UNIVERSITY OF VAASA

FACULTY OF TECHNOLOGY

ELECTRICAL ENGINEERING

Christian Hultholm

ENERGY STORAGE SYSTEMS FOR INTEGRATION OF RENEWABLES

Master's thesis for the degree of Master of Science in Technology submitted for inspection, Vienna, Austria, 08 July, 2008.

Supervisors	O.Univ.Prof. Dipl.-Ing. Dr.-Ing. Günther Brauner (TU Wien), Prof. Timo Vekara (UV) and Prof. Kimmo Kauhaniemi (UV)
Instructor	Dipl.-Ing. Christoph Leitinger (TU Wien)

PREFACE

This Master's Thesis was written at the Institute of Electrical Power Systems and Energy Economics at the Vienna University of Technology. The subject of the thesis was provided by professor Günther Brauner, to whom I am very grateful for the opportunity.

I wish to thank my supervisors professor Brauner and professor Timo Vekara for their guidance and instruction. I would also like to express my sincere gratitude to Christoph Leitinger for his time, advice and constructive comments.

Moreover, I would like to thank all the staff of the institute for contributing to an inspiring and pleasant atmosphere.

Finally, I want to thank my family for their support throughout my studies.

Vienna, Austria, July 2008.

Christian Hultholm

TABLE OF CONTENTS

INDEX OF SYMBOLS AND ABBREVIATIONS

A	Area [m^2]
B	Magnetic field density [T]
C	Capacitance [F]
c_p	Coefficient of performance
$\mathrm{d}m_\mathrm{x}$	Differential mass
E	Energy [J, Ws]
E_cap	Capacity of an energy storage system [Ws]
E_deficit	Energy deficit [Ws]
E_diff	Energy difference [Ws]
E_diss	Energy dissipation [Ws]
E_storage	Status of an energy storage system [Ws]
g	Exponential factor
g	Standard gravity [m/s^2]
H	Effective pressure head [m]
H	Height [m]
I	Continuous current [A]
J	Moment of inertia [kgm^2]
k	Shape factor of the flywheel
L	Inductance [H]
n	Number of moles
n	Number of years
M	Mass [kg]
P	Active power [W]
P_0	Pressure [Bar, Pa]
P_gen	Generated power [W]
P_load	Consumed power [W]
P_max	Maximum available power flow [W]
P_rated	Rated power [W]
q	Interest factor
Q	Reactive power [Var]
Q	Volume flow rate [m^3/s]

R	Gas constant [J/Kmol]
S	Apparent power [VA]
S	Electrode surface [m^2]
S	Solar radiation density [W/m^2]
t_{interval}	Length of an interval [s]
T	Temperature [°C, K]
U_0	Cell voltage [V]
v_1	Wind speed in front of the rotor [m/s]
v_2	Wind speed behind the rotor [m/s]
v_{10}	Wind speed at 10 meters height [m/s]
$v_{\mathrm{cut\text{-}in}}$	Cut-in speed of a rotor [m/s]
$v_{\mathrm{cut\text{-}out}}$	Cut-out speed of a rotor [m/s]
V	Volume [m^3]
V_0	Initial volume [m^3]
V_H	Wind speed at the height H [m/s]
W	Energy [Wh]
x	Distance of the differential mass dm_x [m]
x_{cost}	Investment cost of the energy storage technology [€/Ws]
y_{cost}	Cost of the energy storage system [€]
y_{gain}	Gain from stored energy [€]
y_{net}	Net gains of stored energy [€]
β	Discount factor
δ	Thickness of the double-layer in a supercapacitor [m]
ε_0	Electric constant [F/m]
ε_{r}	Relative static permittivity
η	Efficiency
ρ	Density [kg/m^3]
σ	Tensile strength [N/m^2]
ω	Angular velocity [rad/s]

AA-CAES	Advanced Adiabatic Compressed Air Energy Storage
AC	Alternating current
AFC	Alkaline Fuel Cell
BESS	Battery energy storage system
Br	Bromine
CAES	Compressed Air Energy Storage
CAS	Compressed Air Storage
Cd	Cadmium
$Cd(OH)_2$	Cadmium hydroxide
CERI	Colorado Energy Research Institute
CORDIS	Community Research and Development Information Service
CS	Cryogenic System
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CU	Commercial unit
DC	Direct current
DG	Distributed Generation
DoD	Depth of discharge
DMFC	Direct Methanol Fuel Cell
DOE	Department of Energy (U.S.)
E	Energy
e^-	Electron
EC	Electrochemical
EC	European Commission
EPRI	Electric Power Research Institute
ESA	Electricity Storage Association
ESC	Energy Storage Council
FW	Flywheel
GVEA	Golden Valley Electric Association, Inc.
H^+	Hydrogen ion
H_2	Hydrogen
H_2O	Water
H_2SO_4	Sulfuric acid

HMI	Human Machine Interface
HTS	High Temperature Superconductor
HTV	High Temperature Vessel
IEA	International Energy Agency
IEEE	Institute of Electrical and Electronics Engineers, Inc.
IGCT	Integrated Gate Commutated Thyristor
INVESTIRE	Investigations on Storage Technologies for Intermittent Renewable Energies
IWEI	Iowa Wind Energy Institute
KOH	Potassium hydroxide
V_{RMS}	Root mean square voltage
LHV	Lower Heating Value
Li-ion	Lithium-ion (battery)
Li-metal	Lithium metal (battery)
LiOH	Lithium hydroxide
LTS	Low Temperature Superconductor
LTV	Low Temperature Vessel
M	Hydrogen absorbing alloy
MCFC	Molten Carbonate Fuel Cell
MH	Metal hydride
Na	Sodium
Na^+	Sodium ion
NaBr	Sodium bromide
NaS	Sodium-sulfur (battery)
Ni	Nickel
NiCd	Nickel-cadmium (battery)
NiMH	Nickel-metal hydride (battery)
$Ni(OH)_2$	Nickel hydroxide
NiOOH	Nickel oxyhydroxide
NiZn	Nickel-zinc (battery)
NREL	National Renewable Energy Laboratory
O_2	Oxygen
O&M	Operation and maintenance

OH^-	Hydroxide
PAFC	Phosphoric Acid Fuel Cell
PAR	Project Authorization Request
Pb	Lead
PbO_2	Lead dioxide
$PbSO_4$	Lead sulfate
PCS	Power Conditioning System
PEMFC	Proton Exchange Membrane Fuel Cell
PHS	Pumped Hydro Storage
PQ	Power Quality
PSB	Polysulfide bromide flow battery
PU	Per unit
PV	Photovoltaic
Redox	Reduction-oxidation
REN21	Renewable Energy Policy Network for the 21st Century
RMRCT	Refrigerated-Mined Rock Cavern Technology
Rpm	Revolutions per minute
RTU	Remote Terminal Unit
S	Sulfur
S_n^{2-}	Polysulfide
SCADA	Supervisory Control and Data Acquisition
SCM	Superconducting coil with a magnet
SMES	Superconducting Magnetic Energy Storage
SOFC	Solid Oxide Fuel Cell
T&D	Transmission and distribution
TBD	To Be Determined
Tekes	Finnish Funding Agency for Technology and Innovation
TES	Thermal Energy Storage
TiS_2	Titanium disulfide
TVA	Tennessee Valley Authority
UPS	Uninterruptible power supply
URFC	Unitized Regenerative Fuel Cell
USA	United States of America

V^{x+}	Vanadium electrolyte
VRB	Vanadium redox flow battery
VRLA	Valve-Regulated Lead-Acid (battery)
ZnBr	Zinc-bromine (flow battery)
Zn	Zinc
ZnO	Zinc oxide

UNIVERSITY OF VAASA	**Faculty of technology**
Author:	Christian Hultholm
Topic of the Thesis:	Energy Storage Systems for Integration of Renewables
Supervisor:	Dr.-Ing. Günther Brauner, prof. Timo Vekara and prof. Kimmo Kauhaniemi
Instructor:	Dipl.-Ing. Christoph Leitinger
Degree:	Master of Science in Technology
Major Subject:	Electrical Engineering
Year of Entering the University:	2003
Year of Completing the Thesis:	2008 **Pages:** 134

ABSTRACT

For short durations, energy storage can contribute to improved frequency and voltage control, while it during longer periods offers sophisticated energy management. In the case of renewable energy sources, the power generation is often remotely located and the fluctuations are considerable, which creates pronounced potential for storage.

The energy storage market for small-scale applications has traditionally been dominated by the lead-acid battery, whereas pumped hydro storage has been the only true option for substantial bulk storage. However, the importance of the emerging alternative technologies continues to grow. In this thesis, a comparison of the characteristics, present use, costs and state-of-the-art situation of the alternative technologies is provided, in order to assess which of them have a near-future potential as superior successors to previous technologies. In parallel, their applicability for the needs of renewable energy generation and the directions of development are analyzed. This part of the study is primarily based on comprehensively examining and reviewing application specific literature and applying it to the field of renewable energy generation.

In order to assess the concrete benefits of energy storage for renewable generation, two fictive scenarios, featuring a wind turbine and a photovoltaic based system, respectively, are devised. Both are stand-alone systems modeled with data from a weather station located in Burgenland, Austria, and are completed with a typical Austrian load profile. For the given conditions, the profitability of energy storage proved to be greater in combination with a PV plant, than together with the wind power system. On the other hand, when only considering the situation from an energy perspective, the contribution of large-scale storage is greater in the wind system.

Proper storage enables an optimal exploitation of the obtainable resources and provides a significant contribution to power quality. However, a completely independent system is not economically feasible solely through energy storage. Several emerging technologies, offering attractive improvements, are approaching commercialization, but primarily due to cost-efficiency, as well as reliability, the lead-acid battery and the pumped hydro storage will still remain in key positions.

KEYWORDS: Energy storage, renewables, stand-alone systems

VAASAN YLIOPISTO	**Teknillinen tiedekunta**	
Tekijä:	Christian Hultholm	
Diplomityön nimi:	Energianvarastointijärjestelmiä uusiutuvien energialähteiden integroimiseksi	
Valvojan nimi:	Dr.-Ing. Günther Brauner, prof. Timo Vekara ja prof. Kimmo Kauhaniemi	
Ohjaajan nimi:	Dipl.-Ing. Christoph Leitinger	
Tutkinto:	Diplomi-insinööri	
Suunta:	Sähkötekniikka	
Opintojen aloitusvuosi:	2003	
Diplomityön valmistumisvuosi:	2008	**Sivumäärä:** 134

TIIVISTELMÄ

Lyhyellä aikavälillä energian varastointi voi vaikuttaa taajuuden- ja jännitteen hallintaan myönteisesti, kun taas pidemmällä aikavälillä se tarjoaa ratkaisun kehittyneeseen energian hallintaan. Uusiutuvien energialähteiden kohdalla, tuotanto tapahtuu usein kaukana ja vaihtelut ovat huomattavia, mikä synnyttää selvän varastointitipotentiaalin.

Energian varastoinnin pienimuotoisten sovellusten markkinoita ovat perinteisesti hallinneet lyijyakut, kun taas pumppuvoimalaitokset ovat olleet ainoat todelliset vaihtoehdot energian laajamuotoisessa varastoinnissa. Uusien vaihtoehtoisten teknologioiden merkitys kasvaa kuitenkin jatkuvasti. Tässä työssä on vertailtu vaihtoehtoisten teknologioiden ominaisuuksia, tämänhetkistä käyttöä, kustannuksia ja viimeisintä tekniikkaa edustavaa tilannetta, arvioitaessa millä niistä on lähitulevaisuudessa potentiaalia tulla aiempien teknologioiden merkittäviksi seuraajiksi. Samalla on analysoitu niiden sopivuutta uusiutuvan energiantuotannon tarpeisiin sekä niiden kehityksen suuntauksia. Tämä osuus tutkimuksesta perustuu ensisijaisesti laajaan sovelluskohtaisen kirjallisuuden tarkasteluun sekä sen soveltamiseen uusiutuvan energiantuotannon alalla.

Arvioitaessa uusiutuvan energiantuotannon varastoinnin konkreettisia etuja, on kehitetty kaksi fiktiivistä skenaariota, jotka perustuvat tuulivoimalaan sekä aurinkokennojärjestelmään. Molemmat ovat autonomisiä järjestelmiä, jotka on mallinnettu käyttämällä tietoja Burgenlandissa, Itävallassa sijaitsevalta sääasemalta ja täydennetty tyypiillisellä itävaltalaisella kuormitusprofiililla. Annetuilla oletuksilla, energian varastoinnin kannattavuus on parempi yhdessä PV-järjestelmän kanssa, kuin yhdessä tuulivoimalan kanssa. Toisaalta, kun tilannetta tarkastellaan pelkästään energian näkökulmasta, laajan varastoinin panos on merkittävämpi tuulivoimalan yhdessä.

Asianmukainen varastointi mahdollistaa käytettävissä olevien resurssien ihanteellisen hyödyntämisen ja parantaa merkittävästi sähkön laatua. Täydellisen riippumaton järjestelmä ei kuitenkaan ole taloudellisesti saavutettavissa pelkästään energian varastoinnilla. Kaupallistamista lähestyvät monet uudet teknologiat, jotka tarjoavat kiinnostavia teknisiä parannuksia, mutta pääasiassa kustannustehokkuudesta ja luotettavuudesta johtuen lyijyakut ja pumppuvoimalaitokset tulevat yhä pysymään avainasemassa.

AVAINSANAT: Energian varastointi, uusiutuvat, autonomiset energiajärjestelmät

1. INTRODUCTION

1.1. Background

There are basically two options how to use generated energy: either it is transferred to be consumed immediately or it is temporarily stored. Storing significant quantities of electricity as such is, however, economically impossible (Baxter 2002: 109). This is a contributing factor to price volatility and power quality related problems. Furthermore, it is the premise for energy storage technology.

Storage makes it possible to utilize electricity, produced at times of low demand and/or generation costs, when the production capacity is insufficient or economically unfavorable.

In the case of renewable energy sources, the power generation is often remotely located and the fluctuations are considerable, which creates pronounced potential for energy storage. Harnessing the renewable resources and transferring the energy according to the demand is one of the major challenges for the electric power industry (Baxter 2002: 109; Rose, Merryman & Johnson 1991: 26). Since most renewables, unlike fossil fuels, cannot be stored nor transported as such, they are converted into electricity. In order to match the supply and demand, the need to store the electricity arises. Proper storage enables an optimal exploitation of the obtainable resources and provides a significant contribution to power quality. Therefore, energy storage is achieving a key position in all fields of energy distribution (Alanen, Koljonen, Hukari & Saari 2003: 10; Kondoh, Ishii, Yamaguchi, Otani, Sakuta, Higuchi, Sekine & Kamimoto 2000: 1864).

1.2. Aim and scope

The purpose of this thesis is to study the available energy storage technologies which can be considered suitable for the use together with renewable energy generation. The energy storage market for small-scale applications has traditionally been dominated by the lead-acid battery, whereas pumped hydro storage has been the only true option for substantial bulk storage. However, the importance of the emerging alternative technologies continues to grow. In the thesis, an analysis with the aim of evaluating which of them have a near-future potential as superior successors is carried out. This is implemented through assessments of their characteristics, present use, costs and state-of-art situation. In parallel, their suitabilities for renewable energy generation and the directions of development are analyzed. This part of the study is primarily based on comprehensively examining and reviewing application specific literature and applying it to the field of renewable energy generation.

In order to assess the concrete benefits of energy storage for renewable generation, two fictive scenarios, featuring a wind turbine and a photovoltaic based system, respectively, are devised. Both are stand-alone systems modeled with data from a weather station located in Burgenland, Austria, and completed with a typical Austrian load profile. The concomitant assessment of the gains obtained through energy storage is made both in terms of energy and financial savings

Energy storage is moreover considered the most promising option for reducing fuel consumption in the transport sector (EC 2001: 3). This will, nevertheless, not be approached in the thesis. Nor is storage for portable applications, such as consumer electronics, or electric vehicles examined.

