the DSTATCOM to mitigate voltage fluctuations such as sags, swells and transients. In addition, it can be utilized for providing voltage regulation, power

factor correction, harmonics compensation and stability augmentation. The addition of energy storage through an appropriate interface to the power custom device leads to a more flexible integrated controller. The ability of the DSTATCOM-ESS to effectively supply active power allows the expansion of its compensation actions, reducing transmission losses and enhancing the operation of the electric grid.

Figure 2-15 depicts a functional model of a shunt-connected CP device integrated with advanced energy storage for operation in distribution systems. This model consists mainly of a DSTATCOM, the energy storage system with the related filtering and protection system and the interface between the DSTATCOM and the ESS, represented by the bidirectional DC-DC converter. A DSTATCOM consists mainly of a three-phase static power inverter shunt-connected to the distribution network by means of a coupling transformer with line filter and the corresponding control scheme. The three-phase three-level VSI corresponds to a DC-AC switching power inverter using high-power fast isolated gate bipolar transistors (IGBTs). The integration of the ESS into the DC bus of the DSTATCOM device requires a rapid and robust bidirectional interface to adapt the wide range of variation in voltage and current levels between both devices, according to the specific ESS employed. Controlling the ESS rate of charge/discharge requires varying the voltage magnitude (and polarity in some cases) according to the state-of-operation, while keeping essentially constant the DC bus voltage of the DSTATCOM VSI. To this aim, a combined two-quadrant two-level buck/boost DC-DC converter topology by using high-power fast-switched IGBTs is proposed in order to obtain a suitable control performance of the overall system. This step-down and step-up converter allows decreasing the ratings of the overall power devices by regulating the current flowing from the ESS to the inverter of the DSTATCOM and vice versa. Since there are no requirements for electrical isolation between input and output, no isolation circuit is considered in this work.

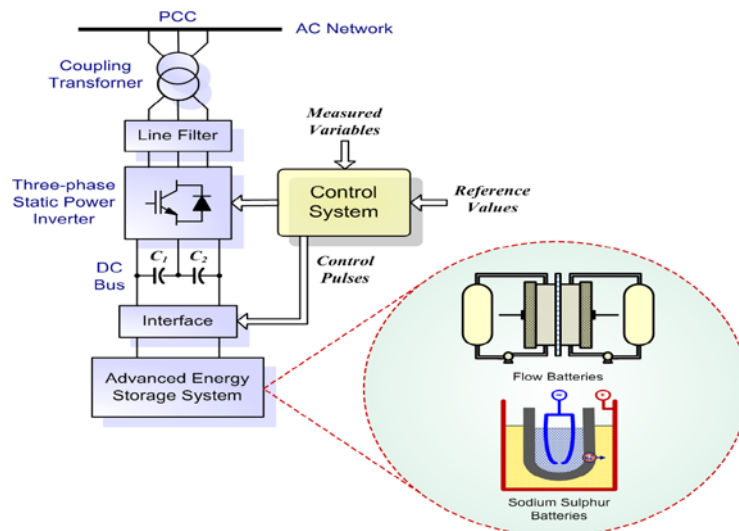


Figure 2-15: Basic circuit of a custom power device integrated with advanced energy storage

2.4.3 APPLICATION OF STORAGE CAPACITY LOCATED IN THE TRANSMISSION SYSTEM

(Patrick Favre-Perrod, Bong- Soo Moon)

2.4.3.1 Applications of storage in transmission networks

Electricity storage applications in transmission networks may pursue different objectives:

- Deferral of investment into new transmission lines
- Reduction of transmission losses
- Increasing the interconnection capacity among loosely coupled subsystems
- Improvement of power system stability
- Stable power system operation and compensation for intermittent power sources

First, a storage system can contribute to deferring the reinforcement of a line or the addition of a new line in a system with an infrequent and marked maximum load, since the corresponding additional line would exhibit a very low utilisation. Secondly storage can also advantageously replace network reinforcements in situations of slow and uncertain load growth. Finally storage systems may represent the only practicable solution when rights of way are too expensive, too long or impossible to obtain. System losses can be reduced in the transmission system by controlling a storage system to reduce load peaks and shift the energy transmission to low load periods. Even if the total transferred energy remains the same, losses are reduced, due to their I^2 dependence. Another reduction of system losses is achieved by using storage to reduce the need for central balancing, and thus the net transmitted energy within the system. In congested networks, storage can contribute to a better distribution of the power flow over the interconnectors, thus increasing the overall transmitted amount of energy. The increased utilisation factor of the interconnectors effectively decreases the adverse effects of congestion.

Based on the high storage capacities required for these applications, it is assumed that transmission applications of storage will be a priority, with the notable exception of the continued use of the existing pumped storage plants.

A generation station or a transmission line fault may occur in a weak power system. At that time, some transmission lines may be overloaded or power cuts may result. Also, if intermittent power sources (wind, solar and tidal power) are connected to the isolated power system, the output of the source fluctuates irregularly; therefore when power sources cannot meet demand, storage systems controlled by the control centre can compensate for intermittent power sources.

For these cases, storage systems which are well distributed and have enough capacity can raise the system voltage and also the back-up devices for power supply to meet power demand. So, storage systems can raise the power system stability, and can support the stable operation of power system and compensate for intermittent power source

2.4.3.2 Factors influencing the value of storage in transmission networks

Different factors may influence the value provided by energy storage systems in transmission networks:

- Investment deferral: new transmission lines add incremental capacity whereas storage can be added at smaller ratings. A storage solution can therefore be advantageous.
- Loss reduction: the value of the storage systems arises from the reduced costs associated with losses and the improved environmental performance of networks
- In congested networks the value of the storage system arises from the difference between the prices in the two zones as well as from the potentially improved utilisation of generation capacities.

Some limitations to the application:

- Conflicts with “must-run” generation: the optimal operation of storage devices may be in conflict with base-load generators. A key point appears to be the flexibility of the rest of the system.
- A too high storage capacity reduces its utilisation factor.

2.4.3.3 Consideration for the installation of storage systems in transmission networks

Each transmission network has unique characteristics. Before we incorporate storage systems into a specific network, we should analyse the targeted power system. Some characteristics encourage the installation of storage systems; while others discourage them. The characteristics of transmission networks are technical, geographical and economical, as follows:

- Technical: power flow, system voltage, stability, fault current capacity
- Geographical: interconnected power system, isolated power system
- Economical: comparisons in ratings, size and weight, capital cost, life efficiency, per cycle cost, etc.

A variety of areas for selecting the location of the storage system installation can be considered.

First, the storage systems installation must satisfy the following conditions;

- The loading rate of transmission lines is high.
- The system voltage is below standard voltage levels.

The fault current and power system: stability need to be checked in detail.

Next, geographical conditions can be considered when installing storage systems in interconnected systems or isolated systems. The storage systems installation must satisfy the following conditions;

- Interconnected power system: high price compared to other areas.
- Isolated power system: only one source exists or not enough power is available for peak demand.

Finally, comparisons between economical considerations should be made. These considerations cover ratings, size and weight, capital cost, life efficiency, per cycle cost and so on.

2.4.4 APPLICATION OF STORAGE CAPACITY IN ISOLATED SYSTEMS

(Joao Peças Lopes, Geza Joos, Marian Piekutowski)

It is recognized world-wide that one of the pathways towards increasing renewable generation relies on implementing energy storage mechanisms due to the variable nature of renewable power sources. The energy storage need is even more undeniable in the case of isolated power systems, such as islands, where renewable energy integration is foreseen to increase considerably.

As a consequence, the scientific community has undertaken some important studies and research activities, which will be briefly recovered henceforth.

When it comes to isolated power systems, the following set of technologies for energy management applications have currently been proposed: battery energy storage; fuel cells; flow batteries; pumped hydro storage; CAES; and flywheels [28].

One of the most mature storage technologies is pumping hydro associated with renewable generation (i.e. wind power). As stated in [29], water pump/generation facilities are added to a wind park and the hydro storage ability makes it possible to: a) store energy produced in low consumption periods to satisfy demand in peak periods; b) store energy in the reservoirs during high wind speed periods to be used afterwards for filling wind-power gaps. When it comes to the particular case of isolated power systems, it is possible to increase wind generation at a competitive cost if all options are examined using externalities. This evidence was ratified in [30], based on an optimum sized economic model of a wind/pumping hydro storage system developed for Gran Canaria island. Furthermore, according to a study developed in [31], for Lesbos Island, the proposed wind/hydro solution, besides allowing wind generation increase, might lead to an improvement of the energy supply stability and the security of supply; reduction of imported oil dependency; minimization of environmental impacts; and regional development free of weighty investment costs. Nevertheless, the research developed in [32], for the islands of Crete and Rhodes – aiming to reduce the annual energy production cost and maximize the wind energy penetration – concluded that the pumped storage introduction in isolated power systems, with high thermoelectric production and wind energy rejection, is not always economically feasible. According to the referred study, the project feasibility depends on each specific power system. Namely, the pumped storage approach is revealed to be particularly suitable for power systems with soaring specific costs from energy generation and high annual consumption of expensive diesel oil. Additionally, according to the study in [33], results showed that including pumped storage can be an effective means of allowing larger penetration of intermittent renewable energy sources, improving both the dynamic security and the economic operation of island systems. In this approach the shedding of pumping units is also considered as a way to keep system stability when sudden wind power losses occur.

In respect to Compressed Air Energy Storage (CAES), this technology is not well suited for small isolated systems, because the rated power of the existing CAES installations is larger than 100 MW. However, on big islands, and according to (Kaldellis, Zafirakis, & Kavadias, 2007) [28], CAES is considered to be a technology capable to compete with pumped hydro storage systems.

Regarding Flywheel Energy Storage Systems, one can find this solution with units in the range of some hundreds of kW. Moreover, its potential operational period is limited by a maximum of a few minutes. Clear benefits can be obtained from the presence of Flywheel Energy Storage Systems in small isolated power systems [28]. As a matter of fact, the introduction of flywheel storage into an isolated hybrid grid

allows an increase of the renewable energy penetration. This statement was inferred by in [34] from a study developed for the island of Flores (Azores, Portugal), in which the addition of a flywheel storage system, in the wind/diesel/hydro power system, has improved the system stability and raised renewable energy penetration, by greatly reducing diesel fuel usage. Flywheels are used in this case to compensate for sudden renewable generation intermittency, quickly balancing the system when facing sudden wind power changes.

Concerning the use of fuel cells, presented, in [35], a study of coupling a wind-turbine with a fuel cell in order to enhance the wind power utilization, in the non-interconnected Greek archipelago grid. The outcome of that study reveals that it is possible to replace conventional power units with a hybrid system, delivering energy at constant power.

When it comes to hydrogen storage in isolated power systems presented in [36] that the surplus renewable generation can be used to produce and store hydrogen and, at times of insufficient renewable generation, electricity is regenerated from the stored hydrogen. The combined operation of renewable generation (i.e. wind power) and hydrogen storage also provides the possibility to use the hydrogen produced from electrolysis as fuel for vehicles, as was stated in [37]. For instance, (Korpas & Greiner, 2007) developed a study in [38] which describes how H₂ storage can be applied in both isolated and grid-connected systems, and how the produced H₂ can be utilized for stationary energy supply and/or as a fuel for transportation. In addition, as a result of a study based on a Norwegian island's power system, it was proposed by (Korpaas, Greiner, & Holen, 2005), in [39], to use H₂ as a fuel for a local ferry. However, according to the assessment presented by (Greinera, Korpas, & Holen, 2006) [40] for a wind–hydrogen energy system implemented on a Norwegian island, it was concluded that an isolated system is a poor alternative, both in what concerns to H₂ cost and from an environmental point of view. Besides, according to a study developed by (Kavadias, Zafirakis, Rozakeas, & Kaldellis, 2008) [41], based on the Island of Crete's information, it was deduced that the optimum size of a hydrogen production facility largely depends on the proportion and time-scattering of the renewable energy being rejected.

Flow batteries, with large electrolytes storage may be applied for large scale energy storage and therefore compete with pumped hydro storage and CAES. This happens because flow batteries' capacity depends on the size of the electrolyte tanks, as affirmed by (Kaldellis, Zafirakis, & Kavadias, 2007) in [28]. In particular, vanadium redox-flow batteries could be a reasonable alternative for load leveling and seasonal energy storage in small grids and stand-alone photovoltaic systems. Specifically, (Joerissen, Garche, Fabjan, & Tomazic, 2003) developed a cost analysis in [42] which shows that vanadium redox-flow batteries could compete with current high capacity lead–acid batteries used in stationary applications. Regarding battery energy storage applications, there are almost no restrictions. However, for instance, Li-ion systems may be used only for very small islands, with a maximum power rate less than 500 kW, as presented in [28].

2.4.5 STORAGE FOR ANCILLARY SERVICES (FREQUENCY CONTROL, RAMP RATE SUPPORT)

(Christian Ohler, Marian Piekutowski, Bong- Soo Moon)

Power systems operation requires the instantaneous balancing of generation and load as indicated by the system frequency. As the load fluctuates in a partially unpredictable way, and as load shedding is generally considered unacceptable, except as a means of last resort, there are particular generators mandated with the task of keeping the balance (active power reserve, frequency control). Unexpected outages of generators also add to the total demand for reserve power, and the size of the largest generators whose outages should be compensated sets the required amount. Depending on the time and duration of deployment, transmission system operators distinguish different types of balancing reserves. The first type, primary frequency control or governor control, provides an immediate response proportional to a frequency deviation of the grid outside a non-critical window. It increases the generator's output if the frequency is lower and decreases the generator's output if the frequency is higher than the grid's nominal frequency. The primary frequency control is performed by a number of generators distributed throughout the connected grid. The second type, secondary frequency control or automatic generation control, resets the frequency to its nominal value and restores the power equilibrium in each control area. The secondary control ramps up to replace the primary control and make it available again for the next contingency. The third and slowest type of reserve power is activated manually upon instruction. Figure 2-16 illustrates the definition of frequency control reserves as used by the UCTE. UCTE requires a total of 3000 MW of primary reserve corresponding to 1.1% of the average system load or 0.6% of total installed power generation capacity.

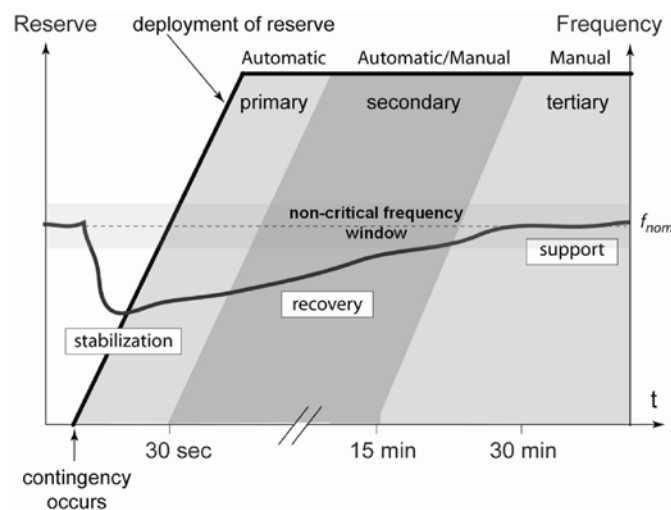


Figure 2-16: Definition of frequency control reserves in UCTE [80]⁵.

Primary frequency reserve is usually provided by throttling thermal power plants. This entails capital costs in terms of idle power generation capacity and operating costs in terms of higher specific fuel consumption off the power plant's design point. Because it is equally likely that power is demanded with positive and negative sign, the task of primary frequency control is well suited for an energy storage unit such as

⁵ Union for the Co-ordination of Transmission of Electricity is the association of transmission system operators in continental Europe with a synchronized grid of 50 Hz frequency serving 500 million people with an annual electricity consumption of 2300 TWh

a battery system. In that application, the energy storage mimics the control characteristic of a power plant operating in primary frequency control mode, injecting power into the system as the frequency drops below and extracting power from the system as the frequency rises above a non-critical window (see Figure 2-17).