Primary (non-rechargeable) batteries, fossil fuels and biofuels can also be held as energy storage media (EC 2001: 3). These are, however, not taken into consideration in this thesis. Thermal storage techniques which are intended for the storage of heat and which are incapable of delivering electricity are also outside of the scope.

More attention is paid to the newer systems than to the older and more well-known ones. Since the energy storage technologies and their market are rapidly evolving, the use of contemporary sources is stressed.

1.3. Structure of the thesis

Chapter 2 describes the applications of energy storage and provides an overview of their requirements. Concurrently, the benefits brought by storage are examined. Chapter 3 continues by defining the characteristics of renewable energy generation and provides an overview of storage technologies suited for the field.

The main part of thesis consists of chapters 4 through 7, which assess the characteristics, present use, costs and state-of-the-art situation of storage technologies based on electrochemistry, electromagnetism, mechanics and thermochemistry, respectively.

In chapter 8, two fictive scenarios, featuring a wind turbine and a photovoltaic based system, respectively, are devised in order to assess the concrete benefits of energy storage for renewable generation. Both are stand-alone systems which are modeled with data from a weather station located in Burgenland, eastern Austria and a load profile representing typical Austrian household consumption.

In chapter 9, the prospects of energy storage is discussed and a review on future prospects is carried out.

2. THE IMPORTANCE OF ENERGY STORAGE

This chapter describes the applications of energy storage and provides an overview of their requirements. Concurrently, the benefits brought by storage are examined.

2.1. Definition of energy storage

According to Ter-Gazarian (1994: 35–36.), energy storage can be specified as:

> "Energy storage in a power system can be defined as any installation or method, usually subject to independent control, with the help of which it is possible to store energy, generated in the power system, keep it stored and use it in the power system when necessary."

2.2. Need for and use of energy storage

Figure 1 illustrates a typical energy storage application. During the night, as the demand is low, the storage is profitably charged from the baseload generating plant. As the demand rises during the day, the plants belonging to the mid-merit category (the supply between baseload and peaking power) are taken into use, but the storage is nonetheless employed, accounting for frequency and voltage control by balancing supply and demand. During the peak period, the storage provides the additional need, which mitigates the need for use of expensive peaking power plants. Generally, these burn natural gas or diesel oil and hence cause substantial emissions. Moreover, economic savings are not only made due to decreased fuel consumption, but also because of the reduced maintenance costs of the peaking units. These reductions can likewise be substantial, as the frequent start-ups cause considerable strain. Also when employing thermal power plants, storage allows them to be operated at more constant and efficient set points, thus increasing their efficiency, maintenance intervals and lifetime. Graphically, this is implied by the flattening generation curve.

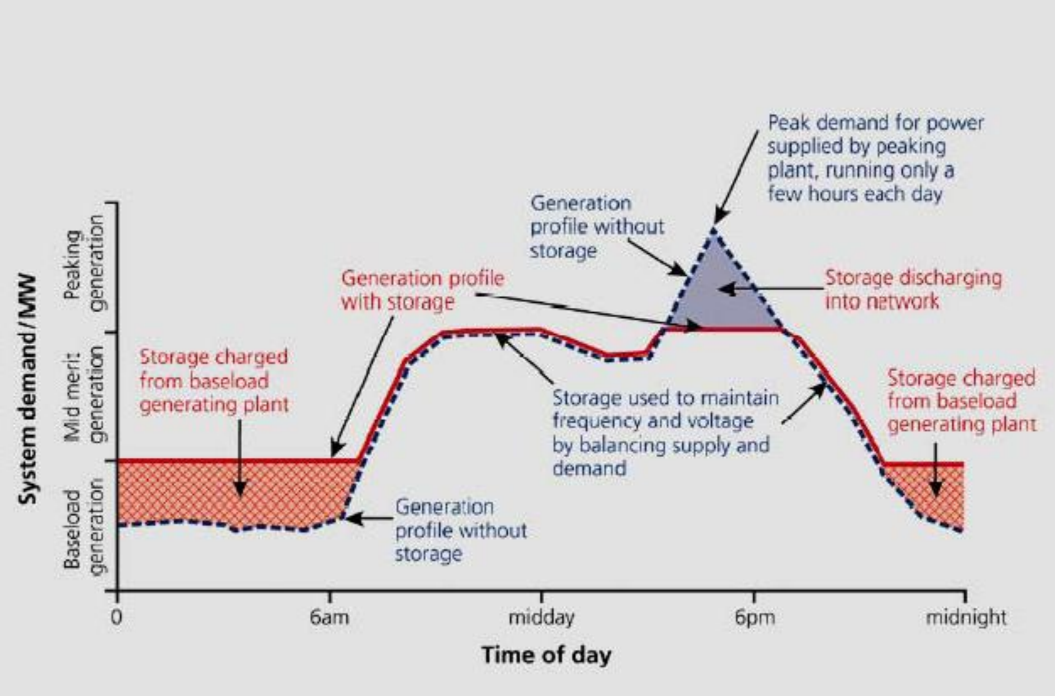


Figure 1. Meeting the demand using energy storage (Joseph & Shahidehpour 2006: 1).

Furthermore, it has to be taken into account that if the energy is generated by intermittent renewables, potentially appreciable amounts produced during the off-peak hours would not be exploitable without storage.

Storage of energy can be successfully applied on all five levels of energy distribution: energy sources, generation, transmission, distribution and service (Alanen et al. 2003: 88). Storage is used for several purposes within the conventional electricity supply system. The central applications are listed below, categorized into generation, transmission and distribution, and customer service. Figure 2, on page 19, illustrates the storage power requirements in relation to the typical storage time for the different utilizations. The application specific requirements and detailed parameters are listed in Appendix 1.

2.2.1. Applications on the level of generation

This chapter describes the different fields of applications of energy storage on the level of generation: system regulation, rapid reserve, peak shaving, load leveling, generation capacity deferral, area control and frequency responsive reserve, and commodity storage.

System regulation: Short-term, random fluctuations in electricity demand can be met through energy storage and hence the need for frequency and voltage regulation by the main plant is avoided. By varying the real and reactive output of the storage, the power and frequency oscillations are rapidly damped. Furthermore, storage can provide ride through during momentary power outages, reduce harmonic distortions and eliminate voltage sags and surges. (Dell & Rand 2001: 6; Jewell, Gomatom, Bam & Kharel 2004: 4.)

Rapid reserve is generation capacity that can be used in order to prevent an interruption in the event of a failure of an operating generation station or transmission lines. Moreover, the use of part-loaded plants that are otherwise held in reserve to meet sudden and unforeseen demands can be abandoned. Normally, the reserve power equals the power output of the largest generating unit. Traditionally, this capacity was provided by a generator “spinning” in synchronization with the supply network, so as to be immediately available. Therefore, the designation s*pinning reserve* is still used as well. However, modern power electronics enable a faster response, with a reserve that does not necessarily spin. (Dell et al. 2001: 6; Dell & Rand 2004: 163, Parker 2001: 19.)

Peak shaving: Energy storage accommodates the minute-hour peak in the daily demand curve (Dell et al. 2004: 163). The stored energy is discharged during the peak and replenished at times of low demand. This can enable substantial economic savings.

Load leveling involves storing excess energy during off-peak hours for use during periods of high demand (Dell et al. 2001: 6). The duration is typically several hours (Dell et al. 2004: 164). This possibility should be taken into consideration as an option to installing expensive, continuous-duty plants for balancing the production. Furthermore, the strategy enables *load following*, i.e. the central power stations match system generation with changes in demand (Dell et al. 2004: 164).

Generation capacity deferral describes the ability of a system to suspend further generation, considering its available storage capacity (Vepakomma 2003: 55).

Area control and frequency responsive reserve: Area control is the ability of a grid-connected system to avoid unintentional power transfer between themselves and with other systems, whereas frequency responsive reserve is a measure of the capacity of an isolated system to momentarily respond to frequency deviations (Butler, Miller & Taylor 2002: 12).

Commodity storage is a superordinate concept that includes the so-called system management applications; load leveling, peak shaving and generation capacity deferral (Parker & Garche 2004: 305).

2.2.2. Applications on the level of transmission and distribution

In this section, the different applications of energy storage on the level of transmission and distribution are defined: transmission system stability, transmission voltage regulation, transmission facility deferral and distribution facility deferral.

Transmission system stability refers to maintaining synchronization between all the components on a transmission line and preventing system collapse (Butler et al. 2002: 12).

Transmission voltage regulation is the ability to maintain the voltages at the generation and load ends of a transmission line within 5 % from each other. This involves supplying high levels of power at selected locations to meet load demands. If the energy storage is placed at the end of the line, the amount of transferred power during peak periods will decrease and hence reduce the resistive losses and provide a net energy saving. (Dell et al. 2004: 164).

Transmission facility deferral refers to the ability of a utility to defer installation of new transmission lines and transformers, on account of adding an energy storage system (Vepakomma 2003: 55).

Distribution facility deferral is equivalent to transmission facility deferral, but on a distributional level.

2.2.3. Customer service applications

Finally, this chapter describes the energy storage applications for customer service: customer energy management, power quality and reliability, and renewable energy management.

Customer energy management involves dispatch of energy stored during off-peak periods to manage demand on utility-sourced power (Butler et al. 2002: 12). From a customer's point of view, this also encompasses peak shaving and load leveling.

Power quality and reliability refers to the ability of preventing voltage spikes, voltage sags and brief power outages from causing data and production loss for customers (Vepakomma 2003: 56).

Renewable energy management refers to the storage of electricity by which renewable energy is made available during periods of peak utility demand at a consistent level. By stand alone systems, the advantages are even more prominent.

2.3. Application-specific requirements on storage duration

In accordance with Figure 2, power quality management requires only a short storage time (less than 60s) for reduction of voltage sags and brief outages. During the interval 10–300s, the storage is to provide electricity, while possible peaking power plants are started (Alanen et al. 2003: 89). On a minute basis, the aim is primarily to secure distribution quality. On a long term, the objective is mainly to smooth the load and benefit from the control abilities of the peak power (Alanen et al. 2003: 89). Capacity for several hours to days is typically for storage of distributed and/or renewable energy. Figure 2 provides a more detailed insight of the required storage times. A complete compilation of the application-specific requirements on storage duration is available in Appendix 1.

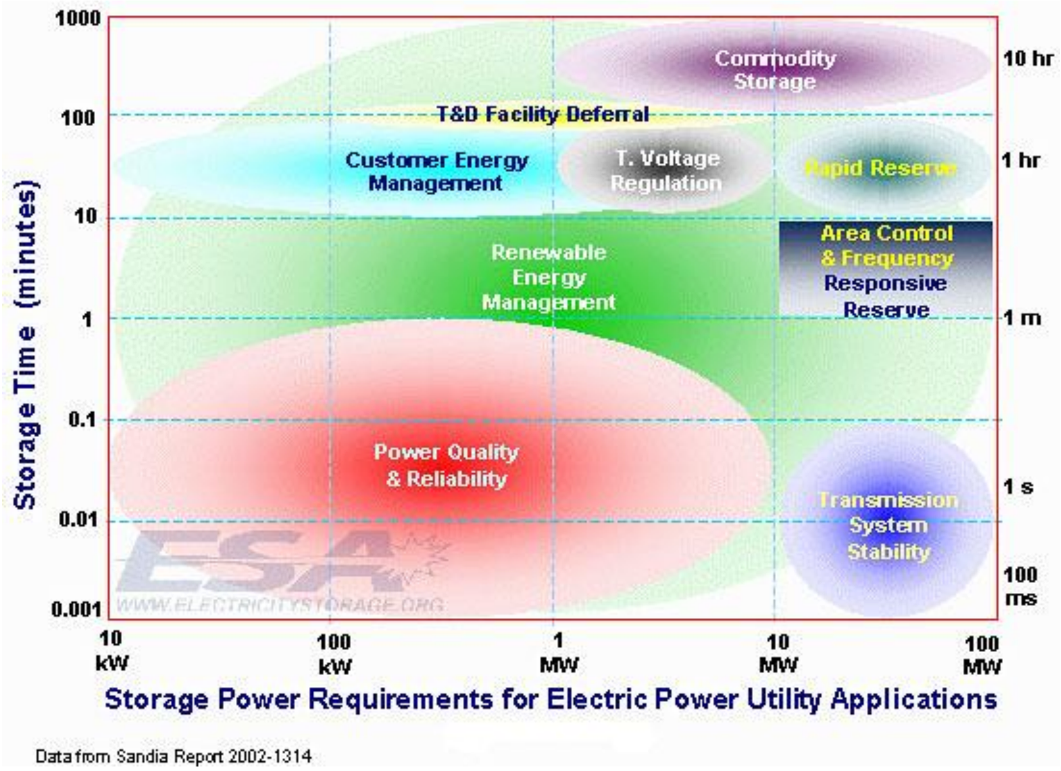


Figure 2. Application specific energy storage requirements (ESA 2008).

2.4. Conclusions

In brief, the objective of energy storage is to improve the supply of uninterrupted, high quality power to the end user. Further objectives include reducing transmission and power losses, as well as achieving strategic advances through improved siting and fuel flexibility. Moreover, cost savings are provided, as the need for additional generation units, transmission lines and transformers diminishes. Decreased environmental impact is also reached as integration of renewables is noticeably promoted and thus emissions are reduced and the effects of electric and magnetic fields are decreased.

3. ENERGY STORAGE FOR RENEWABLES

This chapter defines the characteristics of renewable energy generation and provides an overview of storage technologies suited for the field.

3.1. Background

As constantly more attention is paid to the problems regarding greenhouse gas emissions, global warming and the inevitably approaching depletion of fossil fuels, the importance of renewable energy sources increases rapidly. They offer inexhaustible resources and the generation is basically pollution-free.

Furthermore, renewables contribute to energy independence. Considering the major blackouts that have occurred during the last years, more attention will undoubtedly be paid to this aspect.

The profitability of renewable generation grows steadily, not only because of improving technology, but also due to the constantly rising costs for fossil fuels. Moreover, government support, through beneficial legislation and subsidies, still has an essential role in supporting further integration.

In 2007, worldwide generation capacity of renewable energy (excluding large hydropower) exceeded 240 GW, which entails an increase of 50 % in three years. Thus, their share of the total electricity production now represents 3.4 %. (REN21 2007: 6—9)

Wind power accounts for the largest share of renewable energy generation, 95 GW, and experienced an increase of 28 % in 2007. On the other hand, grid-connected photovoltaics represent the fastest growing technology, with an annual of increase of 50 %, and have now reached a capacity of 7.7 GW. (REN21 2007: 6.)

At least 66 countries worldwide have policy targets for renewable energy, and objectives are already being set for 2020 (REN21 2007: 21). The enormous increase in the employment of renewables clearly continues, which will cause growing challenges in the terms of grid stability and energy availability. An efficient method to manage the situation is to implement energy storage.

3.2. Characteristics for renewable energy sources

Renewable energy sources, such as wind, solar and hydro, all have one common significant constraint: they are not controllable like fossil fuels, which can be conveniently stored and used when required. Consequently, unlike the case of conventional power plants, the electricity generation is directly linked to the available primary energy. Hence, at some times the grid cannot absorb the entire output, which therefore has to be curtailed and the excess capacity remains unexploited. At other times, the demand cannot be matched and additional operating reserves are required, which entails extra costs and often emissions. Moreover, the sites suited for renewable energy generation are often distant from population centers and the grid. Obvious examples are the major wind farms. Hence, the use of storage is a substantial option to constructing new transmission lines.

In the case of wind power, the variations in supply of power to the grid can be in the range of a few hundred megawatts on an hour scale, and even exceed a gigawatt in a day (this is the situation in, e.g., Germany). The impact of the increasing share of volatile wind power on the electricity price can clearly be observed in the deregulated European markets. Within in a day, the price may vary by a factor of ten. (Bullough, Gatzen, Jakiel, Koller, Nowi & Zunft 2004: 2—3.) Although sophisticated methods are used to forecast the production, there will always remain an inherent and irreducible uncertainty in every prediction. Therefore, it is necessary to find means of storing the energy in order to exploit the full potential and to optimally benefit from the green energy, regardless of the intermittent nature.

On an annual average, off-shore wind farms are capable of delivering approximately 40 % of the installed capacity (example: Germany) (Crotogino 2003: 9). Adding suitable energy storage enables predictable and effective electricity generation and ultimately makes the wind farms comparable options to conventional generation.

3.3. Overview of suitable energy storage technologies

An overview of the commonly available technologies, which are suited for the use together with renewable energy generation, is provided in Figure 3.

Energy storage systems utilize different physical and chemical phenomena. For instance batteries and fuel cells are based on electrochemistry; supercapacitors and superconducting magnetic storage (SMES) utilize electromagnetic fields; flywheels, compressed air energy storage (CAES) and pumped hydro storage (PHS) are based on mechanics and storage of heat and cold is based on thermochemistry.

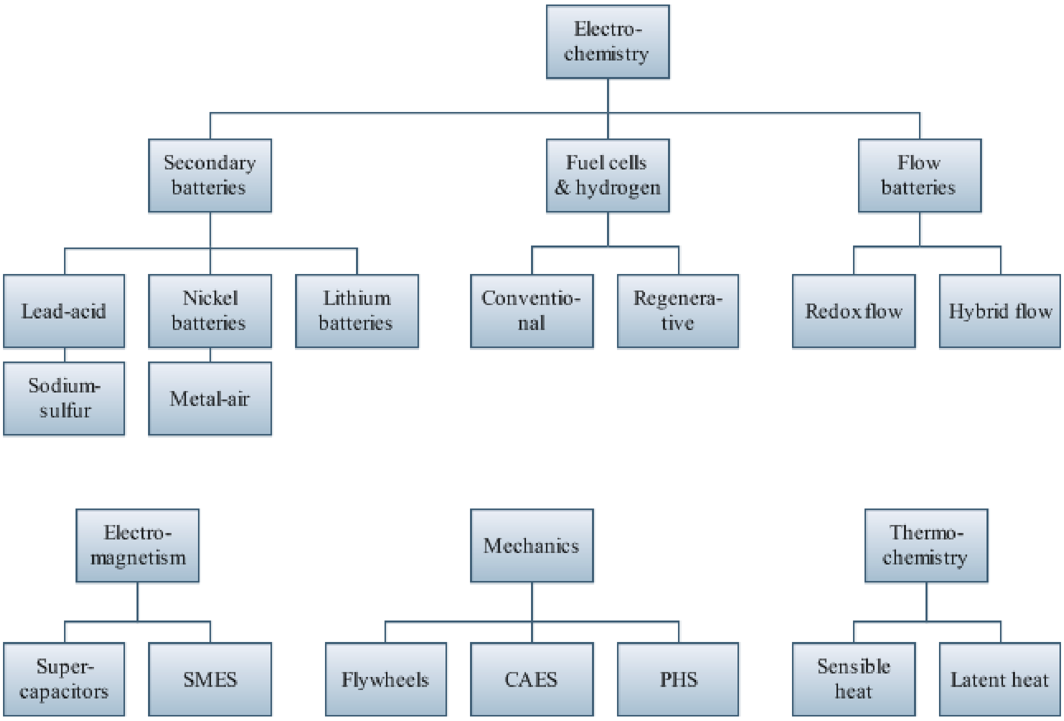


Figure 3. Overview of energy storage technologies

4. ELECTROCHEMICAL STORAGES

This chapter assesses the characteristics, present use, costs and state-of-the-art situation of storage technologies based on electrochemistry: secondary batteries, fuel cells and hydrogen, and flow batteries.

4.1. Secondary batteries

Secondary batteries consist of two or more electrochemical cells and can be charged and discharged numerous times (IWEI 2001: 55). In general, they offer a high energy density, but a low power density.

Batteries, as well as fuel cells, consist of two electrodes, the anode (-) and the cathode (+), fitted on both sides of an electrolyte. The electrodes exchange electrons with the electrolyte and with an external source or load.

During the discharge procedure, the oxidizing electrode, i.e. the anode, sends positive ions into the electrolyte. Thus, the anode itself becomes negatively charged and serves as an electron source for the external circuit. Simultaneously, the cathode consumes electrons from the external circuit and positive ions from the internal circuit. This process is continual in order to maintain electrical current in the external circuit. Figure 4 illustrates an electrical source during discharge. The course of events is reversed during charging. (Ter-Gazarian 1994: 131.)

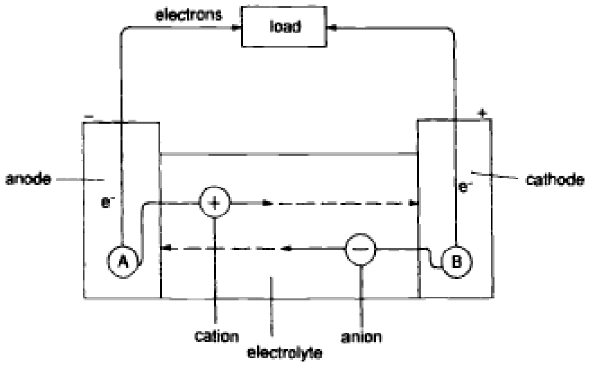


Figure 4. Electrical energy source during discharge (Ter-Gazarian 1994: 132).

The performance of batteries depends on the material used, the manufacturing processes and the operation conditions. Lifetime tests require several years and the development is, consequently, moderate (EC 2001: 6).

A comparison of typical parameters of the most significant secondary batteries is given in Table 1, on page 36. A detailed economic assessment is found in Table 2 (p.38). As illustration of an actual battery energy storage system, the principle diagram of the electric system a large scale configuration is shown in Appendix 2. This also provides an overview of the constituent control and protection system.

4.1.1. Lead-acid batteries

Lead-acid battery storage is one of the oldest and most common technologies for energy storage. It is an economical, reliable and well-known choice. Hence, lead-acid batteries are frequently the storage choice for particularly wind- and solar-powered installations. However, owing to the short life cycle they are not optimal for energy management. (Dell et al. 2001: 10; ESA 2008; IEA 2004: 11.)

There is a wide range of battery designs available. Still, based on the electrolyte a classification in two major concepts can be made: *vented* (aka *flooded*) and *valve-regulated* lead-acid batteries (VRLA). The former and more mature technology employs electrodes and separators immersed in a liquid electrolyte, and has a vented design. Here, overcharge causes water losses due to water electrolysis and gas release, and hence there is a considerable need for maintenance. However, incorporating catalytic recombiners in each cell vent reduces the losses to some extent. VLRA batteries, on the other hand, utilize immobilized electrolytes absorbed in separators or gel. A recombination of a majority of the oxygen generated during overcharge is made within the cell. Thus, the evolution of hydrogen is minimized and water is reformed. Consequently, the need for continuous refilling is eliminated and the concept is close to maintenance-free. Nevertheless, grid corrosion consumes oxygen and always causes some hydrogen evolution and water losses. (IEEE Std 1013: 23; Lailler 2003: 13; Parker 2001: 19.)

The conventional lead-acid battery consists of alternate pairs of plates, one lead and the other lead coated with lead dioxide, which are immersed in the electrolyte; a dilute solution of sulfuric acid. During discharging, both electrodes are converted into lead sulfate. Charging restores the positive electrode to lead oxide and the negative electrode to lead. (Ter-Gazarian 1994: 133.)

The discharge reactions are shown below and the recharge reactions are simply the reverse, with the cathode positive and the anode negative. The reaction at the cathode is (Ter-Gazarian 1994: 133–134)

$$Pb_2SO_4 + 2H_2O \rightarrow PbO_2 + H_2SO_4 + 2H_2 + 2e^-, \tag{1}$$

and at the anode

$$PbSO_4 + 2H_2 + 2e^- \rightarrow H_2SO_4 + Pb, \tag{2}$$

which gives

$$Pb + 2H_2SO_4 + PbO_2 \rightarrow 2PbSO_4 + 2H_2O. \tag{3}$$

Lead-acid batteries allow maintenance-free design, have high charge efficiency along with a wide temperature operation range, and are capable of providing a moderate specific power. Due to these qualities, together with favorable investment costs, lead-acid batteries are the most common storage medium for renewable applications as well. (IEA 2004: 11; IWEI 2001: 55).

The main drawbacks of the batteries are mediocre energy density, short life expectancy and relatively long charge time. Further shortcomings are sensibility to extreme temperatures, discharges and overcharges. Moreover, even though the recycle rate is 95 % in the developed countries, the environmental effects cannot be disregarded. In addition to lead itself being poisonous, the sulfuric acid constitutes another danger. (IEA 2004: 11–12; IWEI 2001: 55; Lailler 2003: 30.)

Figure 5 presents a comparison of the characteristics of two different lead acid-battery designs with those of an ideal energy storage system, defined by the Investire-Network[1]. As the requirements on an energy storage system are case-specific, the figure cannot be considered definite, but still gives a valuable insight in the limitations of the lead-acid battery. Particularly lifetime, maintenance and monitoring and controlling are parameters which limit the use of the lead-acid battery.

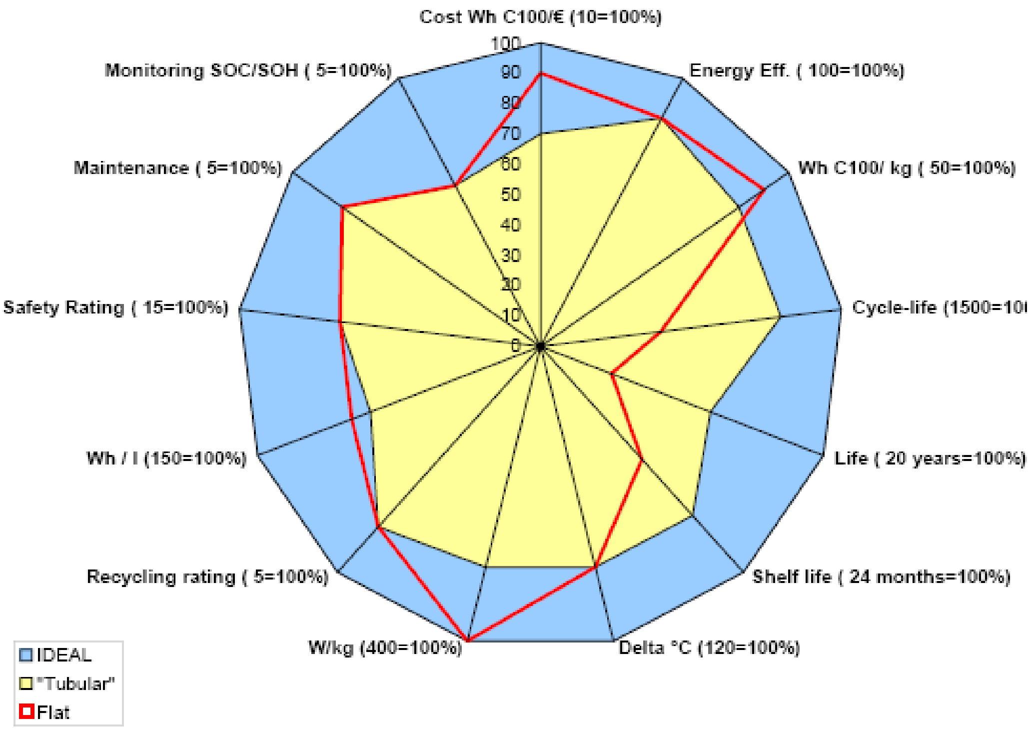


Figure 5. The characteristics of two lead-acid battery designs in comparison to those of an ideal energy storage system (Lailler 2003: 31).

In order to remain a competitive option in comparison to the emerging technologies, further development of especially the lifetime is necessary. This could be accomplished by enhancing the oxygen recombination and the composition of the active materials. Suggested improvements for increased efficiency are, for instance, corrosion protection of the current collectors, development of enhanced active material formulations and more effective system management of battery packs. (Lailler 2003: 25—34.) Another

---

[1] Investigations on Storage Technologies for Intermittent Renewable Energies. Project funded by the Fifth Framework Programme of the European Commission.

possible future for the lead-acid batteries is as a part of a hybrid storage system, e.g. together with SMES, where the weaknesses would diminish.

4.1.2. Nickel batteries

The most important nickel batteries are those based on nickel-cadmium, nickel-zinc and nickel-metal hydride technology. Nickel hydroxide is used as material for the positive electrode in all of them (IEA 2004: 21). The nickel batteries offer, first and foremost, long cycle life, high reliability and outstanding long-term storage qualities

They all utilize alkaline technology, which involves advantages like longer cycle life (i.e. the number of cycles a battery can perform before failure), wider temperature range and the ability to withstand full discharges without compromising lifetime or efficiency. Furthermore, the high electrolyte conductivity allows for high power applications. (Cobasys: 2; Iwakura, Murakami, Nohara, Furukawa & Inoue 2005: 291; IWEI 2001: 56.)

Nickel-cadmium batteries

Nickel-cadmium batteries are alongside with lead-acid batteries the most common ones (Alanen et al. 2003: 48). Cadmium hydroxide is used as material for the negative electrode and a solution of alkaline potassium hydroxide with small amounts of lithium hydroxide serves as electrolyte (Dahlen 2003: 6). The cell reaction by discharge (the charge reaction being its reverse) may at the positive electrode be written as (Surmann 1996: 543)

$$2NiOOH + 2H_2O + 2e^- \rightarrow 2Ni(OH)_2 + 2OH^-, \qquad (4)$$

and at the negative electrode as

$$Cd + 2OH^- \rightarrow Cd(OH)_2 + 2e^-, \qquad (5)$$

which results in

$$Cd + 2NiOOH + 2H_2O \rightarrow Cd(OH)_2 + 2Ni(OH)_2. \qquad (6)$$

Compared to the lead-acid battery, the nickel-cadmium battery offers a greater recharge cycle life, a constant discharge voltage (Alanen et al. 2003: 50) and a superior suitability for cold climate conditions.

On the other hand, the power density and efficiency are lower. Normally, the self-discharge is also higher and the so called memory effect has to be taken into consideration. (IEA 2004: 29.) That means that repeatedly shallow cycling leads to internal structure changes and thus storage capacity losses. However, according to recent studies these effects can be considered rather negligible in stationary batteries (McDowall 2003: 7). Of utmost importance are also the markedly higher costs in comparison to the lead-acid battery.

Another drawback is that the toxic heavy metal cadmium has to be taken care of. Although the recycling is remarkably effective (collection rates of up to 99 %) (Dahlen 2003: 27), the directive *2003/0282 COD* of the European Union (2006: 6—11) states that the use of cadmium in industrial batteries, including those for renewable energy applications, should be prohibited. Therefore, the importance of the nickel-cadmium battery is most likely to decrease in favor for the other nickel batteries.

Nevertheless, noticeable is that the currently largest battery system in the world is constructed with nickel-cadmium batteries (installed in 2003). Further information concerning it is found in Appendix 2.

Nickel-zinc batteries

The nickel-zinc battery is analogous to the nickel-cadmium battery, but is considerably less expensive. The ability to offer high energy density as well as high power density makes it an interesting alternative. Furthermore, zinc is environmentally friendly and easily recyclable (Dahlen 2003: 25).

The positive electrode and the electrolyte are similar to those used in the nickel-cadmium battery, but here zinc hydroxide serves as the negative electrode (Dahlen 2003: 6). The overall discharge cell reaction is (the charge reaction being its reverse) (Ter-Gazarian 1994: 134)

$$Zn + 2NiOOH + 2H_2O \rightarrow Zn(OH)_2 + 2Ni(OH)_2. \qquad (7)$$

The main shortcomings are a short life cycle, separator stability, temperature control and mass production problems. The limited lifetime is inflicted by the high solubility of the reaction products at the zinc electrodes. Redeposition of zinc during charging inflicts dendritic growth, which means that the active material, here zinc, is reduced from its oxidized state and deposited onto a substrate, e.g. an electrode being charged. The dendrites can penetrate the separator and cause an internal shortcut and redistribution of the active material. Possible solutions are the use of electrode and electrolyte additives; penetrator resistant separators and vibrations of the zinc electrode during charging. (Li, Ma, Kukovitskiy & Faris 2007: 1; Ter-Gazarian 1994: 134.)