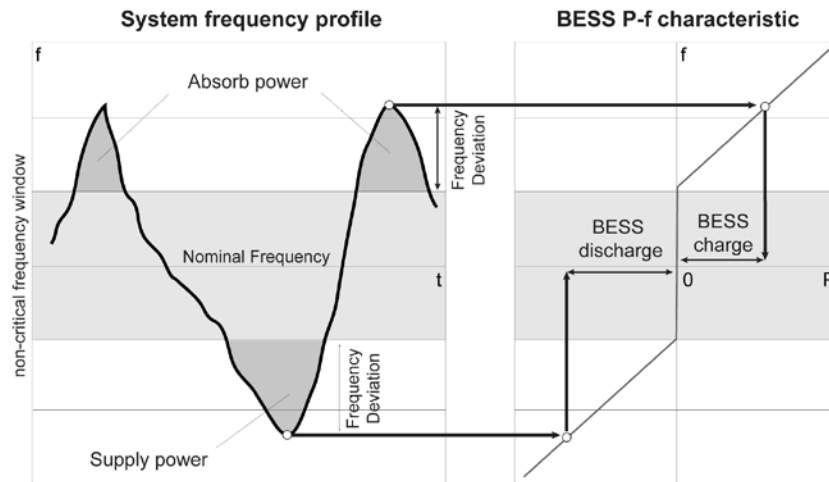


Figure 2-17: Power-frequency (P-f) characteristic of a battery energy storage system (BESS) used for primary frequency control [80].

The capacity of the storage device has to be chosen large enough so that it never runs out of energy. Because any energy storage has only a limited roundtrip efficiency this implies also a slow refill of the storage during times when the frequency is within the non-critical window. It was shown from the analysis of historical frequency data that appropriately sized energy storage with an adequate control strategy can fulfil the technical requirements of the grid code at costs competitive with control prices in the market place [80]. There have been a few practical installations of utility size battery energy storage systems for the frequency control application [81], [82], [83].

2.4.6 INTRADAY STORAGE (DAY-NIGHT)

(Patrick Favre-Perrod)

In these applications a storage system typically undergoes a charge / discharge cycle each day. As a consequence, the energy content of the storage system on day d+1 is largely independent of the charge state on day.

The applications for intraday energy storage may be classified as follows:

- Peak-shaving at distribution level: storage is used for the reduction of the peak load at the distribution substation.
- Load / source decoupling for non-dispatchable and/or stochastic renewable energy sources
- Generator load levelling: storage is used to compensate the difference between the output of a generator and its planned network in-feed.

Table 2-XIX shows the storage system characteristics that are required for these classes of applications.

Suitable technologies for these applications include:

- Peak-shaving: small-scale CAES (using pressure tanks), NaS, Li-ion or Pb batteries;

- Load/source decoupling: CAES (using underground storage), flow batteries, PEM fuel cells combined with electrolyzers;
- Load-levelling: pumped hydro storage, high temperature fuel cells combined with electrolyzers.

Table 2-XIX Expected storage system characteristics for different applications of intraday energy storage

Application	Power [MW]	Stored energy (net capacity) [MWh]	Charge / discharge duration [h]	Storage duration n[h]
Peak-shaving	1	1	1	12
Load/source decoupling	1...10	1...20	1...2	1...6
Load-levelling	10...100	60...1200	6...12	12

The implementation of intraday storage can be done with different levels of centralisation. A centralised approach would typically imply that a storage system has multiple purposes within a network. Decentralised intraday storage implies a different approach: Firstly the sizing of the storage is done for a single application. More importantly ownership and control of such a system will generally be outside of the circle of influence of the network operator.

Using intraday storage schemes, the maximum load of lines and equipment (e.g. transformers) can be reduced, which represents a measure to prevent congestion.

As a consequence, the system reliability can be improved by using storage: intraday storage can provide an economical solution to ensure n-1 security over the peak period. In this case, the stored energy is not fully used in normal operation but is ready to be used in case of a component failure.

The economic advantages of intraday storage include opportunities for deferral of network investments, avoidance of penalties for “energy not served” by renewable generators and more effective maintenance strategies.

2.4.7 STORAGE FOR MORE THAN ONE DAY

(Martin Kleimaier)

In the previous chapters the relevance of energy storage systems has been discussed in the time range up to hours with the focus to cover short-term fluctuations of the renewable sources, thus providing primary and secondary control power as well as minutes of reserve power. Discharge durations and storage durations in the range up to a few hours are generally sufficient for these applications. Up to now the long term fluctuations could be balanced by other power plants. This was possible at the time when wind power was first deployed as it can be assumed that the older conventional fossil-fired power plants which they were replacing would still exist for some time and may be used as back-up in critical situations with low wind. But in the long run and with further increase of wind power plants, this will not be possible any more as these old thermal power plants will come to the end of their life. Then new generation units would be needed in order to cover situations where there is a lack of wind energy. The capacity credit of wind power plants, installed in a given region, describes the percentage of the installed capacity which can be relied on with a high probability. This factor is strongly dependant on the climatic and geographic conditions applicable for a considered region or country. Based on measurements

from Germany it can be seen that for whole Germany (at least on-shore) there are about 700 hours per year where there is literally no wind [136]. These periods can last as long as several days as shown in Figure 2-18 and often coincide with situations of high load in the grid (cold and foggy days in winter or hot summer days - remember the critical situation in Europe in summer 2003). This is the reason why in the DENA-study [137] a capacity credit of only 5 % has been retained. This means that in Germany other generation units with a total capacity of 95 % of the installed wind power plants would be needed in order to replace these wind power plants during low wind periods. The existing capacity of all pumped hydro power plants in Germany is by a large margin to cover these long lasting periods without wind, as indicated also on Figure 2-18.

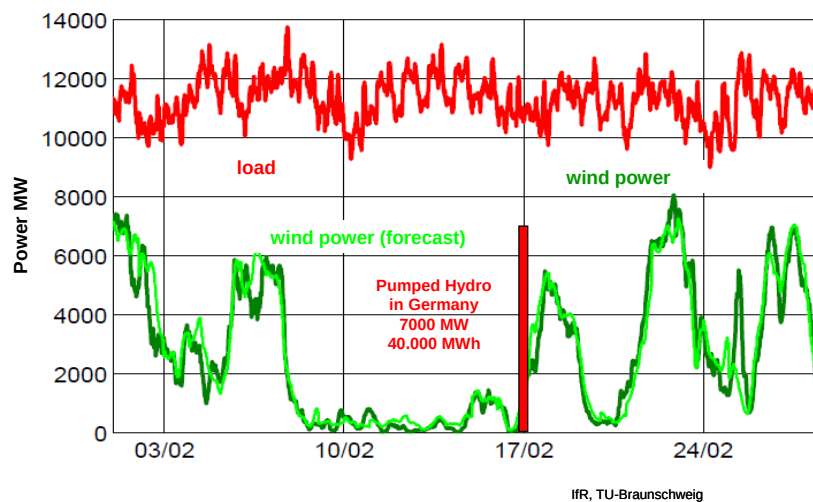


Figure 2-18: Windpower and Load in the Vattenfall High Voltage Grid (February 2008) in comparison with the available capacity of pumped hydro power plants in Germany [138]

In order to cope with generation conditions – either showing a lack or a surplus of power – the power exchange with other countries is discussed to be a possible solution. With further increase of the amount of renewable energy – especially wind energy – this will become more and more difficult as neighbouring countries, exposed to similar climatic conditions, will have to cope with similar generation conditions – showing more or less simultaneously either a lack or a surplus of power. Therefore the distances for energy transmission will become larger in order to connect regions with different climatic conditions or load characteristics. Although the losses increase with long distance transmission, the direct use of electricity at its moment of generation is in most cases still more efficient than storage, even when it comes to long transmission distances of 1000 km and more. This holds true not only from an energetic point of view but also from an economic point of view, at least as long as this can be realized by cost efficient overhead lines. Unfortunately, the construction of new lines – ac or dc – has become very difficult due to the strong opposition of the public to new overhead lines. Underground systems are not yet available for long-distance bulk transmission and will also be much more expensive. Furthermore, one can not be sure if large underground transmission corridors will be better accepted than overhead lines. Situations where there is a lack of renewable energies may be covered by conventional power stations, preferably gas turbines, or in the future also by smaller embedded CHP-units. But also situations with a surplus of wind and/or solar power are to be expected. Already today this can be observed locally and temporarily in regions with a high penetration of wind power like in Germany or in Denmark. This will happen with an ever increasing probability. In order to avoid

wasting the environmentally friendly renewable energy, it is therefore necessary to deal with the possibilities of bulk energy storage systems. These storage systems should be able to balance the fluctuating nature of renewable energies like wind and solar energy within a considered region or country, not only for a few hours but also within longer periods (several days or weeks) or even seasons. When it comes to designing suitable energy storage systems in this context, it is a must to thoroughly analyze the behaviour and availability in time and space of the relevant renewable energy sources. Also the compensation possibilities between different renewable sources, e.g. wind and solar energy, needs to be considered as well as the possibilities of power exchange in the grid. Load management is not seen to be suited to shift the energy consumption for a period of more than a few hours.

Long term bulk energy storage systems need either the possibility to build huge storage reservoirs or a high specific energy density in the storage medium. The former could be realized with large water reservoirs in the mountains (some reservoirs show a capacity of more than 1 TWh), whereas the latter holds true for compressed hydrogen, stored in underground salt caverns. The net energy density of compressed hydrogen, which already includes the efficiency of the conversion back to electricity, is more than 50 times higher than that of compressed air stored in a similar cavern. Although the total efficiency in the hydrogen chain is considerably poor (less than 40 % in a complete cycle: electricity → hydrogen production → storage → electricity) this could be an economic option for long term bulk storage if the cycling frequency is low (e.g. monthly cycling) and if large water reservoirs in the mountains can not be realized.

This has been examined in detail in the VDE-Study [138]. Figure 2-19 shows an example of the economic comparison of different options for long term storage. The costs for hydrogen systems and CAES are expected to decrease during the next 10 years due to learning effects when installed in a larger quantity, whereas the costs for pumped hydro power plants are supposed to be constant over time but are strongly dependent on the relevant site conditions. It can be seen, that hydrogen can become an economic option for such long term storage systems in the future. Another advantage of hydrogen storage is seen in the fact that these salt caverns can be built build close to the shore, thus being well suited for the storage of energy produced in future off-shore wind parks. Nevertheless, it should be mentioned here that hydrogen storage is not an economic solution in applications with more frequent cycling (e.g. load leveling with daily cycling) due to its poor cycle efficiency.

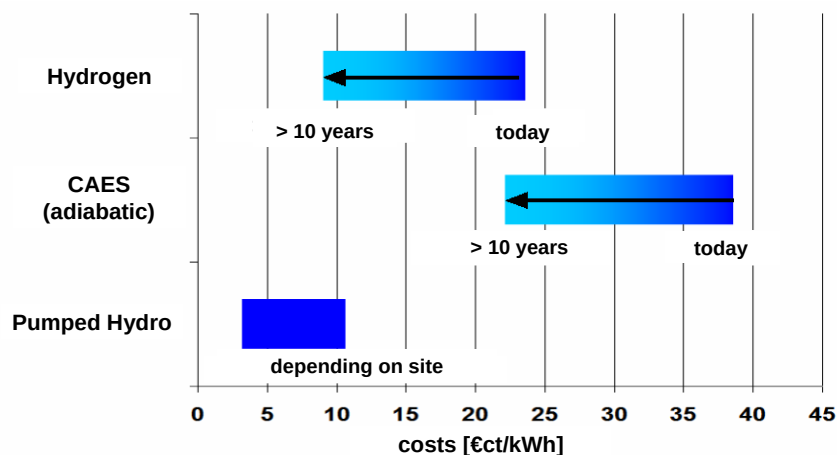


Figure 2-19: Comparison of full costs for long term storage systems [138] (assumptions: 500 MW for 200 hours (100 GWh), 2 cycles per month).

CHAPTER 3 - STORAGE TECHNOLOGIES AND SYSTEMS

3.1 OVERVIEW, TECHNICAL, ECONOMICAL AND RELIABILITY REQUIREMENTS

(Ravi Seethapathy)

Since the invention of the transformer until our current day, the energy production, transmission and distribution sectors have been undergoing tremendous evolution in order to meet continuously increasing power demands. In the process, we have witnessed many power outages that have had catastrophic consequences. Today, utilities have grown to such an extent that many governments have introduced competition in deregulated markets. There are fears that deregulation may open the door to more faults in the grid and costly power outages. Also, the rise in prices of fuel has pushed leading research institutes and government organizations to the promotion of renewable energy sources such as wind and solar power. Again, with this unprecedented step comes a concern of connecting such power sources to the grid and the effects this may have on power quality. In light of all these changes, it is imperative that we assess any new technology using the following three measures: reliability, sustainability and cost-effectiveness [20]. Reliability constitutes that energy be available to the customer at the time and place it is needed and that the energy be of sufficient quality. Sustainability means that the resources and delivery system used can be sustained reliably for an indefinite period of time. Cost-effectiveness means that energy should be produced and delivered at the lowest predictable cost. In response to some of the concerns mentioned above, energy storage applications are being studied to improve the current and future electricity grid systems. There are many applications of energy storage systems (ESS) such as, load levelling, peak shaving, bulk energy trading, integration of intermittent renewable energy sources, island grid, spinning reserve, black start capability, uninterrupted power supply (UPS), flicker compensation and voltage sag correction. The following are the most relevant advantages of ESS [1] [44]:

1. Often single points of failure in a transmission system can affect users miles away due to the cascading effect. This means that even with a highly reliable transmission system blackouts are possible. For example; even though the reliability of the North American Grid is 99.99%, the 0.01% of power outage time (53 minutes/year) may be enough to cause hundreds of millions of dollars in damages to some critical manufacturing sectors and financial data centers. Hence the availability of energy storage systems at load buses may help mitigate the effects of such blackouts.
2. The system operator in an energy market is always in need of fast response balancing mechanisms. Currently, system operators use spinning reserves, which include coal plants. With the introduction of energy storage it will be possible to perform these balancing actions without the need for coal plants hence eliminating that cost.
3. It will allow for the development of generation-storage systems designed to meet the specific needs of unique loads (e.g. military organizations, hospitals, businesses, etc).
4. The power generated by renewable energy systems such as wind and solar is not predictable. This makes it difficult to control the power generated by such systems. However, if coupled with energy storage systems it is possible to make supply

available at periods of high demand. The incorporation of renewable energy increases the sustainability and the long-term cost-effectiveness of the power generation sector.

5. Electricity storage can be used to enhance power quality by reducing harmonic distortions and eliminating voltage sags and surges.

3.1.1 RATINGS

(Ravi Seethapathy)

The three major applications of energy storage are:

1. **Power Quality:** Here energy storage is applied for short periods of time in order to ensure a predictable power outline. Rapid cycling is generally required for better power quality.
2. **Bridging Power:** Used when switching from one power generator to another. Main purpose is to ensure continuity of power supply. Usage is in the order of minutes.
3. **Energy Management:** Used as a storage medium. This helps in applications that involve delivering the power generated to the loads independent of the timing of generation. A good example would be load levelling where energy is bought at low prices and stored for times when prices are high, or generation is low, compared to demand.

Shown in Figure 3-1 is a list of energy storage devices categorized into three types of energy applications (based on their discharge times). This figure illustrates how efficient each type of system is and where they can be efficiently utilized.

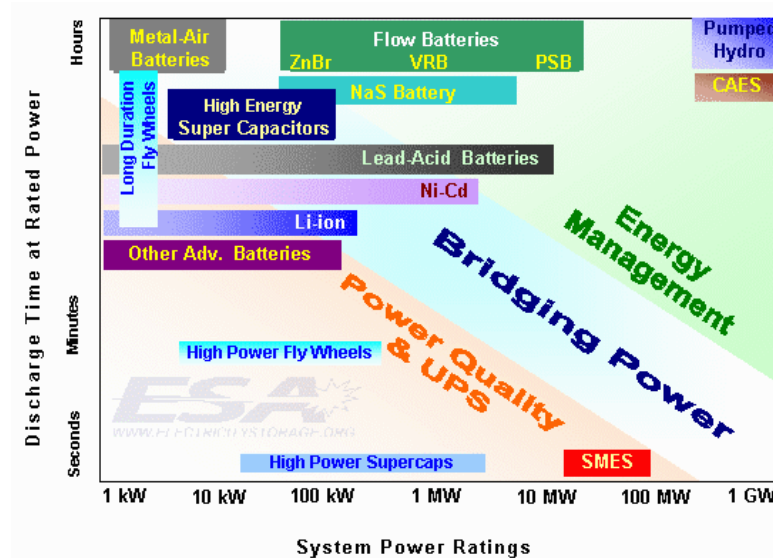


Figure 3-1 Efficiency of energy storage systems

From: Electricitystorage.org: "Technologies and applications". 2003

3.1.2 SIZE AND WEIGHT

(Ravi Seethapathy)

Physical size and weight of storage devices are important factors and have the ability to determine their types of applications. For instance metal-air batteries have the

highest weight energy density, and largest volume energy density, this means that these batteries will be smaller and lighter than a similar powered lead-acid battery, as shown in Figure 3-2. The energy density, volume and weight, ranges reflect the differences among manufacturers, product models and the impact of packaging [44]. The graph in Figure 3-2 illustrates the Weight Energy Density vs. Volume Energy Density for different energy storage technologies. This information may be especially important for selecting battery types for certain applications of power storage [44].