Future improvements of the nickel-zinc battery, as well as of the other nickel batteries, could be achieved through the use of solid or gel electrolytes. Particularly the charge-discharge performance would benefit. (Iwakura et al. 2005: 291–294.)

Due to its important benefits, the nickel-zinc battery has substantial potential to dominate at least the nickel battery group in several niches in a near future.

Nickel-metal hydride batteries

The voltage characteristics of the nickel-metal hydride battery are highly similar to those of the nickel-cadmium battery, whereas 25–50 % more energy is provided and the environmentally harmful cadmium is avoided (Dahlen 2003: 5; Gibbard 1993: 215). Besides the impressive energy density, possible memory effects are reduced (Vechy 2006: 2).

The employed positive electrode and the electrolyte are similar to those of the other nickel batteries, while a metal alloy forms the negative electrode. The alloy, which constitutes the only difference from the nickel-cadmium cell, is reversibly capable of absorbing and desorbing considerable amounts of hydrogen. (Dahlen 2003: 6; Gibbard 1993: 215.) The overall cell reaction by discharge can be expressed as (the charge reaction being its reverse) (Ledran 1993: 74)

$$MH + NiOOH \rightarrow M + Ni(OH)_2. \tag{8}$$

The unique feature of the hydrogen storage alloy is its ability to store hundreds of times its own volume of hydrogen gas at a pressure less than atmospheric pressure (Gibbard 1993: 216).

Traditionally, nickel-metal hydride batteries have been used for consumer electronics like cell phones, cameras and laptops owing to the limited capacity range. Nonetheless, they have started to emerge in the field of stationary applications as well. For instance, Cobasys manufacture low maintenance batteries suitable for renewable energy applications (Cobasys 2007). A breakthrough in this domain has, however, not been reached due to the need to match the application requirements with the characteristics of the new technology (Cobasys: 10).

Among the drawbacks of the battery are also a limited high current delivery capacity and a more complex charging algorithm than the one of the nickel-cadmium battery (Vechy 2006: 3). Seen as its potential successor, the problem that the metal hydride alloy cannot be recycled must be attended to. (Dahlen 2003: 27).

4.1.3. Lithium batteries

The light weight and high electrochemical energy potential makes lithium a suitable material for batteries (Vechy 2006: 3). Based on the used electrode materials and electrolytes, the batteries are classified into lithium metal, lithium metal polymer, lithium-ion and lithium-ion polymer.

Lithium metal batteries

A wide number of different metals have been examined and utilized in the last decades. Therefore, the cell reaction with lithium and titanium disulfide in equation 9 only serves as an example. By discharge it can be written as (the charge reaction being its reverse) (IEA 2004: 13)

$$Li_{Metal} + TiS_2 \rightarrow LiTiS_2. \tag{9}$$

Typically, with current technology only between 25 % and 40 % of the theoretical energy densities are reachable. Depending on the used lithium metal anode, this still means densities ranging from 80 Wh/kg to 960 Wh/kg. Another positive aspect of the battery is the marginal self-discharge, which can be less than one percent per year. (IEA 2004: 14; Jossen et al. 2003: 7.)

The main limitation of the battery is the bad cycle life of the lithium metal electrode. During cycling, a solid electrolyte interface is formed, where lithium particles are deposited. These are electrically isolated and unreachable during discharging. The problem becomes more severe with the number of cycles and ultimately results in formation of dendrites. Comprehensive research, mainly focusing on the electrolyte and its purification, is being undertaken in order to solve the issue. (Jossen et al. 2003: 7–8).

The safety risks formed by the battery are also not to be neglected. The formation of dendrites, which always occur to some extent, results in internal short cuts which generate considerable heat. If the melting point of lithium is reached, a reaction within the electrolyte is activated, which can result in the battery exploding. Suggested safety improvements include the use of mechanical pressure to reduce the dendrite growth and coating of the lithium metal with a lithium ion conductive membrane. (Jossen et al. 2003: 8.)

A key aspect of the research and development is improvement of the cycle life. As for all of the different lithium batteries, the most important target is to reduce the costs, which is mainly to be achieved through adaptation of cheaper materials. (Jossen et al. 2003: 35.)

Lithium-ion batteries

Instead of utilizing any lithium metal, the common feature of the lithium-ion batteries is that the charged negative electrode is a lithium ion intercalation compound of either graphite or a disordered form of carbon. The ions are supplied by the positive electrode material, which is a transition metal oxide. During charging and discharging, the ions move back and forth between the two electrodes. (Blomgren 2000: 97.) The overall cell reaction by discharge is (the charge reaction being its reverse) (IEA 2004: 14)

$$LiMO_2 + 6xC \rightarrow Li_{(1-x)}MO_2 + x\,LiC_6, \qquad (10)$$

where MO_2 symbolizes the employed metal oxide.

This use of material acting as a matrix, in which lithium atoms are inserted, eliminates the problem with the poor cycling efficiency of the lithium metals and thus greatly improves the cycle life. Furthermore, the batteries are interesting because of their superior theoretical energy density, which can be as high as 1000 Wh/kg. Some configurations allow over 80 % of the theoretical values to be reached. In conclusion, current technology can offer densities in the range of 650 Wh/kg. Finally, they also provide a low self-discharge rate. (Jossen et al. 2003: 8–11; Vechy 2006: 3.)

A drawback of the technology is that a complex charging circuitry is needed to maintain stability (Vechy 2006: 3). Generally, lithium-ion batteries have been used for portable applications, but current research aims to commercialize large-scale systems, which have so far been expensive (exceeding 600 €/kWh) (Alanen et al. 2003: 53).

Lithium-ion polymer batteries

Characterizing for lithium-ion polymer batteries is a non-liquid electrolyte. This, a thin lithium ion conductive polymer membrane, enables a shorter distance between the electrodes, thus contributing to a higher energy density. Other advantages include elimination of any leakage problems, increased safety and flexibility in shape design. (Jossen et al. 2003: 12–13).

Although lithium-ion polymer batteries enable more economical mass production methods, the costs have so far been considerably higher than for conventional lithium-ion batteries. However, the price difference is estimated to fade within only a few years. The construction of large-scale systems is likewise still in the research phase. Also similar to the normal lithium-ion batteries, a rather complex charging circuitry is mandatory for stability. (IEA 2004:14; Jossen et al. 2003: 13; Vechy 2006: 3.)

Expected future developments involve refined lithium alloy anodes and new cathode materials with noticeably improved energy densities (Blomgren 2000: 100).

4.1.4. Sodium-sulfur batteries

The sodium-sulfur battery consists of a positive electrode employing molten sulfur and a negative electrode of sodium, separated by a solid beta alumina ceramic electrolyte. As this conducts sodium ions well, but electrons poorly, prevents self-discharge is prevented. During discharge, positive sodium ions pass the electrolyte and are combined with the sulfur, thus forming sodium polysulfides. This reversible process takes place at a temperature of approximately 300 °C. (Bito 2005: 1; Wen 2006: 1.) The global discharge reaction occurring is (IEA 2004: 33)

$$2Na + x\,S \rightarrow Na_2S_x. \tag{11}$$

Advantages of the battery are excellent energy density, high electrical efficiency and long lifetime. In comparison to lead-acid batteries, ten times more energy can be delivered per unit weight. The pulse power capability is also impressive; temporarily (up to 30 seconds) approximately five times the continuous rating can be established. These attributes make them suitable for power quality and peak shaving applications. (Nichols & Eckroad 2003: 3–4.)

Setbacks are relatively high costs and environmental issues because of the reactive materials used. The need for heating is also a restraint. (IEA 2004: 35–36.) Furthermore, a target for development must be the mediocre power density.

4.1.5. Metal-air batteries

Metal-air batteries are the most compact and have, additionally, the potential to become the most inexpensive. Moreover, they are essentially environmentally harmless. The main constraint is that the recharging procedure is complicated and inefficient. (ESA 2008.) Nonetheless, their abilities make them suitable for stand-alone applications.

An electrochemical coupling of a reactive metal anode to an air electrode is utilized to provide the battery with an infinite cathode reactant, oxygen. The charging is either mechanical or electrical. In the former design, the discharged metal and the electrolyte is continuously replaced. The discharge metal electrode is then charged or recycled outside the cell (IEA 2004: 29). The air electrode serves only for the purpose of oxygen-reduction and the battery is restricted to discharge mode. The latter concept, however, employs an air electrode capable of both oxygen reduction (in discharge mode) and oxygen evolution (in charge mode). This solution is still under heavy development due to a lifetime of only a few hundred cycles and an efficiency of merely 50 % (ESA 2008). (Worth, Perujo, Douglas, Tassin & Brüsewitz 2002: 4.)

Development of such bifunctional air electrodes, which are reliable and efficient, is still in an early phase. It may, however, be the key to a more widespread use. Other necessary enhancements include improving the power output, expanding the operating temperature range and preventing hydrogen evolution due to anode corrosion, as well as minimizing carbonation of the alkali electrolyte. (Worth et al. 2002: 4–5.)

Normally, metal-air batteries utilize low-cost metals as anodes, and porous carbon structures or metal meshes covered with catalysts as cathodes (i.e. air electrodes). Common electrolytes are liquid potassium hydroxide and solid polymer membranes saturated with the former. (ESA 2008.) Several types of batteries have been developed, for instance zinc-air, aluminum-air, magnesium-air, iron-air and lithium-air configurations. This overview is, however, limited to the most common of the systems, the zinc-air battery.

Zinc-air batteries

The considerable interest in zinc-air batteries is primarily due to the remarkable theoretical energy density, 1084 Wh/kg, which is more than six times that of lead-acid batteries (Will 1998: 1). However, current technology merely allows one-fourth of this to be achieved (IEA 2004: 31). Furthermore, zinc is non-toxic and can inexpensively be mass-produced.

The overall chemical reaction occurring between oxygen and zinc by discharge can be written as (the charge reaction being its reverse): (Ter-Gazarian 1994: 135)

$$Zn + 1/2\ O_2 \rightarrow ZnO. \qquad (12)$$

The zinc-air couple has poor charge-discharge efficiency due to polarization losses associated with the air electrode. Similarly to nickel-zinc batteries, redeposition of zinc during charging causes electrode shape changes and dendritic growth. However, a specific ion exchange membrane has been developed for zinc-air batteries and is suggested to stop the dendrites from growing (Dahlen 2003: 25). Another approach proposed to improve cycle life and discharge performance by eliminating dendrite growth, is the use of a slight overcharge, approximately 5 %, and stripping the zinc every discharge cycle (Will 1998: 3). Nevertheless, for the time being, the ensuing instability is the main technical issue in the development. As zinc oxide formed during discharge dissolves in the electrolyte, zincate ions are born. The characteristic economical drawbacks of metal-air batteries, short cell lifetime and low efficiency, are indeed the distinct impediments of the zinc-air battery as well. (Ter-Gazarian 1994: 135.)

Current research indicates that the present difficulties will be surmountable. Especially progress within the development of bifunctional electrodes is crucial. Success in this field would to a great extent promote the interest for the battery in the market for renewable energy sources.

4.1.6. Conclusions and comparison

In general, it can be concluded that secondary batteries share the following characteristics:

- fast response times, in the range of milliseconds
- negligible no-load losses
- energy contents and power outputs which are dependent on each other
- short life-time.

However, for applications which require high power rapidly, batteries are not the optimal choice. Neither can any significant development in that direction be perceived. Generalized, the current research objectives are rather to improve cycle lives, reliability, recycling effectiveness and to simultaneously reduce the costs.

Typical parameters of the different battery types are listed in Table 1. The values of the lithium batteries are naturally dependent of the materials used, so an estimation based on the most frequent types is made. Moreover, note that the performance depends on several factors, such as system design, discharge conditions and temperature, and furthermore that the technologies are constantly evolving, wherefore a definite compilation is impossible. In addition, the available information varies a lot. Therefore, the table is based on a vast amount of sources, in order to provide as standardized data as possible.

Table 1. Comparison of the parameters of secondary batteries (Dahlen 2003: 13—17; IEA 2004: 12—36; Jossen et al. 2003: 7—26; Kim 1999: 81; McKeogh 2003: 18; MPower 2006; Nichols et al. 2003: 4; Sauer 2007: 29; Vechy 2006: 4; Wen 2006: 1 & Worth et al. 2002: 9).

Secondary batteries	**Power density [W/kg]**	**Energy density [Wh/kg]**	**Efficiency**	**Self-discharge @ 25 °C [% / m]**	**Lifetime [cycles]**	**Operating temp. range [°C]**	**Nominal cell voltage [V]**
Lead-acid	180	25–50	0.85-0.94	1–4	500–800	–20 – +50	2.0
NiCd	150	45–80	0.60-0.80	20	2000	–40 – +60	1.2
NiZn	300	50–60	0.80	20	600	0 — +60	1.5
NiMH	250—1000	60–120	0.65—0.70	30	1500	–20 – +60	1.2
Li-metal	300	140—180	0.93—0.97	1	250	—20 — +70	4.0
Li-ion	1000	180	0.99—1.00	5—10	1200	–25 – +60	3.7
Li-ion polymer	380	120	0.98—1.00	5—10	1200	–20 – +60	3.7
NaS	150	110	0.75– 0.86	0	2500	+300 — +350	2.1
Zinc-air	80—200	200—300	0.50	8	200	–20 – +60	1.15

m = month

The costs for the most common secondary batteries are listed in Table 2. The costs are recalculated using the conversion factors 1 € = 1.15 $ and 1 € = 1.25 $, which corresponds to the average exchange rates of the concerned years, 2003 and 2006, respectively.

In the assessment, a distinction is made as follows:

- bulk energy storage (10–1000 MW)
- storage for distributed generation (100-2000 kW)
- storage for power quality (0.1–2 MW)

The costs are listed in accordance with this division, as appropriate. Bulk storage applications are primarily load leveling and spinning reserve, which require discharge times in the range of one to eight hours and energy capacities of 10–8000 MWh. Typical examples of applications connected to distributed generation are peak shaving and transmission deferral, where storage durations range between 0.5 and 4 h and capacities correspondingly between 50 and 8000 kWh. To assure power quality, discharge times of 1–30s are sufficient, which entails capacities of 0.028–16.67 kWh. (Schoenung & Hassenzahl 2003: 11).

As indicated by the table, the life cycle costs of all batteries are considerably influenced by the replacement costs, which indeed is characteristic for the technology. This is especially significant for power quality storage, where the expenses are dominated by capital and replacement costs, whereas the operating costs are minimal. Noticeable is also that the balance of plant[2] costs for large lead-acid battery plants may be as high as the costs for the batteries themselves. For smaller storage systems suited for distributed generation this is, however, less prominent.

The estimated energy-related costs for the batteries not available in the table below are 150–200 €/kWh for nickel-zinc batteries, 200 €/kWh for nickel-metal hydride batteries and 64 €/kWh for zinc-air batteries (MPower 2006).

---

[2] Building construction, battery installation, interconnections, heating, ventilating, air conditioning equipment etc.

Table 2. Costs for the most common secondary batteries (Schoenung et al. 2003: 30–32).

Secondary batteries: costs		Lead–acid	NiCd	Li–ion	NaS
Bulk storage	**Energy-related cost [€/kWh]**	130–174	522	N/A	217
	Power-related cost [€/kW]	109	109	N/A	130
	Balance of plant [€/kWh]	130	130	N/A	43
	Replacement cost [€/kWh]	130–174	522	N/A	200
	Replacement frequency [yr]	5–6	10	N/A	10
	Fixed O&M [€/kW–yr]	4.3–13	4.3	N/A	17
DG storage	**Energy-related cost [€/kWh]**	130–174	522	435	217
	Power-related cost [€/kW]	152	152	152	130
	Balance of plant [€/kWh]	43	43	0	0
	Replacement cost [€/kWh]	130-174	522	435	200
	Replacement frequency [yr]	5–6	10	10	15
	Fixed O&M [€/kW–yr]	4.3–13	22	22	17
PQ storage	**Energy-related cost [€/kWh]**	261	N/A	435	N/A
	Power-related cost [€/kW]	217	N/A	174	N/A
	Replacement cost [€/kWh]	261	N/A	435	N/A
	Replacement frequency [yr]	6	N/A	10	N/A
	Fixed O&M [€/kW–yr]	8.7	N/A	8.7	N/A

In conclusion, on account of reliability and inexpensiveness, the lead-acid battery is dominating the energy storage market for stationary applications, renewable systems being no exception. Nonetheless, its mediocre performance will inevitably contribute to a continuously growing interest in the alternative batteries. Although the lead-acid battery is expected to proceed to develop parallel with the emerging options, a gradual transfer to these can already be discerned. In certain niche areas, predominantly within consumer electronics and small-scale applications, the alternatives are traditionally serious challengers. Due to technical as well as economic constraints, the development within large-scale systems is slower, but a similar progression is also to be expected here.