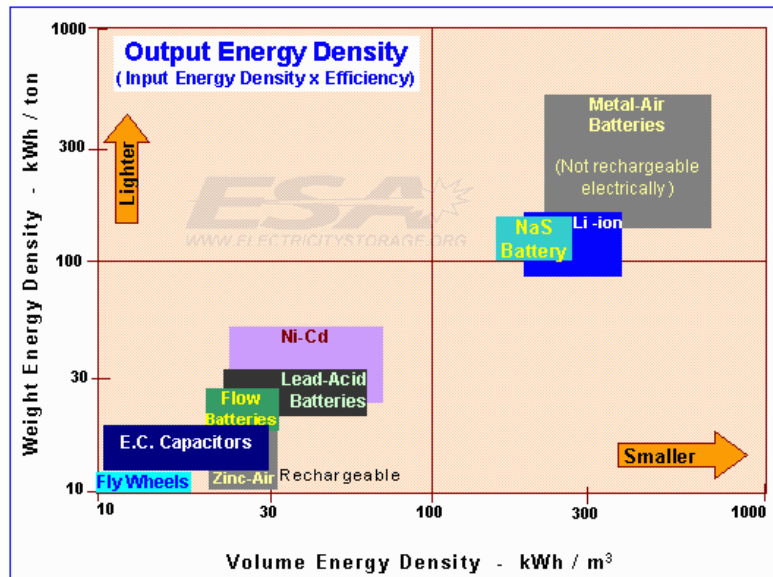


Figure 3-2 Weight Energy Density vs. Volume Energy Density [44]

3.1.3 CAPITAL COSTS

(Ravi Seethapathy)

The overall cost of a project is always a major factor; therefore selecting the appropriate storage device will be affected by capital cost. The graph in Figure 3-3 displays the plot of various battery technologies' costs per unit energy vs. cost per unit power. However, the chart excludes the cost of power conversion, electronics and installation costs. Also the chart does not take into consideration the life cycles of the batteries, hence it is not a sufficient tool to estimate the total ownership cost which would include all these factors [44].

Notes:

1. This chart includes the approximate values of cost in the year 2002. We expect that the cost has continued to change as the technology has been continually advancing [44].
2. From the chart it appears that metal air batteries are the best choice due to their high energy density and low cost, but rechargeable metal air batteries have limited life spans [44].

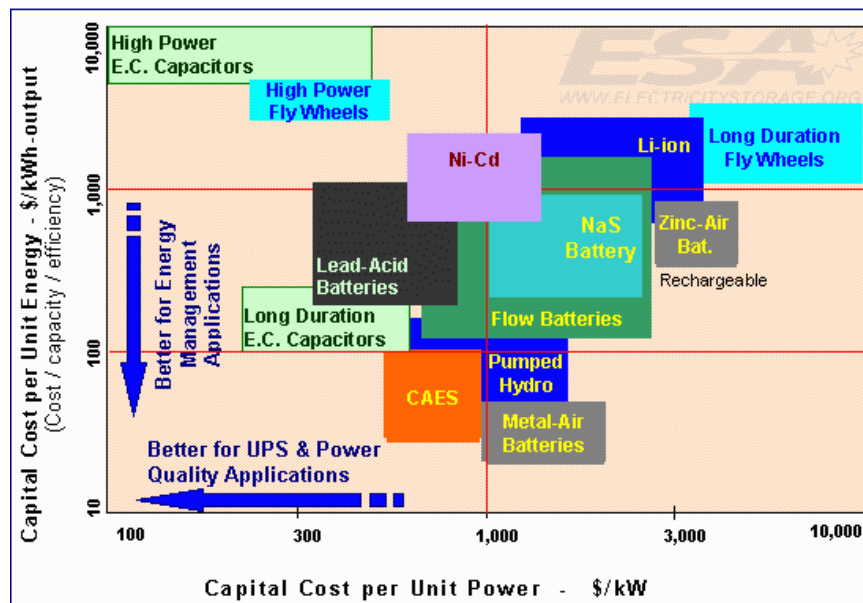


Figure 3-3 Cost per unit energy vs. Cost per unit power [44]

3.1.4 LIFE TIME AND CYCLES

(Henrik Vikelgaard)

The life time of some Energy Storage (ES) devices depends on the number of uses, charge and discharge also called cycles, the depth of each discharge and the age of the device. Also the temperature, under which the device is kept and operated, can influence the total lifetime. For some ES devices only age really counts.

Of course the total economy depends just as much on the real life time of the device as on the price paid.

A good example of an energy storage device whose life time depends on all 3 above mentioned parameters is the lead acid battery.

Owners of a motorbike, or a car, which is stored for a longer period e.g. the winter, have typically learned this lesson. Even though the battery is relative new, much younger than the predicted lifetime, it happens to be dead when spring comes.

The reason for this is that the lead acid typically has quite a high degree of self discharge, and at the same time it doesn't like to be discharged to under a certain level. Left to itself for the whole winter, the lead acid self discharges to a level, which is harmful to the battery. When spring comes it is no longer able to provide either the energy or the power it was rated for. Some of the cells might even have collapsed and short circuited. This is the reason for the application of trickle charging as a useful measure to overcome these kinds of problems. On the other end of the scale is the Super Conducting Magnetic Energy Storage (SMES). Its superconducting coils can last for ever, and will not be deteriorate by any kind of use, subjecte to operating within its specified guidelines. The only restriction in its lifetime will be the age of the auxiliary equipment, such as the power electronics, the cooling system etc.

In between these two extremes we find the rest of the energy storage devices.

For an overview the influence of the different parameters to the lifetime of some storage devices is shown in Table 3-I.

Table 3-I Influence of parameter: Crucial, Medium, Minor, N A (not applicable). The influence is to be understood as relative, i.e. what is most likely to end the life of the device. This again is very much related to the use of the energy storage⁶.

Device / parameter	Age	Number of cycles	Depths of discharge
Lead acid	Medium	Medium	Crucial
Super capacitors	Crucial	Minor	Minor
SMES	Crucial	Minor	N A
NaS	Medium	Crucial	Minor
Li-Ion	Medium	Crucial	Minor

Example

It is not only the number of cycles, but also the definition of a cycle that is important. Let's take a battery pack as an example. From the manufacturer we have been informed that the expected lifetime is 15 years, and the expected number of cycles which can be performed is 3000. What ever comes first ends the lifetime of the ES.

If this ES is used as back up power in an electricity network, supporting an important load, e.g. computers, and for that reason is kept fully charged on stand by, only to be used if (when) the normal network has a failure and is down. In this situation it is not likely that it will be the number of cycles that limits the lifetime of the ES, since 3000 cycles over 15 years equals 200 cycles a year, or more than one every second day.

If the ES is used for production levelling of the output from a wind turbine, the ES will be charged and discharged continuously. In this case, one could fear the 3000 cycles to be reached very soon.

It is also important to know the definition of a cycle, relevant to each specific type of ES, to ensure it is suitable for the use intended.

*"A cycle is a full charge and discharge of the battery. If the battery constantly is charged and discharges 1%, the number of such cycles, that the battery is expected to be able to perform will be a 100 times as many as specified. For our battery we specify at least 3000 cycles. In the 1% charge and discharge case that is 1 equal to 300000 1% cycles."**

Over 15 years this gives us 20000 cycles a year or 2.3 an hour.

Whether this number is sufficient or not, must be judged by looking at the total picture of the context in which the ES is to be used.

The fact that the number of cycles has quite an influence on the real life time of an ES, such as e.g. a Li-Ion battery, is important, not least when the idea of using electrical vehicles as ⁷a local storage for electricity is considered. The idea is to charge and discharge their batteries dictated by the needs of the electricity grid. Doing so can have large influence of the total lifetime of the car batteries, an issue which has been quite troublesome so far.

⁶ Influence of parameter: **Crucial** **Medium** **Minor** **N A (not actual)**. The influence is to be understood as relative, i.e. what is most likely to end the life of the device. E.g. "age" is mentioned as "crucial" for the SMES, since none of the other parameters are expected to be relevant. This again is primarily related to the use of the energy storage.

⁷ Even though the above form of words is taken directly from 2 independent manufactures of two different battery technologies, the definition of a cycle must be confirmed in each case.

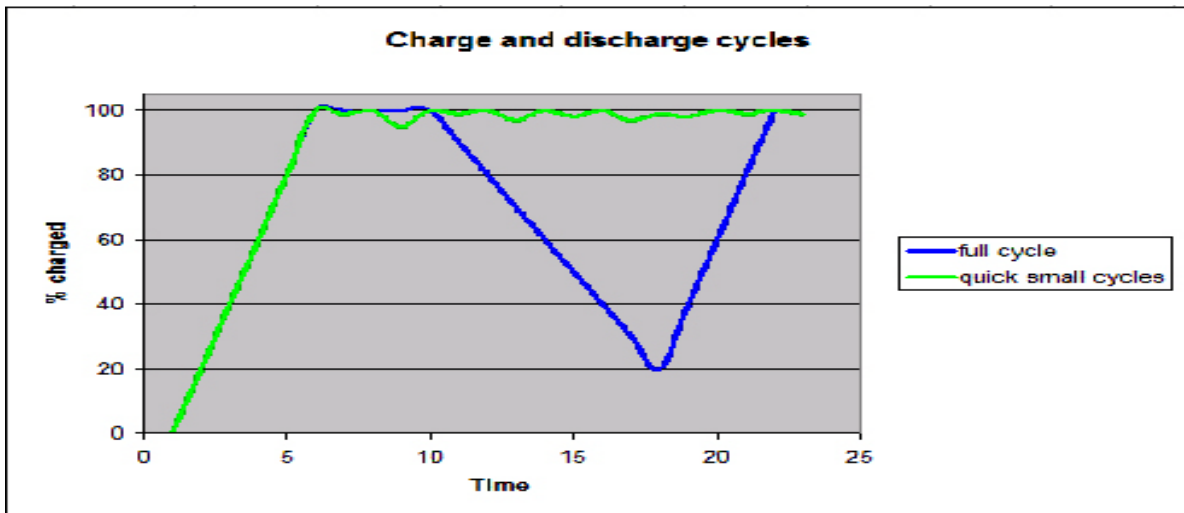


Figure 3-4 The charge and discharge of an energy storage system. Some technologies allow a full discharge others must be kept at a certain level. Normally a 1 kWh system must be expected to produce 1 kWh, but it might need to be charged with more the first time, since the real energy contents could be higher. During normal operation, energy used for charging will always be higher than the outcome, due to the overall efficiency. This can vary a lot depending on the ES system.

3.1.5 LIFE EFFICIENCY

(Ravi Seethapathy)

In order to get a better picture of the real ownership cost of any energy storage system, it is necessary to factor in its life efficiency and cycle life. These parameters are important to consider before selecting a storage technology. Low efficiency, for example, contributes to a higher effective energy cost since now only a fraction of the input energy can be used. Also, short life spans of storage devices contribute to a higher cost, as devices will need to be replaced more often [44]. Figure 3-5 below is a graphical representation of the efficiency of the energy storage device and how many cycles (at 80% depth of discharge (DoD)) the battery is capable of. This graph shows that for a storage device which has requirements of relatively high discharge and high efficiency an EC Capacitor (super capacitor) and Li-ion battery may be considered.

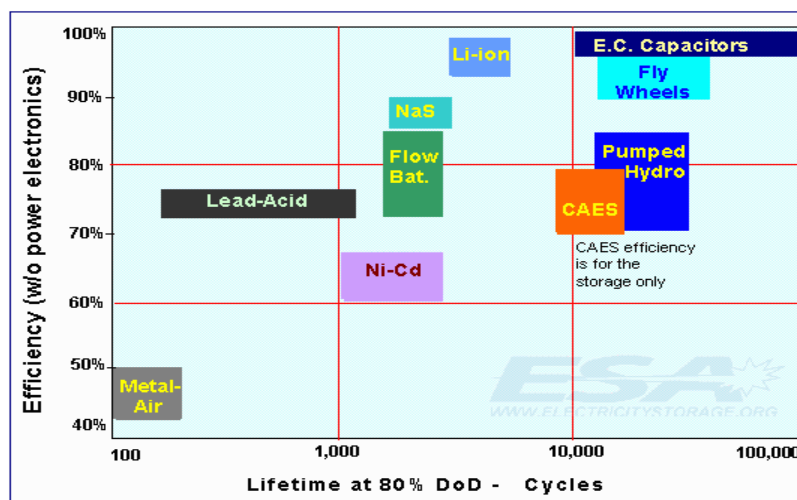


Figure 3-5 Efficiency vs. Lifetime [44]

Energy storage systems with a low cyclic efficiency may still be deployed effectively, especially in circumstances where other factors such as low capital cost (investment) are more important. This may be relevant for applications such as black start, which have only occasional use. Beside the cycle efficiency also the stand-by losses (including auxiliaries) must not be disregarded.

3.1.6 PER CYCLE COST

(Ravi Seethapathy)

Per-Cycle cost is the capital cost of one full cycle (charge and discharge) of a storage device. For frequent charge/ discharge applications, per cycle cost is perhaps the best way to evaluate energy storage cost [44]. The chart below (Figure 3-6) displays the capital cost of a technology taking into account efficiency and cycle life. However the chart does not include the operation and maintenance, disposal, replacement and other ownership expenses. Also, the per-cycle cost is not a good criterion for peak shaving or energy arbitrage (temporary holding for renewable energy) applications that have less frequent charge/discharge cycles [44].

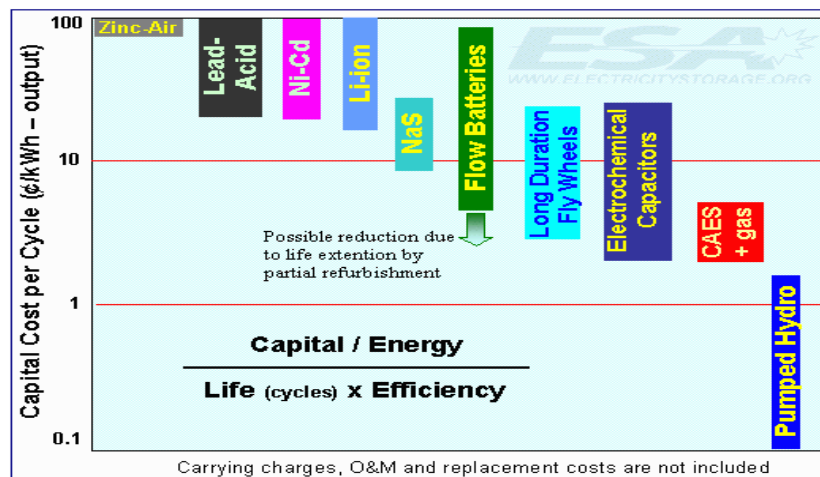


Figure 3-6 Capital Cost taking into account efficiency and cycle life [44]

3.1.7 APPLICATION OVERVIEW

(Ravi Seethapathy)

Based on previous success in energy storage, future applications can be compared for better understanding of their capabilities. As seen from Figure 3-7 Pumped Hydro Energy Storage (PHES) systems and NaS batteries have one of the highest discharge periods (discharge duration); as well from previous data they have high efficiency, long life cycles and comparable capital costs. Due to this there was an increase in the number of PHES systems and NaS systems built in the past (as shown in Figure 3-8). Moreover, as these new technologies reach maturity they are becoming even more promising due to their overall properties. For a clearer understanding of what the energy storage technologies hold and where they are headed see Table 3-II for an overall comparison and application chart.

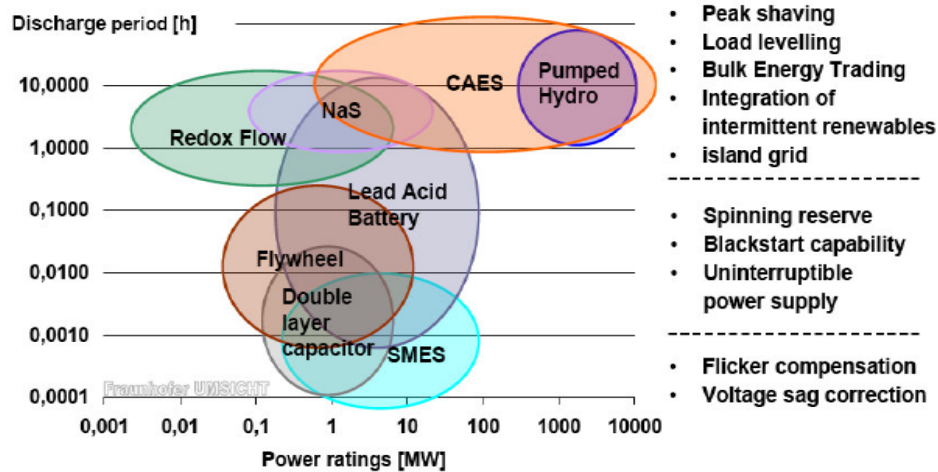


Figure 3-7 Storage Technology Comparison [44]

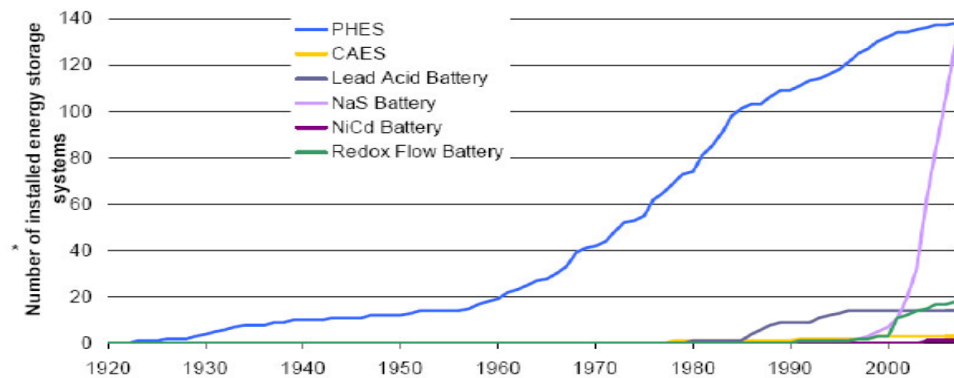


Figure 3-8 Historical Development of Installed ESS [44]

Table 3-II Comparison Chart of Various Energy Storage Technologies [44]

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

● Fully capable and reasonable

◐ Reasonable for this application

○ Feasible but not quite practical or economical

None Not feasible or economical

3.1.8 CONNECTION OF ENERGY STORAGE ON THE POWER SYSTEM

(Anthony Price)

3.1.8.1 Introduction

There are many different options for the connection of an energy storage system to the power network. The energy storage system comprises all the equipment, including control and instrumentation necessary for operation of the device on the power network, and is not just the energy storage medium.

Energy storage systems based on conventional rotating machinery such as pumped hydro plant or compressed air energy storage using a combustion turbine as the final stage of the process can be connected to the network in a similar manner to the connection of an alternator. Most systems require a power conversion system (PCS) between the energy storage medium and the grid supply. For a battery system this would be a DC – AC converter, or for some systems such as flywheel a variable speed converter between the 50 or 60 Hz AC supply and the high-speed alternator / motor which turns the flywheel is required.

Modern PCS are assembled from semiconductor components. Manufacturers choose an appropriate semiconductor topology to match the voltage and power of the energy storage device. Economies in the PCS can be made by increasing the DC voltage of the storage device, or by gaining economies of scale or production by using a modular approach. Some manufacturers are able to use existing designs, such as motor controllers to reduce the costs of designing specialist equipment. This is a rapidly changing area, and commercial and technical details change frequently, depending on the manufacturers of the energy storage medium and the PCS.

Modern PCS are installed with sufficient filters and damping components to reduce harmonics to acceptable levels. Although the first generation of electronic AC / DC power conversion units may have affected power quality, modern energy storage devices are now installed on power systems to improve power quality.

3.1.8.2 Network issues

Network companies have their own standards for the connection of equipment to the network. The standards may depend on the voltage of the connection and the power rating of the device. Typically, large plants (say over 50 MW) connected to the transmission network must comply with a transmission code (such as the Grid Code published by the National Grid Company in the UK [45]) which requires a generator to continue to support the network even when the frequency falls. In contrast, distribution companies still have requirements that the generating plant trips in the event of low frequency or system blackout [46]. This is going to change as it will no longer be tolerable that a ever larger number of dispersed generating units are going to trip upon system disturbances (fault-ride through) thus causing additional problems in the grid. These codes, along with other national and international standards will define how the energy storage device should be operated. Standards will also dictate performance in terms of harmonics, fault currents etc.

Although pumped hydro plants have been operated on power systems for many years, most other types of energy storage are still relatively novel and network companies may adopt different and contradictory approaches to their installation and

operation. When charging, the energy storage plant appears as a load, but when discharging they may appear to be a generator. High power devices connected through a power conversion system could be treated as a DC – DC interconnector, and this may often be the most appropriate standard to use.

3.1.8.3 Energy storage applications and methods of connection

An energy storage device that is to offer services to the network (such as peak shaving, reserves or frequency regulation) will be connected to the network in a similar way to a conventional generator, using a combination of circuit breakers and transformers.

An energy storage device that is to be used as an uninterruptible power supply may be connected in alternative ways such as:

- Off-Line (Standby), a standby UPS uses the line power to keep its battery charged and relies on an integrated transfer switch to switch the supply over from the network to the battery supply. This is not instantaneous, but can occur within a few milliseconds, which is sufficient for many purposes.
- Line-Interactive, in the line interactive UPS configuration, the inverter is always connected to the UPS output and the inverter runs in reverse to keep the battery charged. If the network fails, the transfer switch opens, the battery discharges through the inverter and supplies power to the local load. A line interactive UPS can also provide voltage regulation during sags, attenuate spikes and provide power conditioning.
- On-Line (double conversion), an on-line UPS is popular for large scale installations in the MW category. The incoming AC power is converted to DC and then back to AC for delivery to the local supply. The waveform is then recreated, providing uniform power. Because the inverter is always operating, there is no delay for switch over as in the standby or line interactive modes described above.

3.1.8.4 Point of connection

The actual point of connection is also important. A frequent criticism of policy for renewable energy is the lack of suitable points of connection for distributed renewable generation sources. This comment also applies to the availability of points of connection for electricity storage

For a moderate scale installation of say 10 MW, it may mean that the cost of connection becomes prohibitive. An energy storage plant of 10 MW output, may also need to be recharged at 10 or 12.5 MW (allowing for 25% efficiency loss) making a potential swing of 22.5 MW between charging and discharging. On a small substation, such a high rate of change may be much greater than the transformer auto tap changers can accommodate, and so much of the benefit of fast acting storage is lost. Even on a large substation, a fast changing load may interfere with other users preventing connection.

3.1.8.5 Specific issues - applications

The intended application for an energy storage plant will have implications for the method of connection and the specification of the system (in particular the power

conversion system). For example, a large energy storage system that is required to be grid code compliant and capable of continuing to feed a network, even against a decaying system frequency will need to have a power converter that is capable of independent operation. This is considerably more expensive than basic power conversion units that operate solely in conjunction with a reference network frequency. An energy storage system that is required to provide black start duties to power system equipment must be capable of generating an AC waveform without a reference waveform from the system.

3.1.8.6 Specific issues - technologies

Some battery types require careful consideration of connection issues under certain circumstances. Flow batteries may require a “jockey” battery in order to start pumps and ancillary equipment in the event of a black start. High temperature batteries may require additional power supplies to ensure that battery temperature is maintained to provide either continuous capability or to avoid battery damage.

3.1.8.7 Regulatory effects

In many jurisdictions there is a separation of roles between licensed generators, licensed network companies and supply companies. A network company is often prohibited by law or by regulatory policy from selling or trading in electricity. Therefore, if a network company installs a storage device to support frequency or provide reserve, they would be operating contrary to the terms of their licence if they bought and sold electricity to operate the plant. In some jurisdictions, these regulations are being relaxed in order to allow the introduction of energy storage at the distributed level, but in many places these issues have yet to be explored or tested with the legal and regulatory bodies.

Different regulations apply to different size plants. If energy storage is considered to be generation, then it may be necessary for the plant to be granted a generation licence or permit.

3.1.8.8 Environmental and societal issues

As many energy storage technologies are relatively new, existing product standards may either not apply or not be as relevant as intended. For example, European directives on placing batteries into the market are written to include conventional battery systems but to exclude hydrogen fuel cells systems, which have a similar electrical function [47]. Hence, battery manufacturers will be faced with different cost penalties than developers of other electrical energy storage systems such as flywheels or thermal storage.

In addition, the lack of coherent, internationally accepted standards means that developers may have to work to meet the requirements of standards for batteries and other equipment which were written for other systems. The IEEE PES group is examining many of these standards and plans to report on the applicable standards in due course.

3.2 NATURAL AND PUMPED HYDRO STORAGE

(Ravi Seethapathy, Anthony Price)

Pumped Hydro Storage is the most widely used method of storing energy for power networks. The conventional design incorporates the use of two water reservoirs at different altitudes. During low demand periods, energy from the grid is used to pump water to the reservoir with higher gravitational potential energy. At periods where there is high demand or when the production of the energy is profitable, the water is passed through turbines and allowed to drop into the lower energy reservoir. Certain high dam hydro plants that have a high reservoir capacity can be considered to be used as storage, at least in terms of its rapid response and high ramp rates.

A new use for pumped storage systems is to level the fluctuating output of intermittent power sources. The pumped storage absorbs power at times of high grid generation and low load demand, which can act as additional power during high demands. In certain jurisdictions, electricity prices may be close to zero or occasionally negative (Ontario in early September, 2006), indicating there is more generation than load available to absorb it, and pumped hydro is able to use this to its advantage and store excess power. It is particularly likely that pumped storage may become especially important as a balance for very large-scale photovoltaic generation [44] [66].

Pumped hydro storage systems have an efficiency of 70-85% and are available at any scale with discharge durations as short as a few hours. However, they take a long time to construct and are expensive [44]. On the other hand, the lifetime costs are low since the pumped hydro plants have long lifetimes and can be refurbished. Recent plants, such as Goldsthal, were built for a capital cost of 375 €/kW [134].

Nevertheless it has to be mentioned that, at least in Europe, the construction of new pumped hydro power plants has raised strong public opposition because their construction highly influences the local environment.

3.3 BATTERY ENERGY STORAGE

(Ravi Seethapathy, Anthony Price)

3.3.1 LITHIUM ION (Li-Ion) BATTERIES

At present, lithium ion batteries are dominating the small portable electronic markets. With key advantages such as a high open circuit voltage and extraordinary efficiency of nearly 100%, these types of batteries are becoming more popular as they advance and meet economy of scale [59]. Further, lithium ion batteries do not suffer from memory effect and also have a low self-discharge rate.

On the down side, this type of battery is very expensive (over \$600/kWh) due to its special packaging and internal overcharge protection circuits [44]. This is why Li-Ion batteries have found their use in the portable electronic system since their power to weight ratio makes them a perfect fit (neglecting cost). Yet, if this is to become a suitable option for large scale power integration for peak shaving or storage, the high cost of the batteries must be reduced and, the discharge technology used in “smart” Li-Ion batteries must be adapted [62] (where each cell has a small constant drain of the built in voltage to eliminate permanent power loss capability).

3.3.2 SODIUM-SULFUR (NaS) BATTERIES

This hermetically sealed battery is kept at approximately 300°C and is operated under conditions to allow for fast discharge and recharge. At this temperature the NaS battery operates well due to its low internal resistance, and because of the reversible charging and discharging, the NaS battery can be used continuously [63]. NaS battery cells are efficient (about 89%) and have a pulse power capability over six times their continuous rating (for 30 seconds) [71]. This attribute enables the NaS battery to be economically used in combined power quality and peak shaving applications (sending power to the grid when the demand is high).

More than 250 MW of NaS batteries have now been installed, mainly in Japan and USA and some systems are now operating in Germany. The largest system currently operating is rated at 34 MW and 220 MWh and is installed alongside a 50 MW wind farm in northern Japan [53].

3.3.3 METAL AIR BATTERIES

Metal-air batteries are compact and relatively inexpensive. However these batteries have a life of a few hundred cycles and an efficiency of about 50%. Note that the electrical recharging of metal air batteries is difficult and inefficient; hence most are not rechargeable [44].

3.3.4 LEAD-ACID BATTERIES

Although having the second lowest energy-to weight ratio, next to nickel-iron battery, and correspondingly low energy-to-volume ratio, lead-acid batteries do have the ability to provide high surge currents, i.e., the cells can maintain a relatively high power-to-weight ratio (i.e. a high overall performance as a power source). These abilities, along with their low cost, make lead-acid batteries great for UPS applications and the automobile market.

Its low cost also makes it a popular choice for small power requirements. Applications of lead acid batteries in energy management have been limited due to its short life cycle [44]. One of many implementations of the lead acid battery is by American Electric Power (AEP), which purchased and installed a commercially available 250-kW, 30-s Pure Wave UPS, which uses conventional lead-acid batteries. From May 2001 to May 2004 this unit operated 486 times with an average run time of 1s. Although many of the events were less than 0.5 s, there were several which ran close to the rated 60 s [60]. This shows that although this may be an old technology, it still has the capability of working with large-scale energy storage applications.

There is considerable development work taking place in this technology and improved lifetimes have already been achieved. As there is already an established infrastructure for recycling lead acid batteries the environmental issues have already been addressed.

3.3.5 COMPRESSED AIR ENERGY SYSTEM

(Ravi Seethapathy)

Compressed air energy storage (CAES) systems are systems where in times of excess energy production, energy is used to compress air, and at times of peak energy demand, the compressed air is used to generate electricity.

CAES is an available technology for large-scale energy storage. Unlike a typical natural gas turbine, that consumes two-thirds of the natural gas in a conventional power plant (due to the gas being used to drive the machine's compressor), a compressed-air storage plant uses low-cost heated compressed air to power the turbines and create off-peak electricity, while conserving some natural gas [63]. A few real world examples of this technology are a 220 MW plant, which has been operational in Germany since 1978, and a 110 MW plant, which has been operational in Alabama (USA) since 1991 [68].

There have been many proposals for new installations of CAES using a number of alternative configurations. Many of these thermodynamic cycles avoid the need to burn primary fuel in the energy recovery phase by using an intermediate thermal energy storage system.

3.4 ROTATING STORAGE (FLY WHEELS, INDUCTIVE COUPLINGS)

(Ravi Seethapathy)

A flywheel is a device that uses electrical energy to rotate a rotor at very high speeds. In this way the energy is conserved in kinetic form until it is needed.

Flywheels have the ability to charge and discharge rapidly, and are almost immune to temperature fluctuations. They take up relatively little space, have lower maintenance requirements than batteries, and have a long life span. Flywheels are relatively tolerant of abuse — for example, the lifetime of a flywheel system will not be shortened by a deep discharge unlike a Li-Ion Battery. Although on the down side its power loss on stand-by is much faster than it is for typical batteries [44].

Flywheels are particularly suitable for power quality control. Large scale installations of several 10's of MW have been installed in defence applications and for specialised scientific processes. Such systems would offer inherent stability, minimal power loss, and simplicity of operation as well as increased energy storage capacity, which may show a promising future for use in the power sector [63].

3.5 FLOW BATTERIES

(Ravi Seethapathy)

There are three main types of flow batteries:

- Reduction-oxidation flow battery;
- Hybrid flow battery;
- Redox fuel cell.

Flow batteries can be used for a very high number cycles (charging and discharging cycle). They are also more efficient and have a longer discharge time than lead acid batteries (which are their main competitor). They have an efficiency of 75% to 85% compared to 70% to 75% for lead acid batteries, and a discharge time of several hours compared to less than an hour for lead acid batteries at their rated power.