Until recently, the nickel-cadmium battery has been the primary alternative in basically all fields where the lead-acid batteries are used. Although some considerable applications have been realized, an actual breakthrough has not been reached, mainly because of the higher cost, but also due to dubious performance in terms of self-discharge and efficiency. Recent environmental restrictions are likely to promote the other nickel based technologies.

Owing to the poor energy density of the lead-acid battery, market shares are soon likely to be lost to, particularly, lithium batteries at an accelerating rate as the large-scale applications achieve commercial levels.

A commercially slightly more distant technology, which nonetheless has a great potential is the environmentally benign zinc-air battery. As soon as the air electrodes can be improved, its use will rapidly expand.

A future limiting factor concerning the interest in secondary batteries in general is the growing importance of alternative storage technologies like redox-flow batteries, flywheels, fuel cells etc.

4.2. Fuel cells and hydrogen storages

The development of fuel cells started already in the 19th century, but the improvements in material technology and the growing interest in hybrid vehicles have been crucial for the significant progress within the last few decades. Because of high efficiency potential, low emissions, quietness and flexible use of fuels, they are considered one of the most promising future technologies for energy storage.

4.2.1. Conventional fuel cells

Fuel cells are electrochemical devices that convert the chemical energy of a fuel directly into usable energy, i.e. electricity and heat, without combustion. They are distinguished from secondary batteries by their external fuel store and by the reversible electricity conversion.

A conventional fuel cell as such is operated as a generator, but when combined with an electrolyzer a storage system is formed. The electrolyzer converts electricity into fuel energy and the fuel cell stack converts it back to electricity.

The operating principle of a fuel cell stack is showed in Figure 6. The anode is supplied with fuel, which oxidizes on its surface. Simultaneously, an oxidant is reduced on the cathode surface. These reactions cause ions to flow through the electrolyte and as the circuit is closed, an external current is generated. (Boulanger & Perrin 2003: 8.)

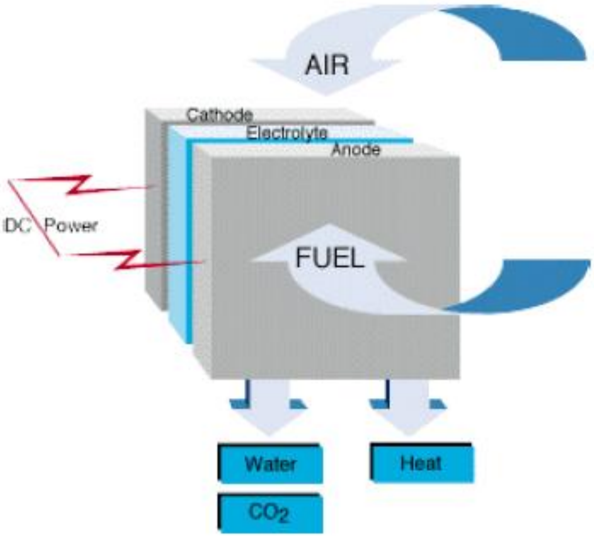


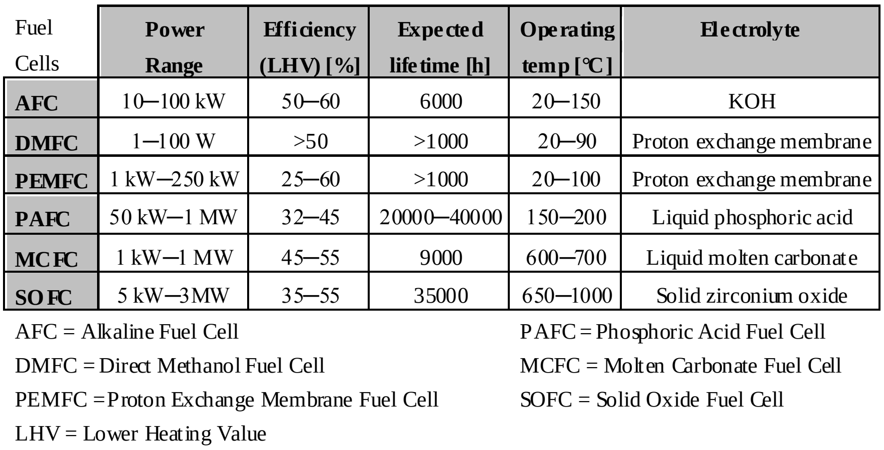
Figure 6. Operating principle of a fuel cell stack (Boulanger et al. 2003: 8).

Fuel cells are often classified according to the electrolyte. The most common technologies along with their typical characteristics are listed in Table 3. Depending on the requirements, all of the different technologies are applicable for stationary applications. However, for the future, the MCFC and the SOFC are the ones primarily aimed at large-scale applications, although the PAFC has dominated the field so far. For decentralized generation, systems of up to 10 MW are already suggested. (Boulanger et al. 2003: 11─26; Nitta 2008: 8─9.)

A substantial benefit of the fuel cell is that there is no self-discharge in the disconnected state and only 2─3 % when connected. The cell lifetimes are also promising as there are no moving parts and the technology of the components is mature. However, the life span decreases as the size of the stack grows and the surface of the electrodes increases. (Boulanger et al. 2003: 19; IEA 2004: 60─61.)

Among the weaknesses of the fuel cell is the efficiency loss of the catalysts, which can occur due to poisoning by e.g. carbon monoxide. Other risks that have to be taken into consideration are that short circuits may take place through the membrane or that a leaking cell will cause efficiency losses of the stack. (Boulanger 2003 et al. 2003: 19.)

Table 3. Comparison of the characteristics of fuel cell technologies (Boulanger et al. 2003: 19; Nitta 2008: 9; Staffell 2007).



Fuel Cells	Power Range	Efficiency (LHV) [%]	Expected lifetime [h]	Operating temp [°C]	Electrolyte
AFC	10—100 kW	50—60	6000	20—150	KOH
DMFC	1—100 W	>50	>1000	20—90	Proton exchange membrane
PEMFC	1 kW—250 kW	25—60	>1000	20—100	Proton exchange membrane
PAFC	50 kW—1 MW	32—45	20000—40000	150—200	Liquid phosphoric acid
MCFC	1 kW—1 MW	45—55	9000	600—700	Liquid molten carbonate
SOFC	5 kW—3MW	35—55	35000	650—1000	Solid zirconium oxide

AFC = Alkaline Fuel Cell
DMFC = Direct Methanol Fuel Cell
PEMFC = Proton Exchange Membrane Fuel Cell
LHV = Lower Heating Value
PAFC = Phosphoric Acid Fuel Cell
MCFC = Molten Carbonate Fuel Cell
SOFC = Solid Oxide Fuel Cell

The most commonly used fuel is hydrogen. As it reacts with oxygen, an electrical charge is formed and the only exhausts produced are water and heat. The reaction occurring at the anode of a hydrogen-oxygen based fuel cell can be written as: (Alanen et al. 2003: 55)

$$H_2 \rightarrow 2H^+ + 2e^-. \qquad (13)$$

Hydrogen can be manufactured either centrally or locally, through water electrolysis such as alkaline electrolysis, proton exchange membrane water electrolysis, steam electrolysis or be received as by-product from a chlorine-alkali electrolysis process (Boulanger et al. 2003: 32—37).

In order to store hydrogen several different technologies have been employed. Most frequently used are pressurized tanks, but systems evolving parallel are liquid storage, storage in the form of metal hydrides and adsorption on carbon nanofibres (Boulanger et al. 2003: 39—43).

4.2.2. Unitized regenerative fuel cells

A unitized regenerative fuel cell (URFC) is able not only of water electrolysis, but also of subsequent recombination of hydrogen and oxygen (Boulanger et al. 2003: 5), i.e. it serves as fuel cell as well as electrolyzer.

It is noticeably lighter than the combination of a generator and an electrolyzer which it substitutes and is moreover expected to form a cheaper solution. When coupled with lightweight fuel storage, the energy density can exceed 400 Wh/kg, which is approximately ten times that of the lead-acid battery. As both hydrogen and oxygen are stored, the round trip efficiency is outstanding as well. The expected lifetime of the URFC is approximately 2000 cycles. (Boulanger et al. 2003: 31.)

The main constraint of the system is the bifunctional oxygen electrode, since the catalyst during the electrolysis suffers from corrosion. Yet, new catalysts, currently under research, show great potential. (Boulanger et al. 2003: 32.)

4.2.3. Conclusions and comparison

To sum up, the key factor to successful storage of electricity via hydrogen is further development of the fuel cell, which is the system component with the lowest maturity. The technology is still extremely expensive in comparison to the alternatives, but is nevertheless estimated to reach commercial status within just a few years (Boulanger et al. 2003: 5—6). For instance, at the end of 2007 a prototype of a SOFC already entered the testing phase (Laine 2007: 13—14).

Table 4 provides the costs for a hydrogen fuel cell and the accompanying electrolyzer.

Table 4. Costs for a hydrogen fuel cell and an electrolyzer (Schoenung et al. 2003: 31).

Fuel cells: costs		**Hydrogen FC**	**Electrolyzer**
DG storage	**Energy-related cost [€/kWh]**	13	None
	Power-related cost [€/kW]	1304	261
	Balance of plant [€/kWh]	0	None
	Replacement cost [€/kWh]	87	43
	Replacement frequency [yr]	6	6
	Fixed O&M [€/kW–yr]	3.3	N/A

Since the expenses are the main limitation, the two most likely combinations for a fuel cell energy storage system are alkaline electrolyzer with compressed hydrogen storage and a proton exchange membrane fuel cell. Other options that are considered economically possible within a near-future are the PEM electrolyzer and hydride storage of hydrogen.

4.3. Flow batteries

Flow batteries differ from fuel cells in that at least some of the electrolyte is not permanently in the reactor, but flows through it.

Currently, there are three sorts of flow batteries that have reached the stage of commercialization and demonstration: the vanadium redox flow battery (VRB), the polysulfide bromide flow battery (PSB) and the zinc-bromine flow battery (ZnBr) (De Boer & Raadschelders 2007: 5).

4.3.1. Redox flow batteries

Flow batteries in general are often referred to as redox flow batteries, but these do actually form the main subgroup. In a redox flow battery, all electroactive components are dissolved in the electrolyte (PhenoScience).

The batteries are charged and discharged by a reversible chemical reaction between two electrolytes in the battery. Unlike in conventional batteries, the electrolytes are not stored in the power cell of the batteries, but in separated storage tanks. In accordance with Figure 7, the electrolytes are pumped through an electrochemical reactor, in which a redox reaction (i.e. atoms have their oxidation number changed) occurs. A semi-permeable membrane in the flow cell separates the two electrolytes, allowing ion flow, but preventing mixing of the liquids. Electrical contact is established trough inert conductors in the electrolytes. As the ion flow crosses the membrane, an electrical current is induced in the conductors. (De Boer et al. 2007: 2–4.)

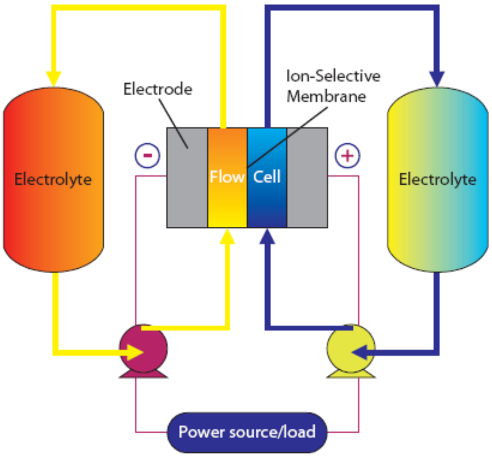


Figure 7. Schematic overview of a redox flow cell energy storage system (De Boer et al. 2007: 4).

The versatility of the batteries is due to the possibility of specifying energy and power content separately. The power rating depends on the design and number of the power cells, while the energy capacity is related to the size of the tanks and the amount of electrolyte (Alanen et al. 2003: 60; De Boer et al. 2007: 2–3).

A system consists of flow cells which, electrically, are connected in series and hydraulically in parallel. Thus, the output voltage is matched to the power conversion system and since the same electrolyte flows through all the cells, their state of charge is equal. (Price 2000: 1242.)

The abilities of flow batteries make them suitable for large-scale projects, such as peak power support at wind farms or distribution level balancing (De Boer et al. 2007: 2).

Moreover, as the costs of increased storage capacity are independent of the electrochemical reactor, the expenses per kWh will decrease with a larger system. Furthermore, since the storage capacity only depends on the size of the electrolyte tanks, there are basically no scale limits (De Boer et al. 2007: 4). Additionally, flow batteries are capable of offering low maintenance and operating costs (Price 2000: 1545). Demonstration projects are currently underway.

Vanadium redox flow batteries

Vanadium redox flow batteries use two different vanadium electrolytes, V^{2+}/V^{3+} and V^{4+}/V^{5+}, which are stored in a mild sulfuric acid. During the charge and discharge cycles, hydrogen ions (H^+) are exchanged between the two electrolyte tanks, through the hydrogen-ion permeable polymer membrane. (Joseph et al. 2006: 5.)

The research on vanadium batteries concentrates on applications in wind farms (De Boer et al. 2007: 5).

Polysulfide bromide flow batteries

Polysulfide bromide flow batteries function like regenerative fuel cells. The electrolytes are solutions of sodium bromide (NaBr) and sodium (Na) polysulfide (S_n^{2-}). As the battery is charged or discharged, only the sodium ions (Na^+) pass the membrane, whereas bromine (Br) and sulfur (S) emit and accept electrons. (Alanen et al. 2003: 66; De Boer et al. 2007: 5.)

The only flow battery system which has been used in large-scale demonstrations is based on PSB technology and is known as Regenesys. Such utility scale plants have been constructed in Little Barford, England and Mississippi, USA; both with an energy storage capacity of 120 MWh and a power capacity of 15 MW. (Schoenung et al. 2003: 17–18.) The cost estimations for such bulk storage are provided in Table 6 on page 47.

4.3.2. Hybrid flow batteries

A hybrid flow battery has at least one electroactive component deposited as a solid layer. It differs from the redox flow battery in that the processable amount of electrolyte is limited. The energy storage capacity is dependent on the amount of solid material that can be accommodated within the reactor. To some extent, charged electrolytes have to remain in the reactor, constraining the storage capacity and the variability of the power output. The limited possibilities to vary energy in relation to power, places in this respect hybrid flow batteries between conventional and redox flow batteries. (Englander 2007: 8; PhenoScience; Whitehead & Schreiber.)

Zinc-bromine flow batteries

Zinc-bromine flow batteries consist of a zinc-negative electrode and a bromine-positive electrode with a micro-porous separator in between. Solutions of zinc and a complex bromine compound are circulated through the two compartments. (De Boer et al. 2007: 5.)

Unless regularly and thoroughly discharged, the performance capacity of zinc-bromine batteries can be reduced. (De Boer et al. 2007: 5–6.)

4.3.3. Conclusions and comparison of flow batteries

Flow batteries are interesting options, particularly due to the decoupled power and energy ratings. Thus, they allow a flexible design and can be designed for high power applications as well as store substantial amounts of energy. They also offer a long lifetime, on account of the possibility of replacing the electrolytes (De Boer et al. 2007: 6). Because of the separated electrolytes, reactions between them are impossible, which prevents any self-discharge. In addition, the batteries have a fast response and a fair energy density. Drawbacks are a mediocre efficiency and the fact they are still in a relatively early phase of development. The parameters of the different flow batteries are compiled in Table 5 and the costs in Table 6.