Lithium ion batteries are not usually comparable because they have a:

- Higher efficiency than flow batteries;
- Shorter discharge duration than lead acid batteries;
- Higher cost than either lead acid or flow batteries.

The power (MW) and energy (MWh) ratings of flow batteries are independent of each other. Therefore, increasing the power from the facility necessitates additional cell stacks, whereas expanding the energy capacity of the system is accomplished by expanding the amount of electrolyte stored within the unit. Flow batteries are currently available in single digit kW to 10's of kW in size, with sizes in the 100's of kW expected to be available in the future [44].

3.6 HYDROGEN AS ENERGY STORAGE

(Zbigniew A. Styczynski)

Under normal conditions hydrogen is a very light gas with a high gravimetric calorific value of 120 MJ/kg. But the volumetrically calorific value is only 10 MJ/Nm³.

After the production, the storage and transportation of hydrogen are the technical challenges.

There are 3 types of hydrogen storage:

- Storage and transport of pressured vaporous hydrogen;
- Storage and transport of cold liquid hydrogen;
- Storage and transport of hydrogen compound in chemical or physical structures.

Gaseous hydrogen is compressed to pressures from 200 up to 900 bars and stored as CGH₂ (compressed gaseous hydrogen) in pressure tank. The compression requires energy and the tanks need to be constructed of the right materials to hold the pressure and avoid the diffusion of hydrogen. To achieve higher energy densities the hydrogen can be stored in a cryogenically liquid state LH₂ (liquid hydrogen). To do this a temperature of -240 C (33 K) is needed and this occurs in specialized isolation tanks. The energy density of LH₂ is about 50% higher than that of CGH₂ at normal operating range. To achieve even higher energy densities some research projects consider a possibility to produce and store hydrogen as so called "slush". These are a mixture of liquid and solid hydrogen phases at even lower temperatures around -259 C (14 K). Slush has a 10% to 20% higher density than liquid hydrogen, but the manufacturing cost is very expensive. In addition to CGH₂ and LH₂, the storage of hydrogen in chemically or physically bounded form is possible. The challenges will be the high weight of the substrate material and the often complex conditions of loading and discharge (time, pressure and temperature).

Table 3-III The parameters of hydrogen at under different conditions are shown [148]

Hydrogen	Pressure [bar]	Temperature [°C]	Density [kg/m ³]	Energy Content [MJ]	Energy Content [kWh]
1 kg	1	25	0,08	120	33,3
1 Nm ³	1	25	0,08	10,7	3,0
1 m ³ gas	200	25	14,5	1685	468
1 m ³ gas	350	25	23,3	2630	731
1 m ³ gas	750	25	39,3	4276	1188
1 m ³ gas	900	25	46,3	4691	1303
1 m ³ liquid	1	-253	70,8	8495	2360

3.6.1 . Gaseous hydrogen storage

Gaseous hydrogen is generally compressed between 200 and 350 bars. Storage pressures of 700 bars and more are currently being tested.

Gaseous hydrogen storage is a closed system. This means that gaseous hydrogen can be stored for long periods with no or low losses if the used materials prevent the diffusion of hydrogen. At 700 bars the density is 40 kg / m³ and about 50% lower than the density of liquid hydrogen and the required energy for the compression is about 15% of the energy content. At these pressures the tank will become very complex and heavy. The storage weight is currently about 20 kg to 40 kg per kg of stored hydrogen. This pressure level will probably be used in fuel cell vehicles.

Furthermore, gaseous hydrogen can be stored under pressure in appropriate caverns. These caverns should not permit the diffusion of hydrogen and extensive security precautions must be taken.

3.7.2. Liquid hydrogen storage

Because of the higher density of LH₂ compared to GH₂ or CGH₂ a significant reduction of the required storage volume is possible. These afford advantages especially for the storage and transportation of large quantities of hydrogen or in mobile applications. But therefore a significant energy demand for the liquifaction and complex technical equipment is needed. The storage tank system has an inner tank and an outer container, with a vacuum between the two for insulation. The vacuum prevents the heat transfer by convection. If heat comes to the inner tank the pressure and temperature increase by the vaporisation of hydrogen. Tanks for liquid hydrogen therefore always have a pressure-release system and a safety valve.

3.7.3. Solid hydrogen storage

Many materials have the property to make physical or chemical compounds with hydrogen. The bonds may be in solid, liquid or gaseous media. The available solid state (hydride) storages on the market have a weight of around 30 to 40 kg per kg of stored hydrogen. In most cases the charge and discharge is very complex.

The storage capacity is today between 3 to 5 percent by weight [150] [151].

Today hydride storages are small cartridges used as hydrogen supply in mobile applications and portable small consumers such as laboratory equipment and in submarines.

3.7 SUPERCONDUCTING MAGNETIC ENERGY STORAGE (SMES)

(Ravi Seethapathy)

SMES is a type of energy storage systems where energy is stored in a magnetic field created by the flow of direct current in a superconducting coil. This system is highly efficient with approximately 95% efficiency from input back to output [63] without any stand-by. SMES systems have many advantages over typical storage systems. The most important advantage of SMES is that the time delay during charge and discharge is quite short. Power is available almost instantaneously and very high power output can be provided for a brief period of time. Other energy storage methods, such as pumped hydro or compressed air, have a substantial time delay of seconds to several minutes depending on the size of the system, and this delay is associated with the energy conversion from the stored mechanical energy back into electricity. Thus if a customer's demand is immediate, then a SMES is a viable option. Additionally, the main parts in a SMES are motionless, which results in high reliability [69]. Due to the energy requirements for the refrigeration of an SMES system and the high cost of superconducting wires, SMES systems are currently used for short duration energy storage. Therefore, SMES is most commonly devoted to improving power quality.

There are several small SMES units available for commercial use and several larger test bed projects underway. Usually, 1 MW units are used for power quality control in installations around the world, especially to provide power quality at manufacturing plants requiring ultra-clean power, such as microchip fabrication facilities. One example of utility applications of SMES systems is based in northern Wisconsin (USA) where a string of distributed SMES units was deployed to enhance stability of a transmission system. The transmission line is subject to large, sudden load changes due to the operation of a paper mill, with the potential for uncontrolled fluctuations and voltage collapse. Developers of such devices include American Superconductor Inc. Most developments are stopped for economical reasons. Today only Japan still has actual developing projects for SMES.

3.8 SUPERCAPACITORS

(Pedro Enrique Mercado)

Capacitors store energy through the electric field produced between two conducting plates (electrodes), when a DC voltage is applied across them. The so-called supercapacitors (SC) or ultracapacitors (UC) use a porous structure of activated carbon for one or both electrodes, immersed in an electrolytic solution (typically potassium hydroxide or sulphuric acid). This structure effectively creates two capacitors (between each electrode and the electrolyte medium) connected in series, as shown in Figure 3-9. Due to this feature, these capacitors are also known as electrochemical double layer capacitors (EDLC or simply DLC). Electrical energy is stored in the device and released according to the same principles as standard capacitors. However, the key difference of the supercapacitor is that with its structure of liquid electrolyte and porous electrodes, a very high effective surface area is obtained (hundreds of m^2/g) compared to the conventional electrode structure.

Furthermore, it ensures a minimal distance between the two plates of the electrodes (few Å). These two factors lead to a very high capacitance per unit of volume, which can reach thousands of times larger than electrolytic capacitors. The electrolyte in the capacitor may be aqueous or organic, where the aqueous capacitors have lower energy densities compared to the organic capacitors. Aqueous capacitors also function under a wider temperature range and are less expensive, too. Also, electrochemical capacitors can be cycled tens of thousands of times and are more powerful than batteries [102]. Supercapacitors share part of the chemistry of batteries, but the aim is to operate them at a voltage range of cells that leads to only electrostatic storage of charge. If they become charged too high, then chemical reactions begin to occur and the cell behaves more like a battery. While supercapacitors can be comparable to lead-acid batteries in energy density and cost, they offer huge advantages which make them almost non comparable in many applications. Because they have no moving parts, and require neither cooling nor heating, and because they undergo no internal chemical changes as part of their function, they are very efficient and robust, and have superior performance at low temperatures. Also, they require practically no maintenance and the lifetime is measured in decades, withstanding thousands of fast charges and deep discharges with no lifetime degradation, which can make them a perfect fit for voltage regulation in the power world. Supercapacitors store only a relatively modest quantity of energy compared to batteries, but they can release it very quickly. For this reason they are usually used as "acceleration batteries" in last-generation electric vehicles. Two types of super capacitors exist: symmetrical and asymmetric supercapacitors. The symmetrical SC uses the same type of material for both electrodes (activated carbon). The asymmetric SC uses metal (Nickel Hydroxide) for one of the electrodes. These capacitors are very promising for higher energy applications, because they have a considerably higher energy density than symmetrical SC (up to 70MJ/m^3) and much lower leakage currents.

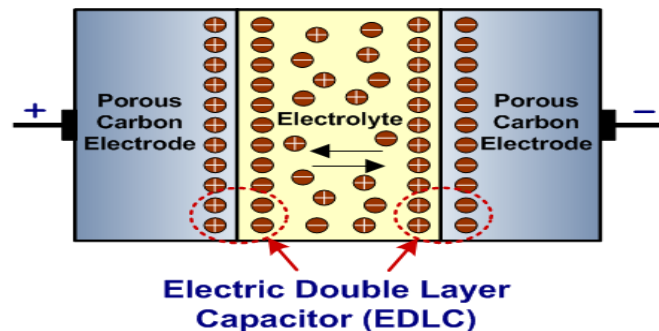


Figure 3-9: Structure of an Ultra/supercapacitor Unit

3.8.1 Outline of EDLC Based Voltage Sag Compensator

The EDLC based Voltage Sag Compensators are developed and about 90 such systems are already in operation in Japan [135]. This device normally allows the power from a commercial network system to continuously flow through the high-speed switching section to the loads in production lines. If any voltage sag occurs in the network, the voltage sag is quickly detected within 2msec, then the loads are separated from the network, and power is supplied from inverters to the loads. Since this switching action is carried out in a very short time, effects on the loads during the voltage sag can be minimized. Further, the inherent feature of the EDLC makes it

possible to quickly recharge the EDLC when the network power supply is recovered to normality after the occurrence of voltage sag, and thus we can use the compensating action repeatedly even if voltage sags occur again and again. The device can compensate for the voltage sag of duration from 1 to 60 seconds for low-voltage systems and from 1 to 20 seconds for high-voltage systems.

3.9 THERMOELECTRIC ENERGY STORAGE

(Christian Ohler)

Thermoelectric energy storage means converts electricity to high temperature heat, storing the heat, and converting the heat back to electricity. In contrast to the storage of heat in applications where the useful energy starts off or ends up in the form of heat (e.g. in air conditioning, thermal power plants, and many branches of the processing industry), a thermoelectric energy storage unit serves *exclusively* the purpose of storing electricity: it is charged with electrical energy, and it delivers electrical energy as it is discharged. There is no established nomenclature for this concept of energy storage, and it is discussed under a variety of different names. Probably the earliest work on thermoelectric energy storage is from F. Marguerre [120], [121] investigating a reversal of the conventional steam cycle to store night time electricity in pressurized water Figure 3-10. The concept was revisited by General Motors in the context of Stirling engines for submarine propulsion with molten salt as the heat storage medium [122] [123]. Exxon reinvented the Marguerre storage in 1976 [124]. Thermoelectric energy storage is considered to be an appropriate storage technology for wind power [125] and has recently received new interest [126] [127]. R&D work related to thermoelectric energy storage is in the concept phase, no demonstration plants have been built so far.

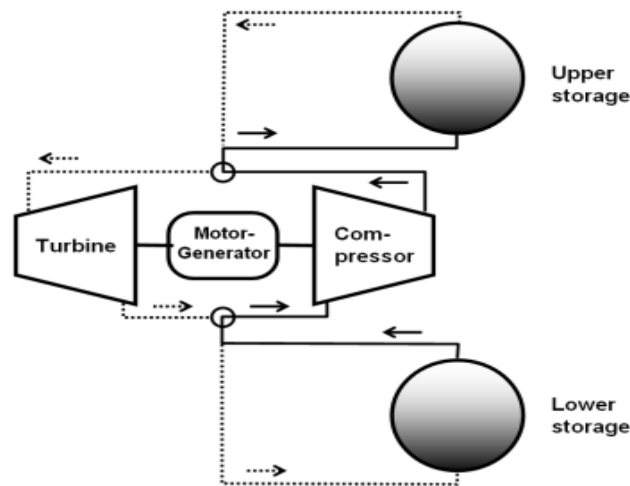


Figure 3-10 Thermoelectric energy storage after Marguerre [120]. The solid arrows indicate steam flow during charging, the dotted lines and arrows the steam flow during discharging.

Thermoelectric energy storage has some similarity to adiabatic compressed air energy storage (CAES) in that it uses turbomachine compressors to convert mechanical work to internal energy of a working fluid. In contrast to adiabatic CAES, however, it stores all energy in the form of heat and no energy in pressure. It avoids the need for pressure reservoirs in geological caverns and is completely location

independent. Thermoelectric energy storage has also a similar cost structure and similar estimated efficiency as adiabatic CAES [126].

3.10 THERMAL STORAGE COMBINED WITH COMPRESSED AIR ENERGY STORAGE

(Christian Ohler)

Compressed air energy storage is a mean to use electricity in order to compress air, store the compressed air, and convert it back to electricity at a later point in time. Compression of air entails the generation of heat. Depending on the treatment of the heat generated during the compression process one can distinguish between diabatic compressed air energy storage, adiabatic compressed air energy storage, and isothermal compressed air energy storage.

In *diabatic* CAES the high temperature heat of compression is radiated to the ambient atmosphere across a considerable temperature difference. It therefore creates irreversibility and the corresponding energy is lost. This limits the efficiency that can be obtained from such systems. During discharge, the expanding air is heated by internal combustion of natural gas, otherwise the air would freeze the turbine. This is the conventional CAES (Figure 3-11).

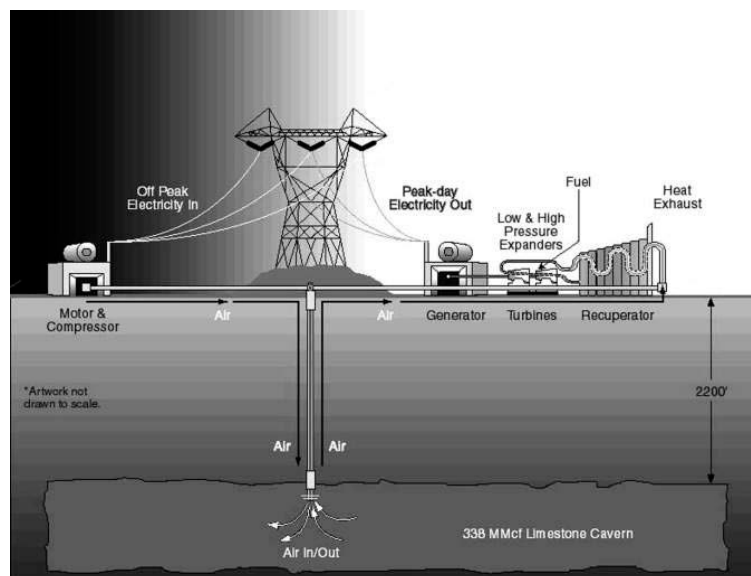


Figure 3-11 Compressed air energy storage concept (source: Sandia National Laboratories, 2001)

Worldwide there exist two plants of this type [128], [129]. The plant in Huntorf, Germany, dates from 1978. During charging it compresses within 8 hours and using 60 MW of electric power 300000 m³ of air from 4.6x10⁶ Pa to 7.2x10⁶ Pa. During discharge, it supplies 290 MW for a duration of 2 hours. It requires 0.8 kWh of electricity and 1.6 kWh of natural gas for each 1.0 kWh of electrical output.

The plant in McIntosh, Alabama, dates from 1991. During charging it can compress within about 36 hours and using 51 MW of electric power 540000 m³ of air from 4.5x10⁶ Pa to 7.6x10⁶ Pa. During discharge, it can supply 110 MW for a duration of 26 hours. It requires 0.69 kWh of electricity and 1.17 kWh of natural gas for each 1.0 kWh of electrical output.

Due to the mixed input of electricity and natural gas into the electrical output, the definition of the efficiency of conventional CAES is ambiguous. On a purely energetic

account, the efficiency of Huntorf and McIntosh are 42% and 54%, respectively. Weighing the natural gas input with 60% (the conversion ratio to electricity that a best-in-class combined cycle plant would achieve), the efficiency of Huntorf and McIntosh are 57% and 72%, respectively. Any Brayton cycle gas turbine consumes about two third of its mechanical power to compress the air before combustion. Conventional CAES can be considered as a way to supply this compression work from inexpensive, off-peak, electricity and not from the instantaneous gas combustion power. As a result, conventional CAES is not a pure storage technology as it is always associated with the simultaneous use of a fossil fuel.

Adiabatic CAES stores the heat of compression instead of radiating it to the ambient [130]. During charging, the ambient air is compressed and heated to about 650 °C. As it leaves the high pressure part of the compressor, it enters into a heat accumulator and transfers the heat to a solid or liquid heat storage material in an insulated container. The cold pressurized air is stored in the pressure reservoir (Figure 3-12), heat is stored separately in the heat accumulator.

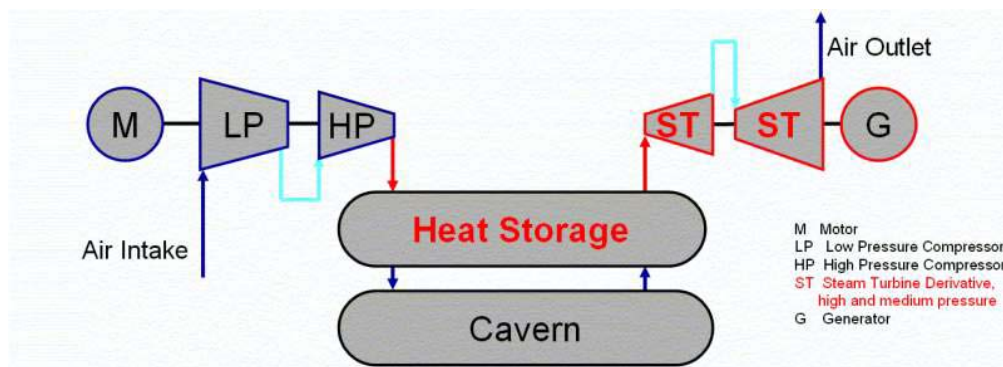


Figure 3-12 Schematic of an adiabatic compressed air energy storage unit [Bullough2004].

During discharge the pressurized cold air passes through the heat accumulator in the reverse direction and heat and pressure are recombined to provide a hot pressurized air stream for powering a turbine. There is no combustion of a fossil fuel, thus adiabatic CAES is a pure storage technology.

As of today, there is no demonstration plant of the adiabatic CAES type. An EU funded research project ("Advanced Adiabatic CAES", 2003-2007) studied system and individual component design and predicted a round-trip efficiency of 70%. Meanwhile the companies RWE and General Electric have announced a joint development of adiabatic CAES technology with a demonstration plant scheduled for 2012 [131]. Both conventional and adiabatic CAES have the same fundamental cost structure as pumped hydro storage. Power output and energy capacity of the plants can be chosen independently, and the major part of the capital cost scales with the power. The specific cost per unit of power declines with the size in power due to the scaling laws of turbomachinery equipment. Capital cost estimates for an adiabatic CAES system are 1000-1500 USD/kW at 100 MW plant size.

The energy capacity of the plants is defined by the size of the pressure reservoir and the heat accumulator with relatively low marginal capacity costs (e.g. 20 USD per electrical kilowatt hour of storage). Such pressure reservoirs can be economically constructed by solution mining of salt caverns such as they are used for the storage of hydrocarbon fuels [132]. CAES is thus suited for storage times of several hours up to several days. *Isothermal* CAES also radiates the heat of compression to the ambient atmosphere, but in contrast to diabatic CAES, it radiates the heat at a temperature close to the ambient and avoids the irreversibility associated with heat

transfer across a large temperature difference. This process requires a special device that acts simultaneously as a heat exchanger and a compressor. Such isothermal compressors are difficult to realize, current development attempts use reciprocating compressors with liquid pistons [133].

CHAPTER 4 - VEHICLE TO GRID CONNECTION

(Joao Peças Lopes, Zbigniew A. Styczynski)

The basic concept of Vehicle to Grid (V2G) is that Electric Vehicles (EVs) can absorb or provide power to the grid while parked, acting as dispersed storage [84]. Several uses for this type of storage can be described as either applied to ancillary services delivery or by providing load shifting and peak shaving capabilities. V2G can supply both primary reserves and secondary reserves as ancillary services.

For primary reserve, each EV has to react to frequency deviations and inject or absorb active power proportionally to the frequency change.

For secondary reserve, the EVs are not autonomous, thus they have to respond to a hierarchical structure of control [85],[86] In this case the DSO may interact, through intermediate control structures, with individual Vehicle Controllers (VC). When secondary reserve is requested by the Transmission System Operator (TSO) its request will be received by the DSO that go through the referred hierarchy using set-points to activate the reserve.

V2G storage capability can also be used to perform peak shaving. DMS can enforce EVs to recharge during valley hours and require that they inject power into the grid during peak period. Nevertheless, this management approach is limited by vehicles' owners needs that give permission to do so. This control strategy, if properly applied, allows simultaneously reducing load and generation required in peak hours. Obviously, the opposite happens in valley hours, i.e. load and generation required increases. The load shifting and peak shaving described will have an impact on the technical, environmental and economic level. First, it might decrease pollutants emissions and energy generation costs by keeping the most "dirty" and expensive generators disconnected during peak hours. Second, investment deferrals can be achieved by postponing the installation of peak generators, since load decrease in peak hours will make the amount installed of power that is currently available enough to feed all the consumption for some more years. Finally, V2G can play a major role in the renewables expansion, once without some form of energy storage the amount of renewables that can be safely and reliably connected into the grid is limited [87].

All the potential benefits described, arising from the dispersed storage that V2G can provide, are directly dependent on battery development. Among all the emerging technologies available on the market nowadays, the main contenders for V2G usage are Valve Regulated Lead Acid (VRLA), Nickel-Cadmium (NiCd), Nickel-Metal Hydride (NiMH), Lithium-ion (Li-ion) and sodium nickel chloride (ZEBRA) [88].

Due to the fact that VRLA batteries are one of the cheapest technologies available, their use for V2G is attracting growing attention as they offer the possibility to cycle in a partial State Of Charge (SOC). VRLA batteries' number of life cycles is similar to NiMH and Li-ion technologies, but their specific energy and specific power values are much lower, 25-35 Wh/kg and 150 W/kg, respectively [89].

NiCd batteries have as main disadvantages their high cost, extreme toxicity and thermal issues when charging. However, they have much higher energy density than VRLA and tolerate deep discharge for long periods, which results in larger usable energy. The specific energy and power of the NiMH batteries are much higher than the VRLA, 40-60 Wh/kg and up to 1100 W/kg, respectively. They are more cost effective than NiCd technology but the number of life cycles is much smaller.

Li-ion batteries have very high specific energy and power values, 80-120 Wh/kg and 500-800 W/kg, respectively. They need an extra circuit to shut down the system

when the battery is discharged below a predefined threshold, given that very deep discharges can provoke irreversible damages. They have a reduced number of life cycles, similar to VRLA technology. Starting from time of manufacturing, regardless of whether it was charged or the number of charge/discharge cycles, this kind of battery declines slowly and predictably in capacity.

With a specific energy of 100-120 Wh/kg, ZEBRA seems to be the most cost effective technology. These batteries have a specific power of 150-180 W/kg and they are by far the technology with the highest number of life cycles. They operate at high temperatures (235-350 °C), which demands a preheating mechanism and some kind of thermal management.

In general there are some problems common to all battery technologies, which need to be dealt with when using V2G [90], [91]. These problems are not inherent to the V2G usage only but also apply to the problems that occur with road usage of EVs.

The first major issue deals mainly with security. The limitations imposed by temperature rise and non-uniformity of temperature distribution behave as a bottleneck for the potential of the usage of the EV batteries. This effect was first described for the road usage but the stress batteries are subjected to when performing this activity is also present when providing primary reserve. Constant changes on the system's load reflect different operating states, which leads to thermal runaway of the batteries.

The second problem is related to vehicle autonomy, as the primary function of the vehicle is mobility. This problem is strongly bonded to the state of charge estimation, which for a very intensive usage is difficult to determine.

The last major issue is related with battery lifetime. Batteries have a finite number of charge/discharge cycles that in EV road usage with regenerative braking or reserve delivery impose an aggressive operation regime due to frequent shifts from injecting to absorbing modes.

Finally, regarding the grid conditions it is likely that in order to enable fast charging/discharging modes, the grid may have to be reinforced. The present grid was planned for typical values for the maximum load per type of consumer. It may not be capable of responding to the demand from the addition of a new high power element. Some national studies; concerning the E-mobility⁸ have been already finished. The results of the German study show that 1 Mio. of E-vehicles is expected to be in use in Germany by 2020. Nevertheless it will not have a significant influence on the power system operation (1Mio E-vehicles is about 400 MW which is less the 1% of normal power network demand in Germany). The infrastructure of the power system is able to support this amount of new demand. Moreover the study points out that the use of EVs for supporting the integration of renewable energy sources is very limited. The German study could be use as a benchmark for other countries.

⁸ Elektrofahrzeuge. Bedarf, Stand der Technik, Handlungsbedarf. VDE ETG. Frankfurt Juni 2010.

CHAPTER 5 - USE OF STORAGE IN THE FUTURE POWER SYSTEM TAKING INTO ACCOUNT REPRESENTATIVE SCENARIOS

5.1 METHODOLOGY OF INVESTIGATION

(Zbigniew A. Styczynski, Pio Lombardi)

In order to design the capacity of a storage system, specific parameters such as the type of storage, its functionality and investment costs are needed.

For a general estimate of the storage capacity it is possible to use a universal storage model, e.g. reservoir model, and adopt specific parameters of the storage as charging-discharging efficiencies, depth of discharging-charging and the discharging gradients. Taking these parameters into account, storage capacity for some specific scenarios can be calculated.

Table 5-I Total installed storage capacity world wide and their application [139]

Technology	Total installed	Size ranges	Potential application
Pumped Hydro	110 -GW	Up to 2.1 -GW	- load levelling - spinning reserve
CAES	477 MW	25 MW - 350 MW	- peak shaving - spinning reserve
Batteries			integration with renewables
Lead Acid	125 MW		
Na-S	~ 200 MW	100 W -	load levelling
Redox	38 MW	20 MW	peak shaving
Ni-Cd	26 MW		- spinning reserve - power quality
Flywheels		kW scale	power quality
SMES		10 - 100 MW	power quality
Supercapacitors		7 - 10 MW	power quality

One example concerning a necessary storage size for a wind farm is provided here. It corresponds to a typical situation for some European regions. A 3.5 GW wind generation supplies a region which has a 1-GW maximum and 300 MW minimum load. Both the yearly produced energy by the wind generation (1600-equivalent full load hours) and energy consumption are equal. In order to supply the maximum load of 1 GW, a Net Transfer Capacity (NTC) connection of 1-GW is necessary for reliable supply (2-GW physical capacity is necessary to fulfil the n-1 conditions). Calculating the energy flow during one year it is possible to obtain the storage capacity (statistically), which is necessary for the full integration of the produced wind energy without Net Security Management Systems (NSM) activities (Figure 5-1). The required storage size will be smaller if the NTC of the interconnection is increased by network extensions. For example, if 1 GW NTC is considered, and if the renewable generation is fully integrated, storage of 70 GWh is needed. If the NTC changes to 1.5 GW and 2 GW a storage capacity of, respectively, 35 GWh and 15 GWh is required. Setting the storage costs at 0.10 €/kWh the generation costs of a wind farm,

connected by a line with NTC 1 GW, will almost double if the strategy for full integration of the wind energy is assumed. Depending on the connection length, to increase the NTC could also be a good strategy for the integration of renewable generation, from a region with overcapacity to those where the load can be economically transported. The optimal (technical and economically) capacity of the storage in the analyzed generation region will also depend on the utilization of the storage (number of cycles) which was not considered in this example. Therefore, a complex control strategy of the storage device has to be modelled, which should also include system services in order to lower the costs. The negative consequence of the full integration of wind overcapacity without storage or necessary NTC capacity was demonstrated on November 4th, 2006 in Europe and ended in a pan European power system disturbance close to blackout. The costs of this disturbance could be specified close to the cost of the storage calculated here.

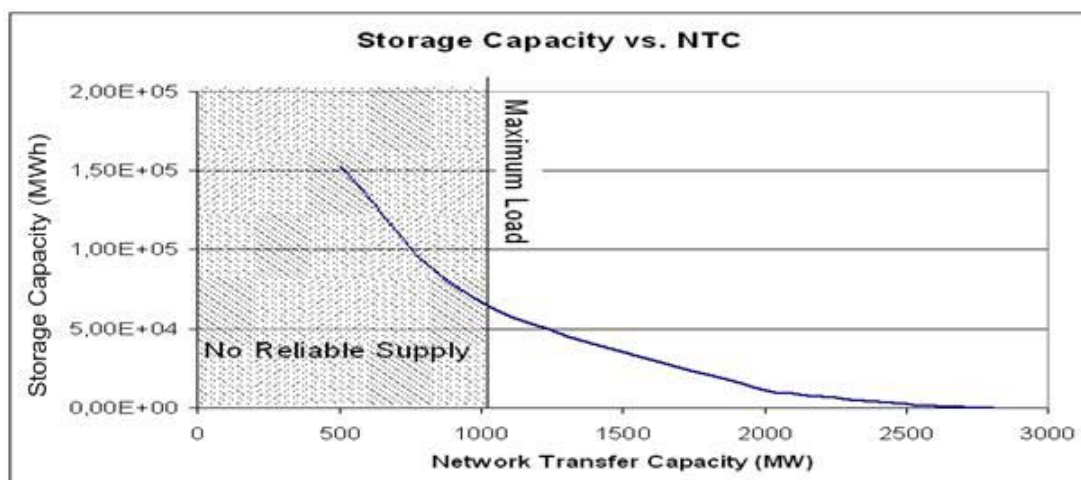


Figure 5-1 Calculation of the storage capacity for the surplus wind generation

In the following section, an example on the estimation of the storage capacity world wide will be given. Three scenarios have been analyzed:

- Scenario 1, the wind energy covers 50% of the total electricity demanded;
- Scenario 2, the wind energy covers 70% of the total electricity demanded;
- Scenario 3, the wind energy fully covers all of the electricity demanded.

The input data for the estimation are the electricity consumption and the installed power. For Germany the data collected in [140] were considered, while for North America, Central & South America, Europe, Eurasia, Middle East, Africa and Asia & Oceania data collected in [141] were used. The German data concerns the year 2008, while for the other geographic lands data concerns the year 2006. As before, a wind generation profile was used that is characterized to have a full load of 1600 hours and a conventional power plant was used with a profile of 5450 full load hours. Both the electricity generation profile and the electricity demand profile come from measured data of two German networks and from data found in literature [142]. The electricity demand profiles concern both residential and industrial sectors. Table 5-II shows the results of the simulation for the three scenarios.

Table 5-II Result of the storage analysis for the three scenarios

		Germany	Europe	North America	Central & South America	Eurasia	Middle East	Africa	Asia & Oceania
E_(wind) 50%	P_{Con} [GW]	62,47	302,54	416,97	73,59	109,75	51,20	44,05	504,88
	P_w [GW]	215,58	1044,00	1438,90	253,96	378,72	176,69	151,99	1742,20
	P_{Storage} [GW]	182	886,7	1222	215	321	150	129,1	1479
	E_{Storage} (η=80%) [TWh]	23,04	111,7	154	27,18	40,53	18,91	16,268	186,46
E_(wind) 70%	P_{Con} [GW]	37,48	181,53	250,18	44,16	65,85	30,72	26,43	302,93
	P_w [GW]	301,81	1461,6	2014,4	355,54	530,21	247,37	212,79	2439,1
	P_{Storage} [GW]	256	1241	1711	310	450	210	180,7	2071
	E_{Storage} (η=80%) [TWh]	32,26	156,43	215,6	36,05	56,74	27,15	22,77	261,05
E_(wind) 100%	P_{Con} [GW]	0	0	0	0	0	0	0	0
	P_w [GW]	431,16	2088	2877,8	507,92	757,44	353,39	303,99	3484,5
	P_{Storage} [GW]	366	1773	2444	431	643,3	300,1	258,3	2959
	E_{Storage} (η=80%) [TWh]	46,204	223,48	308	54,36	81,064	37,82	32,53	372,93
Installed pumped storage capacity in year 2008 [GW] [143]		3,803	37,378	24,012	0,750	3,985	1,140	1,580	46,653

It is important to note that these results have only an indicative value since they consider a unique wind and load profile.