Table 5. Comparison of the parameters of flow batteries (De Boer et al. 2007: 7; McKeogh 2003: 18).

Flow batteries	P [MW]	E [MWh]	Energy density [Wh/l]	Discharge duration	Efficiency	Lifetime [cycles / years]	Maturity
VRB	< 3	0.5–5	16–33	< 10	0.70–0.85*	12 000 / 10	demo / c.u.
PSB	< 15	0–120	20–30	< 20	0.60–0.75*	2 000 / 15	demo
ZnBr	< 1	0.01–5	60–90	< 4	0.65–0.75*	2 000 / 10	demo / c.u.

c.u. = commercial unit

*AC-AC efficiency

Table 6. Costs for the flow batteries (Schoenung et al. 2003: 30─31).

Flow batteries: costs		VRB	PSB	ZnBr
Bulk storage	**Energy-related cost [€/kWh]**	N/A	87	N/A
	Power-related cost [€/kW]	N/A	239	N/A
	Balance of plant [€/kWh]	N/A	43	N/A
	Replacement cost [€/kW]	N/A	130	N/A
	Replacement frequency [yr]	N/A	10	N/A
	Fixed O&M [€/kW─yr]	N/A	13	N/A
DG storage	**Energy-related cost [€/kWh]**	522	N/A	348
	Power-related cost [€/kW]	152	N/A	152
	Balance of plant [€/kWh]	26	N/A	0
	Replacement cost [€/kWh]	522	N/A	87
	Replacement frequency [yr]	10	N/A	8
	Fixed O&M [€/kW─yr]	17	N/A	17

5. ELECTROMAGNETIC STORAGES

This chapter assesses the characteristics, present use, costs and state-of-the-art situation of storage technologies based on electromagnetism: supercapacitors and superconducting magnetic energy storages.

5.1. Supercapacitors

Several different names, including double-layer capacitor, ultracapacitor and electrochemical capacitor, are used for the technology, which in this thesis is referred to as supercapacitor. The invention is known since decades, but as with fuel cells, the growing interest in hybrid vehicles and in energy storage as well, has increased its importance.

An appreciably enlarged electrode surface, a liquid electrolyte and a distance of only a few molecular diameters between the electrodes distinguish them from normal capacitors (Willer 2003: 4). On the contrary to secondary batteries, supercapacitors possess a high power density, but instead a considerably lower energy density.

The supercapacitor consists of two electrodes immersed in an electrolyte, a separator and current collectors. Electric energy is stored in an electrochemical double-layer formed at the interface between the electrodes and the electrolyte. Positive and negative ionic charges within the electrolyte accumulate at the surface of the electrode in order to compensate for the electronic charge at the electrode surface. As the dipoles are separated, they align in the double-layer, shown in Figure 8. The extreme thinness of this layer coupled with large electrode active area is the reason for the high capacity in comparison to normal capacitors. The figure also illustrates a schematic diagram of supercapacitor consisting of a single cell. (Kötz & Carlen 2000: 2484; Martynyuk 2007: 24; Willer 2003: 5.)

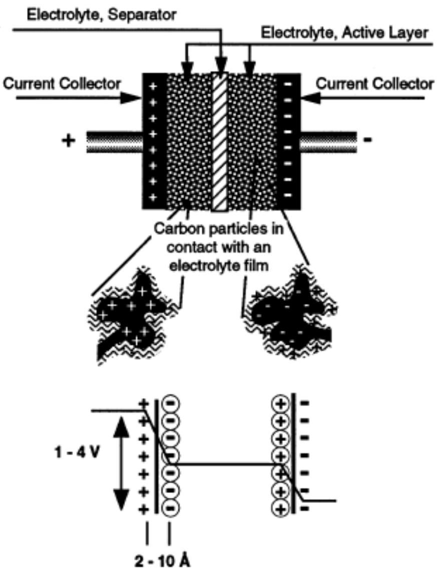


Figure 8. The principle of a supercapacitor and the potential changes at interface between the electrodes and the electrolyte (Kötz et al. 2000: 2485).

The energy stored in a supercapacitor is calculated as

$$E = \frac{1}{2} C U_0^2 , \tag{14}$$

where C is the capacitance and U_0 the cell voltage. The capacitance is obtained as

$$C = \frac{\varepsilon_0 \varepsilon_r}{4\pi\delta} \int dS , \tag{15}$$

where ε_0 is the electric constant, ε_r the relative static permittivity, δ the distance between the electrode surface and the center of the ion (i.e. the thickness of the double-layer), and S the surface of the electrode. (Alanen et al. 2003: 81; Kötz et al. 2000: 2484—2485.)

Commonly used electrolytes are aqueous ones, such as potassium hydroxide and sulfuric acid, as well as organic ones, like acetonitrile. These determine the cell voltage, which lies in the interval 1—3 V. Moreover, since the electrodes normally employ carbon metal oxide or polymeric materials, neither charge penetrations through the double-layer, nor electrochemical reactions occur. Thus, a long cycle lifetime and a high power density are achieved. The surface areas of the electrodes may be as high as 3000 m^2/g. Other advantages include high efficiency, short charge times (less than a minute), insensitivity to deep discharges and maintenance-free operation. The provided capacitances may be as high as 5000 F and supercapacitors in the range of 1 MW are already available. (IEA 2004: 37─41; Willer 2003: 5─22.)

The main drawback which has to be effectively countered is the ability to store energy, which in comparison to secondary batteries is very limited. Moreover, besides the pressing need for cost reduction, the main targets of current research and development are an increased life span (exceeding 10 years) and improved recyclability. An improvement of the active materials through the utilization of nanotechnology has also been suggested as a future prospect. (Alanen et al. 2003: 84). (Willer 2003: 16─17.)

5.2. Superconducting magnetic energy storage

Superconducting magnetic energy storage (SMES) technology was one of the first applications of superconducting materials (i.e. materials cooled below a certain temperature at which the resistance drops to zero) and is thus known since decades. Originally, the concept was simply based on a direct current flowing nearly losslessly in a superconducting coil, storing energy in the magnetic field caused by the current. (Alanen et al. 2003: 76.)

The electric energy stored in the magnetic field is proportional to the inductance of the coil and is given by (Alanen et al. 2003: 77)

$$E = \frac{1}{2} L I^2 , \tag{16}$$

where L is the inductance of the coil and I the DC current flowing through it.

In order to reach a commercial status, modern systems employ refined superconducting materials, advanced cooling systems and power electronics. Currently, there are two dominating technologies: LTS (Low Temperature Superconductor) and HTS (High Temperature Superconductor) systems. The former are cooled to nearly 4 K (-269 °C) with liquid helium, whereas approximately 100 K (-173 °C) is sufficient for the latter which utilize liquid nitrogen or special refrigerators. LTS systems are already commercially available, while the HTS technology is still under development. (Alanen et al. 2003: 76; IEA 2004: 67.)

In addition to a superconducting coil with a magnet (SCM), an SMES system normally consists of a power conditioning system (PCS), a cryogenics system (CS) and a controller. The PCS serves as an interface between the AC unit and the SCM, transferring and converting energy as requested. The CS cools the SCM and keeps it at operating temperature. (Xue, Cheng & Sutanto 2005: 1524.) The above described composition is illustrated in Figure 9.

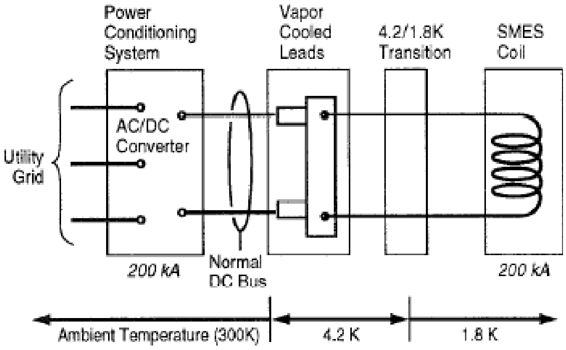


Figure 9. Plant diagram of an SMES system (Luongo 1996: 2216).

Because of the cryogenic temperatures (i.e. below -150 °C / 123 K) there are virtually no resistive losses. Further advantages include instantaneous response (in the range of milliseconds), fast recharge, high power, long lifetime and excellent efficiency, since no conversion to other energy forms take place. Moreover, the systems are compact, quiet, safe and environmentally benign. However, attention must be paid to the possible health impact of the magnetic field, which can exceed 9 T. (IEA 2004: 69—70; Luongo 1996: 2214; Xue et al. 2005: 1524.)

Traditionally, SMES systems provide 10—100 MW and are primarily designed for load leveling, but the current development aims at producing smaller ones as well, suited for power quality management. Hence, common applications also include damping system oscillations, improving voltage stability, stabilizing transmission lines and serving as a spinning reserve. (Alanen et al. 2003: 76; Luongo 1996: 2214; Xue et al. 2005: 1525─1527.)

Suggested future measures focus on improving the circuit topologies, control methods and configurations of the PCS (Xue et al. 2005: 1529). Moreover, an increase of the limited energy density would further broaden the possibilities.

5.3. Conclusions and comparison

Supercapacitors are an attempt to combine the quality of capacitors to store considerable amounts of power and the ability of batteries to store significant quantities of energy. Particularly the capability to store energy must be developed, in order to make them able successors. Nevertheless, they already form a potential alternative for applications, which require high power for short durations, e.g. peak shaving. Another interesting application is their use together with a storage system, which is more suitable for long-term conditions, typically batteries.

SMES systems offer fast, flexible and reliable performance and are in general very versatile. Owing to recent progress in commercialization, a more widespread employment is definitely expected in the near future.

Critical for both technologies is the further need for cost reductions. In terms of energy density, they are usually not even comparable to the other storage methods, as the aims are different. Table 7 provides an overview and comparison of their parameters and Table 8 a cost analysis.

Table 7. Comparison of the parameters of the supercapacitor and the SMES (Alanen et al. 2003: 78; IEA 2004: 40─72; Willer 2003: 5─13).

Electromagnetic storage	**Power density [W/kg]**	**Energy density [Wh/kg]**	**Efficiency**	**Discharge duration**	**Self-discharge [% / month]**	**Lifetime [cycles / years]**	**Operating temp. range [°C]**
Supercapacitors	100─10 000	0.1─5	0.85─0.98	<5s	50	100 000─500 000 / 10	–40 – +60
SMES	1 000─100 000	4─75	0.90-0.99	1s─5h	─	100 000 / 20	–269 – –173

Table 8. Costs for the supercapacitor and the SMES (Schoenung et al. 2003: 32).

Electromagnetic storage: costs		**Supercapacitor**	**SMES**
PQ storage	**Energy-related cost [€/kWh]**	26087	43478
	Power-related cost [€/kW]	261	174
	Replacement cost [€/kWh]	0	0
	Replacement frequency [yr]	None	None
	Fixed O&M [€/kW–yr]	4.3	8.7

6. MECHANICAL STORAGES

This chapter assesses the characteristics, present use, costs and state-of-the-art situation of storage technologies based on mechanics: flywheels, compressed air storage concepts and pumped hydro storage.

6.1. Flywheels

The use of flywheels for short-term storage of kinetic energy is an old concept, and in more recent times they have proved to be useful for longer durations as well. Traditionally, they have been used in rotating engines to smooth torque pulses. These are relatively simple constructions, where the flywheel is directly mechanically coupled to regulate the shaft speed. The newer application is storage of electrical energy which is achieved by addition of an electrical machine and a power converter.

During charging, an accelerating torque increases the speed of the flywheel and thus the amount of energy stored in the rotor. The capacity is dependent on its mass, form and rotational speed. When the energy is needed, the machine is operated as a generator fed by the decelerating flywheel.

The kinetic energy stored in a rotating mass is proportional to the moment of inertia J and the squared angular velocity ω, i.e.

$$E = \frac{1}{2} J\omega^2 . \tag{17}$$

Moreover, the moment of inertia is a function of the mass and the shape of the flywheel and is equal to (Alanen et al. 2003: 67; Ruddell 2003: 6)

$$J = k\int x^2 dm_x , \tag{18}$$

where k is the shape factor and x the distance of the differential mass dm_x from the axis of rotation. Hence substitution of equation (18) into equation (17) yields

$$E = \frac{1}{2} k \omega^2 \int x^2 dm_x \; . \tag{19}$$

Thus, as seen in equation (19), angular velocity is of greater importance than mass for a high energy storage capacity.

The tensile strength σ defines the upper limit of the angular velocity. For a material with the density ρ, with the mass concentrated at the rim at the radius r, the tensile stress is given by (Ruddell 2003: 6)

$$\sigma = \rho r^2 \omega^2 . \tag{20}$$

Hence, material dependence is considered in equation (21)

$$E = \frac{1}{2} m \frac{\sigma}{\rho} , \tag{21}$$

which gives an estimation of the maximum storable energy. In accordance with the equation, composite materials with lower density and higher tensile strength than metal, achieve a higher energy density.

Besides the inertial composite rotor and an integral asynchronous motor-generator, a normal storage system consists of magnetic bearing supports, vacuum housings, compact heat exchangers, a control system and power electronics for the electrical conversion (Bitterly 1998: 13). A schematic of a flywheel module is shown in Figure 10.

Based on rotational speed, flywheels are usually divided into *low speed* and *high speed* classes. The former normally have operating speeds of up to 6 000 rpm and employ steel rotors and conventional bearings. Normally, they only deliver power for tens of seconds. The latter can reach up to 50 000 rpm and utilize composite materials for the rotor and magnetic bearings. In this case, energy for hours of power delivery can be stored. Low speed flywheels are already available on the market and the high speed concept is currently being commercialized. (IEA 2004: 41; Ruddell 2003: 4.)

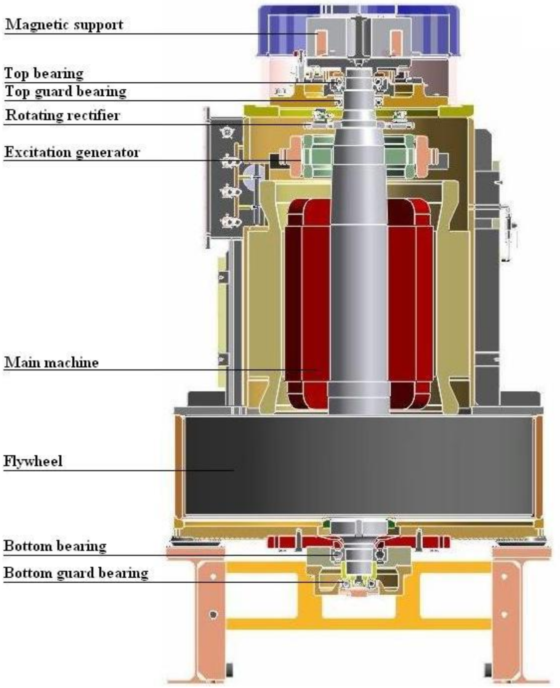


Figure 10. Schematic of a flywheel module (Piller:1).

The main advantage of flywheels is that they can be charged and discharged at high rates for numerous cycles. Full capacity can be reached in approximately seven minutes and sub-second response times are typical. Furthermore, the state-of-charge is easily assessed as a function of the angular velocity. (Makansi & Van der Linden 2005; Ruddell 2003: 4─10.) Other benefits are excellent efficiency, relatively high energy density and negligible environmental impacts.

Common applications are those requiring continuous cycling, high reliability and high power. These include load following, peak power supply and UPS-systems. (Ruddell 2003: 11.)

As for the other emerging storage technologies, the high costs are the primary restraint. Another setback is the comparatively high standing losses. Current systems have self-discharge rates of approximately 20 % of the stored capacity per hour. Therefore, present technology is not suitable for long-term storage. However, these improvements within these areas are naturally the main aims of the ongoing research. Other development topics are bearings which incorporate superconducting materials. Compared to conventional magnetic bearings, losses may be hundredfold reduced (Mikkonen 2002: 786). Recent projects funded by the European Commission have focused on the use of flywheels together with renewables, especially for smoothing power fluctuations from wind turbines. (Ruddell 2003: 4—12.)