With reference to Europe and to the first scenario, a total storage capacity of 886 GW is needed. Assuming a charge-discharge efficiency of 80% a reservoir capacity of 111,7 TWh is also required. According to [144], in 1998 the hydro pumped reservoir capacity in Europe was 179,7 TWh which is mainly concentrated in the Scandinavian countries. It is possible to conclude that hypothetically in Europe it is possible to supply 50% of the total electricity demand with wind energy. It should also be mentioned that the actual NTC between Scandinavia and Central Europe is only a few GW and the generation capacity from hydro power in these countries is only in

the order of a few tens of GW only whereas a charging power of 887 GW would be necessary.

Considering a distributed location of storage systems, i.e. batteries in electrical vehicles with a storage capacity of 18 kWh (three phases charging), and the first scenario, then more than 50 million EVs should be connected to the network in Europe in order to absorb the electrical surplus power of nearly 900 GW produced by wind turbines. Table 5-III shows the necessary number of electric vehicles. With respect to the stored energy, these 50 million EVs would only represent a storage capacity of less than 5TWh even if a huge car battery of 100 kWh would be considered.

Table 5-III Number of electric vehicles used as storage system

	E(wind) 50%	E(wind) 70%	E(wind) 100%
	Numbers of V2G [millions]		
Germany	~11	~15	~24
Europe	~50	~70	~97
North America	~70	~96	~136
Central & South America	~20	~17	~25
Eurasia	~18	~25	~36
Middle East	~9	~12	~17
Africa	~7	~11	~15
Asia & Oceania	~97	~115	165

In conclusion, the above simulations give a rough estimate of the required storage capacity in different geographical areas. Three different scenarios have been analyzed taking in consideration the wind energy as the only renewable source which supplies the power to the grid. Both the storage capacity and the storage capacity reservoir have been estimated. Moreover, a rough evaluation of the number of electric vehicles that could also work as a storage system has also been estimated.

5.2 TECHNICAL ASPECTS (examples)

(Suresh Chand Verma)

The current status of major storage technologies and their characteristics along with their suitability for such functions have been discussed in Chapter 3 of this report. In addition, the applications of different storage technologies for grid stability and operation support (frequency regulation, voltage support etc.), power quality support, load leveling and peak shaving have been described elsewhere. Hence, the focus here is on the main technical aspects by considering two projects in Japan relating to the energy storage usage to integrate the intermittent renewables to the grid.

1. Rokkasho-mura Futamata Wind Farm with NAS[®] Battery.

Since 2008, the Japan Wind Development Co. has been operating a large scale wind farm located in Rokkasho-mura in Japan. The installed capacity of this wind farm is

51 MW and is combined with a 34 MW sodium-sulphur (NAS[®]) battery system supplied by NGK Insulators, Ltd. In this wind farm, the NAS battery system has been primarily used to achieve the following objectives:

- To stabilize power output fluctuating from wind power;
- To increase the firm capacity of wind power.

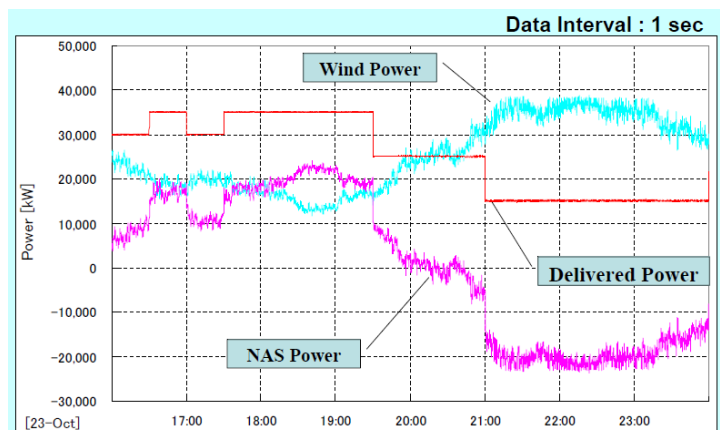


Figure 5-2 NaS[®] battery application for Wind farm (Source: NGK)

From the field data shown in Figure 5-2, it is clearly demonstrated that the NAS[®] battery system is quite effective in stabilizing the fluctuation in the power output and delivering the scheduled firm capacity. The battery system can store the surplus power during night and release during peak hours during the day. The micro weather forecast system, energy storage management system, wind farm management system and power management system have been quite instrumental in achieving these objectives.

2. Wakkanai Mega Solar Project with NAS[®] Battery

Besides to the Rokkasho-mura Futamata Wind Farm, Wakkanai Mega Solar project with a final PV installation capacity of 5MW and NAS battery of 1.5MW is underway to test the grid stabilization functions with large scale PV power generation. The project is sponsored by the New Energy and Industrial Technology Development Organization (NEDO) and is being carried out by the Hokkaido Electric Power Co., Inc. (HEPCO). The NAS[®] battery would be used to absorb the surplus PV generation up to noon (12:00 noon) and release energy during peak demand which is around 2 hours later (2:00 p.m.) in summer. The NAS[®] battery combined with the electric double layer capacitor (EDLC) due to be installed is to smooth the fluctuation in power generation. In order to bridge the supply demand gap as well as to smooth power output fluctuation. It is planned to add a NAS[®] battery system with a capacity 1.5 MW. Figure 5-3 and Figure 5-4 show the operating performance of the 2MW PV with 0.5MW NAS battery. The PV output can be made constant and firm capacity can be maintained during 9 hours with the help of NAS[®] battery system.

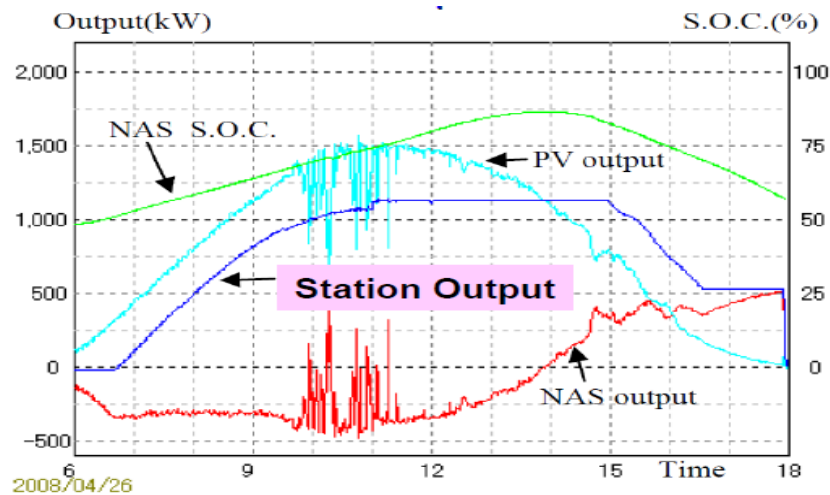


Figure 5-3 Fluctuation suppression using NAS[®] battery for PV generation (Source: NGK)

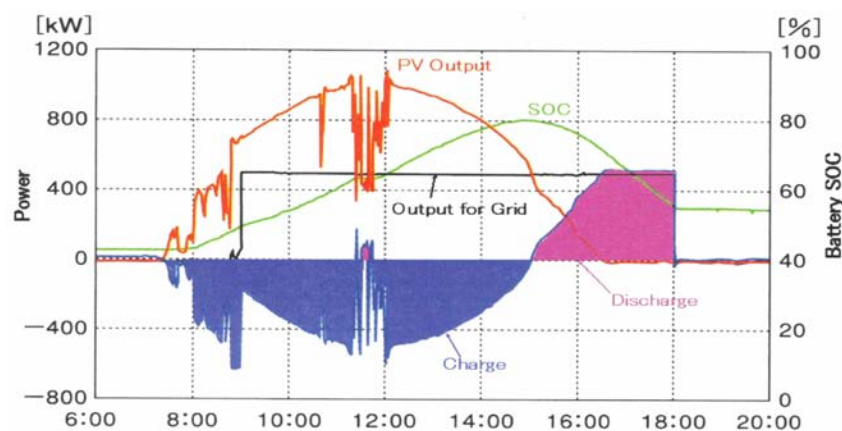


Figure 5-4 output by NAS[®] battery for PV generation (source: NGK)

In conclusion, the NAS[®] battery offers applications that include the suppression of power fluctuation and constant power output by matching supply demand or peak shifting etc. for integrating the intermittent renewable resources. The NAS[®] batteries used in both the projects have been an on-site installation, and the main factors that influence the decision about the dimensions of the NAS[®] battery system are as follows;

- Stabilize power output fluctuating (fluctuation data of demand and supply);
- Increase the firm capacity or constant power (Supply demand match on daily basis).

Finally, it is expected that as the number of large scale wind farms and mega solar plants with storage systems increase, the following additional aspects to optimize the storage systems may become important and require proper attention;

- Hybrid storage system;
- Clustered/Distributed storage installation;
- Centralised/Distributed control;
- Coordination of functionality.

CHAPTER 6 - ENERGY STORAGE ECONOMICS

(Marian Piekutowski, Christian Ohler, Geza Joos)

6.1.1 Applications of Energy Storage

This section explores the economics of potential applications of energy storage, and discusses sources of revenue and potential benefits which could justify the investment.

Table 6-I summarises the applications of energy storage systems, identifies the costs of energy storage and the costs of alternative solutions, which may be used as a shadow cost for the energy storage service. It should be noted that the benefits following pointed out are not based on real installations, but they are simply approximations. The benefits and value streams of installing energy storage systems, especially batteries, will be different for every application and location. Real values of energy storage costs as well as their benefits should be carried out by experienced industry specialists.

Table 6-I Summary of energy storage systems applications

Functional requirements	Issue and solution	Revenue sources
Power quality support		
Short duration (seconds) 1 event per hour, 5 events per day, 100 events pa	Voltage sags, reclosure events, Full power discharge (FPD) Flywheel, EC Capacitors, SMES, chemical storage	Reinforcement of distribution system, duplication of feeders (reduce system impedance) \$500-1500/kW
Long duration power quality Infrequent, 1 event pa	FPD of 4 hours	
Grid Stability		
Angular Power oscillations with frequency 0.2 to 2.5Hz 1 event per day, 10 events pa	FPD to support 20 oscillatory cycles Flywheel, SMES, chemical and ultra capacitors	Network reinforcement, generation controls improvements or SVC \$500-1000/kW
Voltage 1 event per day, 10 events per year	FPD 1 second, combined injection of active and reactive power SMES, chemical, ultra capacitors	Local reactive power support (SVC, STATCOM, switched capacitors) \$500-1000/kW
Frequency control		
ancillary services support		
Fast (peak less than 10 seconds and up to 60 sec) Contingency reserve 1 event per day, 10 events pa	FPD less 30 seconds	Improvement of governing system, additional fast response generation, transmission upgrades, \$500-1000kW
Slow (60 seconds peak and up to 300s) Contingency reserve 1 event per day, 10 events pa	FPD less than 150 seconds	Additional fast response generation, transmission upgrades, \$500-1000/kW
Delayed (300 seconds peak and up to 30 minutes) Contingency reserve 1 event per day, 10 events pa	FPD from 15 minutes to 2 hours Pump storage, CAES	additional fast response generation, transmission upgrades, \$500-1000/kW
Regulation control 2 cycles per hour, with 10 minutes advance notice	Continuous cycle equivalent to 7.5min FPD and charge cycle (triangular waveform)	
Load shifting		

3 – hr 60 events pa	FPD 3 hours Shifting low value energy to periods of high value Distribution and transmission peak load management CAES, pump storage, chemical (NaS, VRB)	Spot market trading opportunities Substation or transmission upgrade
10 – hr 250 events pa	FPD for 10 hours CAES, pump storage, chemical (NaS, VRB)	Substation or transmission upgrade \$500-1000/kW
Market energy arbitrage Off-peak-on-peak exchanges, which is equivalent to low and high spot price	High capacity and long duration cycles, typically FPD 4-12 hours	Dispatch optimisation, maximisation of market benefits NaS appears to be close to commercial applications, pump storage, Provision of contingency FCAS, reduction of spot price Flywheels and some batteries can be applied
Ancillary services	Depending on service offered, fast FCAS requires minimum FPD of 1 minute while for slow/delayed FCAS minimum FPD is 10 minutes	
Regulation services	Some generators are not good providing regulation service	Provision of regulation FCAS Pump storage,
Wind (intermittent) generation Management of intermittency	Large and difficult to predict variations in generation FPD	Compliance with the Code requirements
Connection simplification Shaping outputs to fit constrained transmission		Enhancing production value Avoided wind energy spill Improvement of the value of non-firm transmission connection
Distribution/Transmission system Peak shifting Critical load support		Delay in capital investment and avoiding the use of diesel engines
RAPS Management of intermittency, power quality Minimisation of wind spill UPS function Seasonal energy shifts		Displacement of carbon based fuels Recovery of spill energy

6.1.2 Drivers for Energy Storage

This section discusses energy storage applications and opportunities to create revenue for funding of such projects.

Market opportunities: Energy arbitrage

Electricity markets do not follow a uniform design and each of them has different characteristics and offers different products. In some systems interconnections may

support an opportunity to trade energy between regions, while in other systems only intra-regional opportunities may exist.

Dispatch optimisation results in lower electricity prices during off-peak periods than prices during peak periods reflecting excessive supply. In the Australian electricity market the peak prices are typically 100 to 200% higher than overnight prices for considerable periods of time. The energy storage plant can purchase electricity during the low price period and discharged and sell energy during high prices. Figure 6-1 shows an example of two regional markets spot prices displayed as function of time (number of 5 minute dispatch interval) and interconnected power flow between these regions. The Tasmanian system (TAS1) is predominantly hydro and it has the ability to act as an energy storage to the Victorian system (VIC1). If the spot price in Victoria is low (\$10 to \$40MWh) Tasmania would import the energy (negative flow) and minimise water released from the storage. Once the spot price in Victoria is high or is expected to be high (over \$40MWh) Tasmania bids are lower reflecting intention to export. It is noted that in a 24 hour period the interconnected flow varies from (import) -420MW to (export) +600MW and there are two power flow reversals. Additionally, there are also short periods of time when the spot price can be much higher for a limited number of dispatch intervals during an energy shortage caused by a contingency event and following activated constraints.

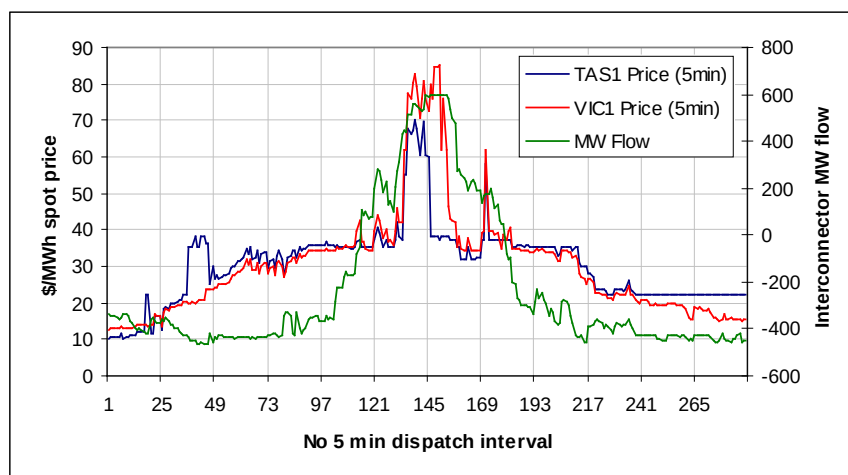


Figure 6-1 Operation of market interconnector

This type of operation has provided a partial justification to establish interconnection between the two systems. Tasmania uses only a natural hydro storage system. The storage capacity can be further augmented by the installation of a pump storage plant between existing reservoirs. Similar behaviours of off peak and on-peak prices can be observed in many systems. Most power systems do not have an available hydro storage facility however other types of storage may be gradually used in this application. Spot price volatility is a fundamental characteristic of the evolving electricity markets. The energy storage plant can be a useful tool for electricity traders, as well as a price risk hedge for retailer and industrial consumers of power. It is noted that the introduction of emission trading, carbon tax or any other equivalent mechanism will have an effect on market outcomes and it may introduce uncertainties to the long term outlook of daily price variations. This in turn may affect benefits produced by the price stabilising effect of the energy storage.

Ancillary services

Ancillary services provide the following functions: balancing electrical supply and demand (Frequency Control Ancillary Services, FCAS), maintaining power quality (Voltage Control Ancillary Services, VCAS) and providing black start capability. Energy storage can support the first two functions, although the second function could be also effectively addressed by power electronics (SVC, STATCOMS).

In the Australian electricity market FCAS is co-optimised with the energy market and its price is available for each dispatch interval. The additional cost of FCAS is recovered from generators while lower service fees are paid by customers consuming load. Consequently there is a flow of revenue between generators supplying FCAS and the generators producing energy only, e.g. wind farms. The cost of VCAS is included in the system capacity charge to customers. The bundled pricing of ancillary services makes it difficult to identify their true market value. Some thermal generators have limited ramp rate capability and their contribution to regulation service may be limited. An energy storage plant (such as pump storage, CAES and to lesser extent chemical storage) can respond quickly and over a wider range of its output. The higher ramp rate allows more services to be offered (energy, regulation and contingency and FCAS) to the market. Energy storage can provide ancillary services with significant, responsive load (FACS lower service). The amount of pumping or compressing load can be modulated (variable speed drive) and this characteristic might be offered as FACS service. Battery storage or flywheels may also be considered in this application. However as FCAS services are typically valued at less than 10% of spot energy price, storage opportunities in this application might be limited at present.

Efficiency improvements: Generation

Energy storage improves the value and efficiency of generation and transmission assets. During periods of low demand many generators are forced to reduce the output in order to stay on line, resulting in higher operations and maintenance costs, lower efficiency (heat rates), and in some cases longer periods of start/stop operation. Through a price arbitrage mechanism energy storage can help existing assets to increase the capacity factor and the efficiency. Energy storage can improve the efficiency of generators during peak period by absorbing variations in the system demand that would otherwise force operation of assets outside their optimal performance range. In case of an operational constraint forcing commitment of an additional generator at a low output, energy storage can be discharged until demand increases enough for the additional generator to operate at efficient outputs.

Transmission and distribution

Energy storage enables additional power to flow without requiring costly and time-consuming system upgrades. By shifting power flow from the high demand period to the low demand it eliminates existing transmission constraints. This could allow delaying transmission/distribution development (installation of additional transformer or transmission line) for some time until it is most cost effective and thus free up investment capital for other urgent projects. As a by product of storage installation, transmission losses might be lowered and plant utilisation increased. In some cases energy storage can make it possible to gain the time required for environmental approval for a new line or it can maintain supply if the line replacement is not possible.

Growth of intermittent renewable resource: Firming up service

Energy storage is an enabling technology for increasing penetration of intermittent renewable energy sources. The energy storage can improve the value of intermittent renewable power generation capacity and change the role of the generator from energy supplier to power producer. It is difficult to sell a firm contract on the market for wind energy unless the energy is firmed-up by another generator or storage. Improved predictability of intermittent generation helps to reduce the amount of supporting reserve (FCAS). Energy storage will further minimise forecasting errors. In some countries large wind farms are required to perform similarly to conventional power plants. They are expected to participate in dispatch process and submit energy bids. Energy storage could help the wind farm to minimise departures from the pre-dispatch process. The price that can be received for this type of generation is highly discounted due to its non-firm nature. The wind power might be generated during off-peak periods when spot price is low. By storing some energy generated by renewable sources and delivering it to the grid as a firm, bankable product shaped to match high demand, the energy storage can maximise the revenue received for renewable power. However, since renewable generation presently attracts significant subsidies valued based on actual energy generated, integration of energy storage would complicate finances of the project and it is likely to reduce potential gains very significantly.

Remote area power supply

Traditionally this area was the most attractive to demonstrate applications of energy storage due to very high cost of generation, typically about 10 times higher than the generation costs in a large system. The primary energy in small remote power systems is supplied by diesel generators which have low capital costs so the peak supply is usually not a problem but very high fuel costs due to use of expensive fuels and high costs of transport. In such locations the application of renewable energy sources is very attractive as the equivalent (levelised) fuel price of wind generation is about 4 times lower than the cost of energy generated by a diesel engine. However due to daily load variations on some occasions not all wind generation can be used to supply the load and some wind energy needs to be spilled. Energy storage can absorb all/part of the wind energy spill and release it when the wind farm output is unconstrained. Additionally, in remote systems the energy storage can also absorb fluctuation in wind generation output (quality of power supply), provide UPS function in case of sudden loss of one of diesels, provide reactive power if required and participate in frequency control.

Multiple complementary applications

Energy storage offers flexibility to the power system management. A single application of energy storage is unlikely to provide economic justification, however the possibility of changing storage control strategies depending on the market requirements could allow maximisation of revenue.

6.1.3 Costs of Generation

In order to visualise the value of energy storage let us first provide a short overview of the long run marginal costs of electricity.

Levelised costs of energy

Levelised energy cost (LEC) is a cost of generating electricity for a particular system. It is an economic assessment of the cost the energy-generating system including all the costs over its lifetime: initial investment, operations and maintenance, cost of fuel, cost of capital. A net present value calculation is performed and solved in such a way that for the value of the LEC chosen, the project's net present value becomes zero. This means that the LEC is the minimum price at which energy must be sold for an energy project to break even. The following Table 6-II shows estimates of LECs based on EPRI report Program on Technology Innovations: Integrated Generation Technology ID 1019539, 11/25/2009

The data in Table 6-II indicate that the highest generation costs are expected to be in remote power systems. The cost of wind generation is higher than the thermal generation, but wind energy typically attracts additional incentives effectively reducing the energy costs.

Table 6-II Generation energy costs estimated through LEC

Generation source	Unitised capital cost \$/kW	Levelised Energy costs \$/MWh
Nuclear 1400MW	4860 in 2015 4127 in 2025	84 in 2015 74 in 2025
Pulverised coal 750MW	2650 (2008) 4435 with carbon capture 2025	66 101 in 2025
Integrated gasification CC 768MW	2960 w/o CC 4083 with CO2 capture	71 92 (2025)
Fluidised bed combustion 750MW 2008	2460	69
Combustion turbine CC 750MW 2008	880-902	74-89 67-81
Wind, 100MW plant, 2008	2350 (2015-2025)	99 (2015, 35%) 82 (2025 42%)
Solar thermal 150MW 2008	4851-6300	225-290
Biomass 75MW, 2008	3580	90
Diesel 1MW, 2008	500	400
Remote location		

6.1.4 Costs of Storage

The energy storage costs vary significantly depending on the type of storage and required functionality. Low storage costs are typically associated with support for quality of power supply while high costs correspond to solutions requiring a high volume of storage. Especially the number of cycles, a given storage system can run, will influence the specific storage costs. Table 6-III indicates that the present and future costs of energy storage are high, and they are unlikely compete with base load generation. However, energy storage will be viable when the marginal cost of electricity exceeds the costs of charging and discharging the storage and losses. This can happen when the generating plant operates under low load factor and storage

may offer multiple services including energy supply, load levelling, peak shaving, reserves, regulation, reactive power supply and power quality. Storage may be a valid option also for some special applications such as extreme unreliability of a conventional supply, need to compensate for fluctuating generation or in applications like EVs where a premium is attached to the portability.

Table 6-III Current and projected storage costs

Storage Technology	Current costs \$/kWh	10 years projected costs \$/kWh
Flooded lead-acid	150	150
Sealed lead-acid	200	200
Low speed flywheels	380	300
NaS	450	350-\$250/kWh plus \$300/kW
Asymmetric lead-carbon	500	<250
NiCd	600	600
Zebra Na/NiCl	800	150
Ni-MH	800	350
High speed flywheels	1000	800
Li-ion	1333	780
VRB	20kWh - \$1800/kWh 1000kWh - \$600/kWh	25kWh - \$1200/kWh 100kWh - \$500/kWh
Electrochemical capacitors (burst applications)	\$356kW	\$350/kW

Apart from the capital cost and functionality there are many factors which can impact economics of storage projects including:

- Annual maintenance costs,
- Service life (some new technologies may have a life service as short as 7 years)
- Inclusion in the price of the power converter
- Round cycle efficiency (could vary between 50 and 90%)
- Number of a charge/discharge cycles
- The depth of discharge
- Speed of charging
- Overload (burst) capability and its impact on life cycle.

All of the above aspects need to be considered in context of required functionality of energy storage.

CHAPTER 7 - SUMMARY OF THE INVESTIGATION OF THE WORKING GROUP

(Zbigniew A. Styczynski)

Nowadays, power generation is mainly based on fossil fuel sources such as coal, oil and natural gas - whose reserves are limited- and only a minimal part of the generation is based on renewable sources. Considering the present energy consumption rate and the presently known level of reserves of fossil sources, it is possible to assert that the fossil sources could still supply energy for the next one hundred years. But, to meet a world commitment to a cleaner atmosphere, the development of power plants based on renewable energy sources are then an unavoidable necessity if it desirable to maintain our present standard of living and provide the possibility for developing countries to raise their standards of living as well. At present, the generation from renewable energy sources covers only 10% of the total energy generated world wide. It is mainly produced by hydro power plants. In some countries like Norway, renewable energy sources (mainly hydro and biomass) contribute to generation almost 100% of the internal energy consumption. In other countries like Denmark, wind energy and other renewables supply approximately 30% of its electricity demand. Unfortunately, not all the power plants based on renewable energy sources are able to produce energy when it is required. Some of them such as wind and solar have a variable generation profile which requires the system to use fossil fuel based plants for balancing the variable generation. This modus operandi is a limiting factor to the development and integration of renewable energy in the power system because of the additional costs. Existing power systems are based on the paradigm that the generation has to follow the load. Future power systems should be based partially on the opposite paradigm: the load should match the generation across a very broad range. To achieve such a revolution, demand side management programs, which are based on electricity market models (tariffs), could be adopted. Nevertheless, it is a process which takes a long time and it has to be coupled with changes in lifestyle. Another possibility is to use the traditional power station to control of the renewable dominated power system, but optimal better solution is to use energy storage systems, both electric and thermal, as a buffer between the variable generation of the plants based on renewable sources and the energy consumed by end users. The WG C6.15 on Electric Energy Storage plans to investigate the possibility of using this technology for the optimal integration of renewable energy into the power system.

This report firstly explains the needs to use energy storage systems in the power system (example Europe) focusing on the important targets such as the reduction of the green house emissions, the reduction of fossil energy consumption and the increase of renewable energies. Such considerations are described in Chapter 1.

Chapter 2 describes the importance of energy storage for realization of the future power systems. At the beginning of the chapter the status of the present power systems and how they will change is described. Then, the actual and future scenarios related to the use of renewable energy sources in the power system for different areas such as Europe, North America, Argentina, Russia, China, Japan and Australia are illustrated. Then, a short overview of the other two candidate solutions (stronger interconnection and load management) for integrating renewable energy in the power system is given. Subsequently, the applications of energy storage systems at distribution and transmission level as well as for isolated systems are reported.

Finally the chapter ends with the description of using energy storage for ancillary services and for long time energy storage used to shift energy from off-peak to on-peak delivery.

Chapter 3 deals with storage technologies and systems. An overview on the classification of storage depending on their application and rating is given. Then, the present status on storage efficiency and storage costs is profiled. A technical description of all of the energy storage technologies such as hydro plants, batteries, compressed air, rotating systems, hydrogen, superconductive magnetic, supercapacitors and thermal-electric storage systems are given at the end of the chapter.

In Chapter 4 the application of using electric vehicles as energy storage systems is given. The advantages and disadvantages of such a new technology are analyzed. Among all the emerging technologies available in the market nowadays, the main contenders for vehicles to grid usage are Nickel-Metal Hydride (NiMH), Lithium-ion (Li-ion) and sodium nickel chloride (ZEBRA) batteries. Li-ion batteries have a very high specific energy and power value, but a reduced number of life cycles. The ZEBRA batteries seem to be the most cost effective solution. They have also a very high specific energy value comparable to the Li-ion technology. The main disadvantage of using electric vehicles as storage deals with security. The limitations imposed by temperature rise and non-uniformity of temperature distribution behave as a bottleneck for the potential usage of the electric vehicles batteries. Another problem is related to vehicle autonomy, since the primary function of the vehicle battery is range of driving, not power delivery to the grid which would shorten battery life. Finally, in order to offer the possibility for fast charging/discharging the grid will need to be modified to accept these new loads.

Chapter 5 deals with the use of storage in the future power system taking into account representative scenarios. Three main scenarios have been simulated for different countries, macro areas and continents. The simulations aim to estimate the amount of storage systems if 50%, 70% and 100% of energy demanded is supplied by wind energy. World wide, a storage capacity of 600 TWh will be necessary to integrate 50 % of wind energy. For Europe about 110 TWh is necessary and for Germany about 23 TWh. Those values can not be reached by only using pumped water storage technology since there are geographical limitations problems. Electric vehicles connected to the grid can be a candidate solution to answer to the need of energy storage. The simulations point out that more than 50 million electric vehicles should circulate in Europe (11 million in Germany) if such a solution is the only one adopted.

The economical of storage systems are analyzed in Chapter 6. The fiscal revenue for different storage systems used in different applications has been evaluated. The present and future costs of energy storage are still high and they are unlikely to compete with base load generation. However the energy storage will be viable when the marginal cost of electricity exceeds the costs of charging and discharging the storage and losses. This can happen when the generating plant operates under low load factor and the storage offers multiple services including energy supply, load levelling, peak shaving, reserves, regulation, reactive power supply and power quality. Furthermore for some very special applications, such as extreme unreliability of a conventional supply, need to compensate for fluctuating generation or in application like EVs where a premium is attached to the portability, they may be a valid solution.

To conclude, energy storage systems, both electric and thermal, will be the key to integrating variable renewable sources in the power systems of the future, to reduce

the production of pollution and decrease the consumption of fossil resources. In the future of energy storage systems in combination with other Smart Grid measures such as Demand Side Management will be suitable to accommodate a truly “balanced” electricity generation system.

CHAPTER 8 - RECOMMENDATIONS FOR STORAGE USE IN THE POWER SYSTEM

(Zbigniew A. Styczynski)

Reducing the dependence on fossil sources and increasing the generation from renewable sources is the challenge of the coming years. Wide applications of Energy Storage Systems (ESS) providing effective management of variable output produced by renewable energy sources, such as wind and solar, will help to achieve this goal.

This paper has summarized the investigation carried out during the last two years by the CIGRE WG C6.15 on the integration and support of ESS in the power networks with a high penetration of renewable energy sources. An overview of the most promising storage technologies was provided. Moreover, a general example of the storage capacity dimensioning was given and the performance of ESS in some pilot projects was described. Finally the storage costs have been shown.

In order to increase the use of ESS in power systems, the CIGRE WG C6.15 provides the following recommendations:

- Considering the current cost of technology, a financial incentive scheme is required to support the launch of ESS applications. A scheme similar to the storage bonus proposed in Germany or Investment Tax Credits discussed in the USA could be examples of positive support. The incentives scheme might be time limited and correlated with national strategies concerning the power system development.
- Encourage legislation to support applications of energy storage technologies at different electricity consumption levels e.g. residential, commercial, and industrial.
- Support of national programs for medium and large scale pilot or demonstration projects using different storage technologies (like in Japan).
- Complete a guideline for using energy storage as a primary source of frequency control and supply of ancillary services to replace the use of coal and natural gas-fired generation assets currently used in this application.
- Inform and support engineers during the planning phase through guidelines, which consider and address the deployment of energy storage systems as a technical alternative that ensure network security in the case of large scale penetration of variable renewable energy sources and, in this manner, drive the evolution of the electricity industry towards energy storage. Develop methodologies that quantify the social benefits of energy storage technologies.

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