6.2. Compressed air storage technologies

As for most of the energy storage technologies, the basic principles behind compressed air energy storage have been known a long time, but the concept has still not been widely utilized. The systems store energy by compressing air into a reservoir. When energy is needed, the air is released and the pressure is used to drive a turbine connected to a generator. Depending on the used storage facility, two different constructions are distinguished: CAES and CAS. Furthermore, an improved adiabatic CAES modification is examined.

6.2.1. Compressed air energy storage

The compressed air energy storage (CAES) system is based on conventional gas turbine technology and utilizes the elastic potential energy of compressed air (Ter-Gazarian 1994: 100). To optimize the use of the storage space, the compression phase includes cooling of the air, which is pressurized to approximately 75 bar and stored underground in an airtight facility. This is the most important part of the CAES system. There are basically three different solutions in use: constructed rock caverns, salt caverns and porous rock formed by water-bearing aquifers are potential alternatives. Aquifers may be particularly interesting because the compressed air displaces water and thus sets up a constant-pressure storage system. Additionally, they are currently the most economical option (Vepakomma 2003: 58). After the air is released from the reservoir, it is preheated in a recuperator, which reuses the energy extracted by the compressor coolers. Next, the air is mixed with gas or oil, which is burnt in the combustor. The ensuing combustion gas expands in a turbine connected to a generator. (Cheung, Cheung, De Silva, Juvonen, Singh & Woo 2003: 17; Lee, Kim, Park, Moon & Yoon 2007: 2—3.) Figure 11 illustrates the operation of a typical CAES system.

To this day, only two CAES plants have been realized. The first one was constructed already in 1978 in Huntorf, Germany and has a power output of 290 MW. Nearly two decades ago, in 1991, the most recent system was built in McIntosh, USA, with a power rating of is 110 MW. However, in the U.S. alone, more than 10 plants are currently being planned. A considerable modification in the upcoming ones is that the compressor and gas turbine will no longer be mechanically connected through a shaft. Instead, a motor-compressor unit and a gas turbine unit operate separately, and are only electrically connected. The largest storage plant in Norton will have an estimated output of 2700 MW. (Crotogino 2003: 6─7).

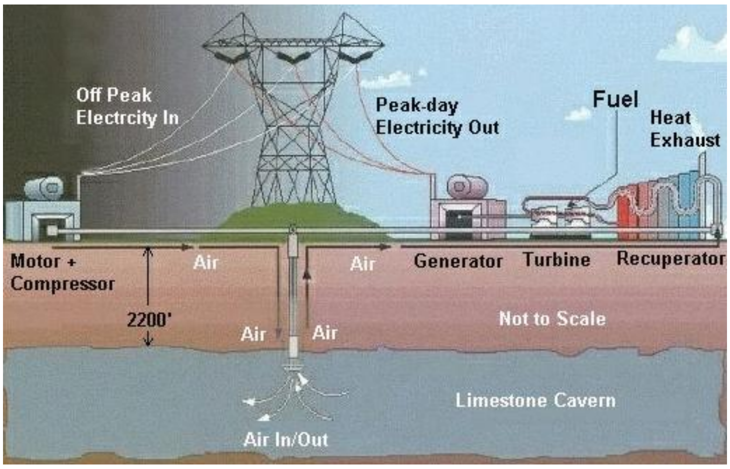


Figure 11. Schematic of a CAES system (ESA 2008).

Calculating the specific energy for an unusual shaped volume is difficult, but assuming an isobaric CAES system where the piston moves without friction, a simplified volumetric energy density is given by (Lee et al. 2007: 2)

$$E = \frac{1}{V_0} nRT \int_{V_o}^{V} \frac{dV}{V} = \frac{1}{V_0} P_0 V_0 \ln \frac{V_0}{V} = P_0 \ln \frac{V_0}{V}, \tag{22}$$

where V_0 and V are the initial and final volumes, n the number of moles, R the gas constant, T the temperature and P_0 the pressure.

The advantages of CAES include the use of an unlimited and free storage medium and a construction made of well-known and reliable parts. Owing to the modular design, upgrading is favorable since the system parameters are independent of each other: the ability to store energy is adjusted by the number of motor-compressor units, the electricity generation output is increasable through additional gas turbine units, and the storage capacity can be raised by employing further caverns. Flexibility is indeed characterizing for the technology; full load output can typically be reached within ten minutes. (Crotogino 2003: 4―8). On the other hand, the need for appropriate caverns has restricted extensive implementation of the technology. However, solution mining[3] has been suggested as an attractive possibility, and suitable Palaeozoic salt deposits are indeed available in large parts of northern Europe (Bullough et al. 2004: 6―7).

The systems are mainly used in centralized energy generation and may have energy storage capacities up to 10 GWh power outputs up to 2700 MW (Bauer & Lee 2004: 7; De Boer et al. 2007: 6). Because CAES systems are incapable of reverse operation (i.e. compression of air) and often suffer from poor efficiency (below 50 %), they are considered insuitable for stand-alone systems (Cyphelly 2002: 5). Furthermore, as the majority of the expansion power has to be generated by a fuel burner to avoid excessive temperature decreases, the constructions are not renewable energy concepts. Nevertheless, the technology is reckoned to form a successful combination with wind farms. Moreover, the dependence on fossil fuels is suggested to be attended to by the use of biofuels (Denholm 2006: 1356).

6.2.2. Advanced adiabatic compressed air energy storage

To avoid the losses in form of heat energy that inevitably occur during the compression phase of a conventional CAES system, *advanced adiabatic CAES* (AA-CAES) technology is suggested. In the adiabatic cycle, heat energy is extracted and conserved in a thermal energy store before the compressed air is transferred to the cavern. When energy is needed, the air is brought back and is recombined with the heat energy, prior to the expansion through an air turbine. (Bullough et al. 2004: 1―2.)

---

[3] Extraction of soluble minerals from subsurface strata by injection of fluids and controlled removal of mineral-laden solutions.

This procedure does not only increase the storage efficiency but, above all, obviates the need for burning fossil fuel and thus eliminates the problem with the emissions. Thus, AA-CAES offers a solution to the major constraints for employment of compressed air as a truly renewable energy storage medium.

The key component, the thermal store, is designed to have a storage capacity in the range of 120—1200 MWh, with a substantial heat extraction rate and a high consistency of the outlet temperature. Of central importance is the store container, based on which a division into liquid and solid systems is made. The former often employ a heat exchanger, which averts the need for a pressurized container, but entails additional costs and complexity. A dual-media approach with nitrate salt and mineral oil has to be employed to cover the temperature range from 50 to 650 °C. This concept is being tested for solar thermal power stations. The alternative is to use a solid medium, which enables a high surface area for heat transfer and the use of cheap materials, such as natural stone, concrete and metal. On the other hand, the costs for pressurized containers are greater. (Bullough et al. 2004: 6.)

Apart from the thermal store, the structure of the system is basically the same as for the conventional CAES plant. However, the components require supplementary modifications. Essential is further development of the compressor design, in order to reach higher pressures (up to 160 bar) as well as temperatures (up to 600 °C) simultaneously. (Bullough et al. 2004: 5; Meyer 2007: 3.)

The development of the technology is still in its infancy, but e.g. the *Framework 5 Programme* of the European Commission actively undertakes research. The aim is to reach an efficiency exceeding 70 %, to a cost of 800—1200 €/kWh and 8—12 €/kW. A demonstration plant is estimated to be constructed in five to ten years. (CORDIS; Meyer 2007: 3.)

6.2.3. Compressed air storage

The compressed air storage (CAS) concept, occasionally referred to as CAES-surface, is an interesting modification of the larger CAES system. The air is pressurized by a transformer and stored in high-pressure tanks. In this manner, power ratings of up to 100 MW are still achievable (McKeogh 2003: 18). The two configurations mainly used today are the liquid piston design and the direct air-to-oil interface system.

The *liquid piston design* employs a fixed displacement pump/motor, which is controlled by a solenoid powered 4-way spool valve. This works in a pulse width modulation servo-loop with a flywheel designed to maintain a low-rippled speed for the motor/generator. The gas pressure is varied in order to the energy content of the system. Owing to the low speed of the compression and expansion processes, an almost perfectly isothermal operation is achieved. (Cyphelly 2002: 5—6.)

This design is considered the more probable short-term successor to lead-acid batteries, as it can be constructed from already available standard parts. Furthermore, it is close to maintenance free. The constraints are high weight and volume, wherefore high power but low capacity applications are likely. In this field, the system is already a cost and performance competitive alternative. However, the stand-by losses are still high and further improvements are necessary. (Cyphelly 2002: 6—13.)

The *direct air-to-oil interface* transforms air pressure into oil pressure by cyclical expansion or compression phases. This technology enables the use of an approximately ten times smaller cylinder volume, since the vessels are only filled with air. This requires the addition of an interface with a control valve and an air-oil heat exchanger, which ensures an isothermal process during compression and expansion. Because the air is taken from the atmosphere (compression) or exhausted (expansion) a muffler-filter arrangement is necessary. (Cyphelly 2002: 5—6.)

Besides the higher cost due to the need for additional non-standardized components, the efficiency of this system is 5—7 % lower and anti-corrosion effect is lost. On the other hand, there is no need for an oil reservoir and the storage volume is reduced. This design is suggested for seasonal storage. The technology is currently still under research (IEA 2004: 63). (Cyphelly 2002: 6—10.)

Another future possibility is to store the pressurized air containers underwater, at the bottoms of lakes or seas. The benefit of this system would be a constant charge-discharge pressure, determined by the depth.

6.3. Pumped hydro storage

Pumped hydro storage is also an old concept and was until 1970 the only commercially available option for large-scale energy storage. At the time present, it is still the most used utility-scale technology, with a total of more than 90 GW installed. (Cheung et al. 2003: 13; ESA 2008). This mainly owes to the provided capacity, which is currently both in terms of energy and power superior to all other available solutions.

A pumped hydro storage plant uses two reservoirs, one located at a higher elevation than the other. Energy is stored by reversing the turbines and pumping water from the lower to the upper reservoir. The stored water can be released on demand and the operation is similar to that of a hydropower plant. As the water flows back into the lower reservoir, turbines coupled to generators are powered. The power capacity is set by the difference in height between the reservoirs and by the flow rate. A schematic of a storage system is seen in Figure 12.

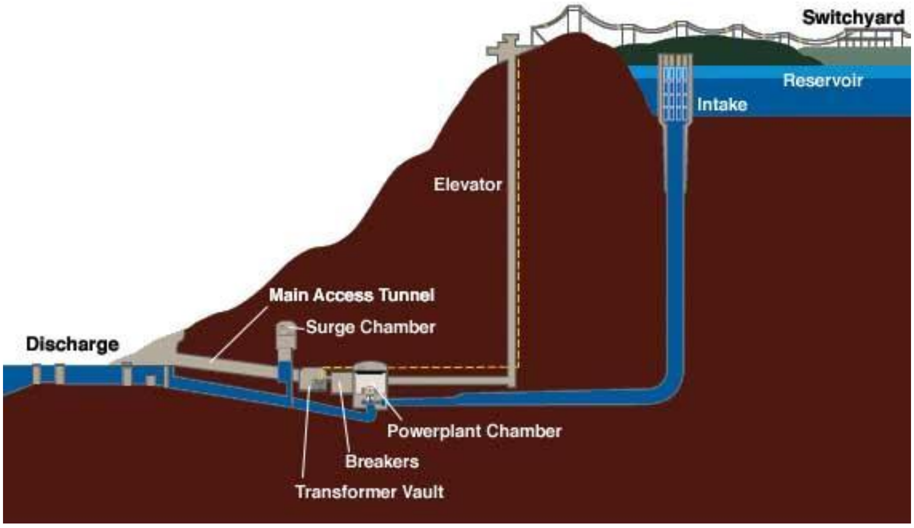


Figure 12. Facility diagram of a pumped hydro storage system (TVA).

In contrast to the early constructions, with a separate motor and dynamo, modern systems use combined generator-motor –units. Thus expenses for separate pipes are saved and currently efficiencies exceeding 80 % are reachable. (Cheung et al. 2003: 13.) The largest existing power output, 2400 MW, is achieved by a plant located in Guangzhou, China built in 2004.

The available power output for a hydro system is (Paish 2002: 540)

$$P = \eta \rho g Q H \, , \tag{23}$$

where η is the hydraulic efficiency of the turbine, ρ the water density, g the standard gravity, Q the volume flow rate and H the effective pressure head of water across the turbine.

Due to the large storage capacity and negligible self-discharge, pumped hydro storage can normally store energy for more than half a year. Moreover, despite the size, the respond times are rapid, cold starts typically taking one to four minutes. Full charge is normally reached within 5—20 minutes. Furthermore, no pollution or waste is produced and the effects on the landscape are, unlike those of hydroelectric dams, minimal. Owing to the simplicity of the design and the huge storage capacity, the operating costs per unit of energy are typically lower than for the other technologies. (Bradshaw 2000: 1554; Cheung et al. 2003: 14.) However, the capital costs, for building dams and huge underground pipes, are massive, which limits the use considerably.

Moreover, according to Brauner (2008: 39), further increases in power rating and storage capacity are still crucial for the use of pumped hydro storage together with wind and photovoltaics, due to their low number of full load hours (approximately 2000 h/year and 1000 h/year, respectively).

Since hydro generators typically have rapid start-up and response times, which additionally is combined with flexible water release timing, they are considered ideal for balancing wind energy fluctuations (Tekes 2007: 25). This concept could be further developed by implementing pumped hydro storage as well.

Obviously, feasibility is closely linked to the geographical properties of the terrain and suitable locations are difficult to find. Consequently, the majority of the existing storage systems are conventional hydro power plants equipped with synchronous machines. These are run at constant speed in order to obtain high efficiencies. However, evolving concepts employ cycloconverters, which allow the turbine to operate at variable speed. This entails advantages such as improved efficiency at partial loads, increased turbine lifetime and a highly dynamic control of the power delivered to the grid. (De Doncker, Meyer, Lenek & Mura 2007: 3)

As an alternative to conventional pumped hydro storage plants, *underground installations* are suggested in order to expand the geological possibilities. Since the system only requires an area large enough for an upper reservoir, the siting is more flexible. Expressly in the combination with renewable energy sources, this is of utmost importance, as the storage can be located at the sites optimal for generation. Suitable geology is, however, necessary for the underground cavern which serves as second reservoir.

A further advantage of such a system is increased efficiency due to the vertical water flow, which eliminates losses associated with transverse flow. The employment of a single surface reservoir also reduces the environmental impact, and potential river dams and overground powerhouses are superfluous. Moreover, wildlife habitat disruption and noise are reduced. (Levine, Martin & Moutoux 2007: 11.)

Although no large-scale underground pumped hydro storage plant has been realized, several studies indicate that installations sized between 1000 and 3000 MW have economic potential. Case studies even suggest that the system is economically competitive with lead-acid batteries (Martin 2001: 73). Moreover, explicitly the expansion of renewable energies is increasing the interest in the technology. (Levine et al. 2007: 11–24).

6.4. Conclusions and comparison

Whereas the parameters for older flywheels are comparable to those of the lead-acid battery, newer technology is able to match supercapacitors in terms of specific power (Ruddell 2003:9) and advanced batteries in terms of energy density. With respect to cycle life, flywheels are supreme.

Flywheels represent more than 95 % of the so-called new energy storage technology sales (flywheels, SMES and supercapacitors) and are also considered one of the most promising technologies for replacing the lead-acid batteries for a large variety of applications. The sales rate is expected to grow approximately 8 % per year. A key factor driving the market is the predicted growth in utilization of renewable energy. (IEA 2004: 40; Ruddell 2003: 5.)

CAES offers energy storage capacities and power outputs that are second only to those of pumped hydro storage. Currently, its main renewable application is planned to be together with wind parks. However, when combined with biofuels, CAES represents an interesting alternative for several applications in the large-scale storage category, mainly competing with the more established pumped hydro storage. Geological restraints are, however, a constraint for more extensive use.

The modified AA-CAES undoubtedly yields great future potential, as a completely green, high-efficient solution. The parts for the system are already far developed and an optimization of the overall system is currently the target of the research.

CAS is a mature, reliable and environmentally benign technology suited for high-power, long-term load-leveling applications. Already available at reasonable costs, further improvements within energy efficiency and self-discharge, would certainly make it an able successor the lead-acid battery.

Pumped hydro storage is clearly the largest available system and therefore offer unique possibilities, but is due to high investment costs able to compete with lead-acid batteries only for considerably larger applications. Furthermore, the potential for storage in America and Europe has already been utilized to a vast extent, wherefore major expansion would have to be implemented in the developing countries in Africa and Asia (Cheung et al. 2003: 15).

An interesting future possibility is also to utilize the huge capacity of pumped hydro storage on a much larger scale, for balancing energy between regions. Thus, local conditions could be fully exploited, as wind turbines, photovoltaic arrays and storage facilities all are optimally sited.

From a siting perspective, underground pumped hydro storage is a more flexible alternative, which therefore is attractive in the combination with renewable energy sources.

Table 9 provides a representative compilation of the parameters for the energy storage technologies utilizing mechanical energy.

Table 10 provides an overview of the costs for flywheels, compressed air energy storage, compressed air storage and pumped hydro storage. Since the costs for flywheels are highly system-specific, the sizes are specified as follows: the high-speed flywheel for distributed generation has a power capacity of 18 kW and an energy storage capacity of 37 kWh, whereas those for power quality applications are in the range of 120–200 kW and suited for storage between 20 seconds and 15 minutes.

Table 9. Comparison of mechanical storage technologies (Boyes & Clark 2000: 5; Cyphelly 2002: 8; De Boer et al. 2007: 6; Dell 2004: 162; IEA 2004: 45–74; McKeogh 2003: 18; Ruddell 2003: 9–10).

Mechanical storage	**FW: Low / High**	**CAES / CAS**	**PHS**
P [MW]	< 1.65 / < 0.75	25–3 000 / 50–100	100–4 000
E [MWh]	<100	200–10 000 / N/A	500–15 000
Power dens. [W/kg]	160*	N/A	N/A
Energy dens. [W/kg]	5–100	N/A / 3.2–50	N/A
Efficiency	0.90 / 0.93	0.64 / 0.60–0.73	0.70–0.85
Self-dis. [% / month]	72	25**	–
Resp.time	< 1	s–min	s–min
Dis.duration	1–20 h / 1–4 h	1–20 h / 1–4 h	4–1000 h
Lifetime [cycles (years)]	10e5–10e7 (20)	10 000 / 20 000–100 000 (30)	N/A (75)
Op.temp.range [°C]	–20 – +40	N/A / –10 – +50	N/A

*Estimation based on Ruddell 2003: 9

**Stand-by mode (There is no self-discharge in open circuit conditions)

Table 10. Costs for the mechanical storage technologies (Schoenung et al. 2003: 30–32).

Mechanical storage: costs		FW: High	FW: Low	CAES	CAS	PHS
Bulk storage	**Energy–related cost [€/kWh]**	N/A	N/A	2.6	N/A	8.7
	Power–related cost [€/kW]	N/A	N/A	370	N/A	870–913
	Balance of plant [€/kWh]	N/A	N/A	43	N/A	3.5
	Replacement cost [€/kWh]	N/A	N/A	0	N/A	0
	Replacement frequency [yr]	N/A	N/A	None	N/A	None
	Fixed O&M [€/kW–yr]	N/A	N/A	2.2	N/A	2.2
DG storage	**Energy–related cost [€/kWh]**	870	N/A	N/A	104	N/A
	Power–related cost [€/kW]	261	N/A	N/A	478	N/A
	Balance of plant [€/kWh]	0	N/A	N/A	43	N/A
	Replacement cost [€/kWh]	0	N/A	N/A	0	N/A
	Replacement frequency [yr]	None	N/A	N/A	None	N/A
	Fixed O&M [€/kW–yr]	870 €/year	N/A	N/A	8.7	N/A
PQ storage	**Energy–related cost [€/kWh]**	870–108700	43478	N/A	N/A	N/A
	Power–related cost [€/kW]	261–290	261	N/A	N/A	N/A
	Replacement cost [€/kWh]	0–13900	0	N/A	N/A	N/A
	Replacement frequency [yr]	>16	None	N/A	N/A	N/A
	Fixed O&M [€/kW–yr]	4.3	4.3	N/A	N/A	N/A

7. THERMAL ENERGY STORAGES

This chapter assesses the characteristics, present use and state-of-the-art situation of storage technologies based on thermochemistry: sensible heat storage and latent heat storage.

Thermal energy storage is one of the most traditional concepts for storing energy. Essentially, it involves capture of energy which is contained in a thermal reservoir until required. Basically, two different storage mechanisms exist: sensible heat storage and latent heat storage. The former is based on the heat capacity of the storage medium, whereas the latter utilize the energy associated with a change of phase of the medium; such as melting, evaporation or a structural change. Several low-temperature applications (below 150 °C) are used to provide heating and cooling, but these are rather heat generation technologies than energy storage techniques. Thus, these systems are not analyzed in this thesis. However, systems with higher temperatures (exceeding 150 °C), allow heat to be transformed into electricity in a thermal machine (steam generator-turbine alternator). (IEA 2004: 73; Ter-Gazarian 1994: 57–62.)

7.1. Sensible heat storages

The arrangement employs two reservoirs with different temperatures. During the storage phase, a heat pump is driven to transfer heat from the cooler reservoir to the warmer. When the energy is required, the thermal engine transforms the heat into mechanical energy, which is finally converted into electrical power.

The sensible heat storage process described here utilizes a solid storage medium, which is the most common solution, even though groundwater-based systems do exist as well (Alanen et al. 2003: 13). The low temperature vessel contains porous solids, which allow vertical gas circulation and consequently heat exchange between them. As the storage phase starts, the top of the bed of solids is at a medium temperature level T_2 (e.g. 380 °C), while the bottom temperature T_3 is low (e.g. -74 °C). The high temperature vessel features an analogous construction, except that the temperature T_1 of upper layers of solids is extremely high (e.g. 780 °C) and the bed temperature T_0 is approximately equivalent to the ambient temperature (e.g. 20 °C). The reservoirs are coupled by a heat pump which comprises a compressor and an expander. The gas circulates in a closed loop. (Ruer 2007: 2—3.)

During loading, the solids in the low temperature vessel gradually cool down and the thermal front between the solids at T_2 and T_3 moves upwards. Simultaneously, the opposite occurs in the high temperature vessel, wherefore the corresponding front travels downwards. (Ruer 2007: 3.) The operating principle during the storage phase of the system is shown in Figure 13.

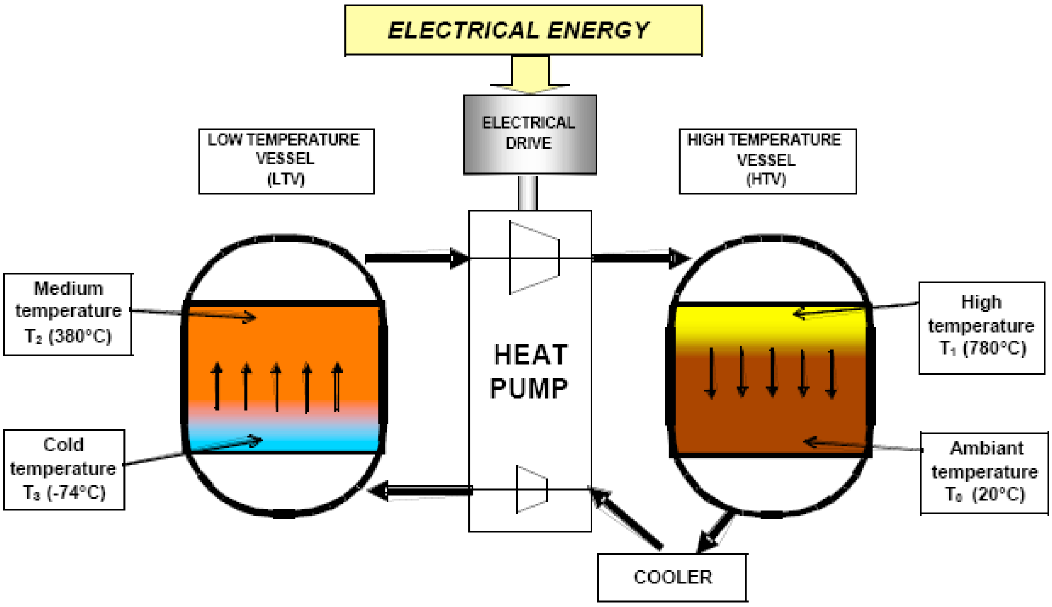


Figure 13. Schematic of a thermal energy storage system during the storage phase (Ruer 2007: 3).

As the energy is retrieved, the heat pump is replaced by a thermal engine and the electrical drive by a generator. In this case, the gas circulates in the reverse direction and is cooled prior to compression, in order to minimize the required work. (Ruer 2007: 3—6.)

Large reservoirs make the system suitable for storage for several hours and the storage capacity can even be tens of thousands of megawatt-hours. The effective energy density is in the range of 35 to 50 kWh/m^3 and overall efficiencies exceeding 70 % are achievable. Moreover, the system is not restricted by geographical conditions and only requires a cooling medium; water or air. (Ruer 2007: 6─11.)

In the foreseeable future, the operating temperature is expected to rise from an approximate 800 °C to over 1000 °C, which will entail energy densities of 60 to 100 kWh/m^3 and efficiencies higher than 80 % (Ruer 2007: 11). Further progress in material technology is the key, since these extreme temperatures cause problems such as corrosion and heat shocks (Ter-Gazarian 1994: 63).

7.2. Latent heat storages

Latent heat storage, i.e. phase change based storage, is a technology based on the use of materials with high latent heat[4] of fusion and crystallization. The enthalpy of the phase transition, i.e. the energy released or bound, is utilized. Most commonly employed is the change between solid and liquid states. Commercially used storage media are water, salt solutions, hydrates of inorganic salts and fatty acids. In comparison to sensible heat storage, a higher energy density per degree of temperature change, over the temperature range surrounding the fusion point, is achieved. Furthermore, heat can be supplied at a constant temperature which enables storage of large amounts of heat, with small temperature differences. (Alanen et al. 2003: 14; Ter-Gazarian 1994: 63.)

As the stored heat is released, it can be used to generate electricity by driving steam turbines. Such an arrangement is especially interesting for small stand-alone systems, since it is more compact than a conventional solution with secondary batteries. An attractive combination is together with solar power and suitable applications are, for instance, solar homes, local radio transmitters, mobile telephone stations and satellites. (Venere 2001.)

Problematic is, however, the formation of voids when the materials freeze and consequently shrink. Hence, the heat transfer of the material, which is stored in series of met-

---

[4] The amount of energy, in the form of heat, released or absorbed by a substance during a change of phase.

al cells, suffers from gaps. Certain sizes and shapes, e.g. torus formats, of the cells are suggested to improve the control over the voids. (Venere 2001.)

7.3. Conclusions and comparison

A system based on storage of sensible heat offers the unique combination of flexible siting and the ability to hold energy amounts suitable for bulk storage. Owing to these properties, the concept has the potential to become a competitor to the established pumped hydro storage and compressed air energy storage for large-scale applications. However, the actual costs of the system still need to be defined, in order to evaluate its competitiveness.

Latent heat storage systems are only suited for small-scale applications and are due technical limitations likely to remain a niche.

8. CASE STUDIES

8.1. Initial arrangements

8.1.1. Background

In order to assess the concrete benefits of energy storage for renewable generation, two fictive scenarios are devised. Both are stand-alone systems which are modeled with data from a weather station located in Burgenland, eastern Austria. In the first system, an Enercon E-40 is employed, representing a commonly used wind-turbine in Austria (Austrian Wind Power 2007). The second scenario features a simplified photovoltaic system. A load profile for 100 households is used as basis for the models. The concomitant analysis is implemented in two steps. First, an assessment of the gains in form of energy is made, and is then extended by an evaluation of the profitability of storage.

The fundamental concept of the following scenarios is presented in Figure 14. Comparisons are made between a traditional solution, consisting of only generation and load, and a more advanced system employing energy storage.

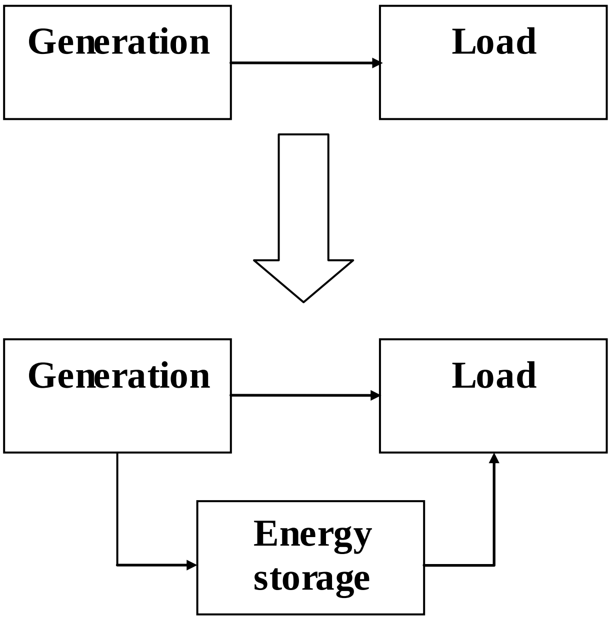


Figure 14. Fundamental concept of the scenarios.

8.1.2. Weather station

The weather station, which is located in the state of Burgenland in eastern Austria, provides information regarding wind speed [m/s] and solar radiation [W/m^2], which are used as basis for the generation models. The values are given every half an hour for the year 2006.

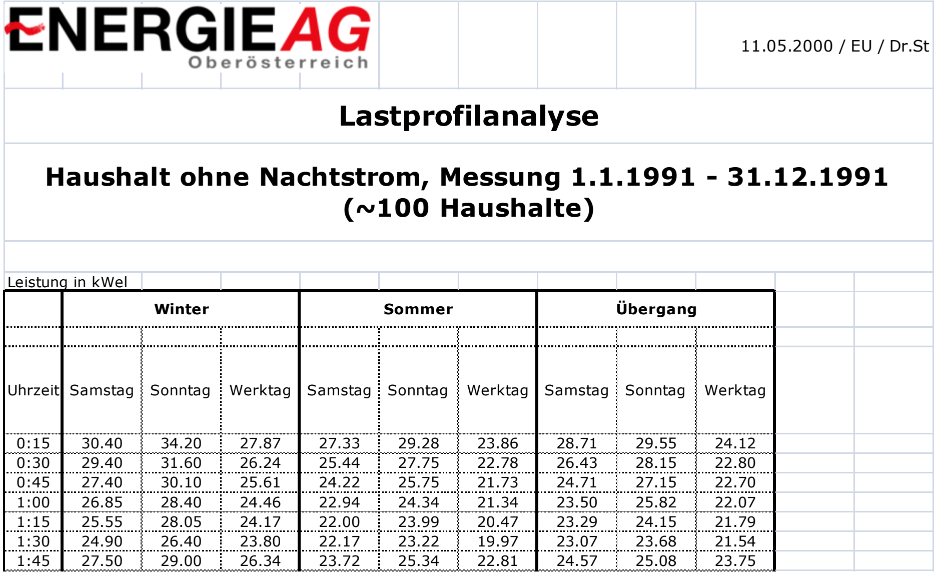
8.1.3. Load profile

The employed load profile, provided by Energie AG Oberösterreich (2000), is an estimation of the electricity consumption for 100 Austrian households in 1991. Considering the autonomy of the models, it is essential that the selected load profile is expressly for households without *Nachtstrom*, i.e. with a special night tariff and thus without the possibility of utilizing off-peak electricity. A sample of the used data is displayed in Table 11.

In order to make the data comparable with that of the weather station, as well as to enable an up-to-date assessment, an approximation of the increase to the level of 2006 is performed. Therefore, the total increase of the electricity consumption of Austrian households between the concerned years is considered. The increase from 269.245 to 276.128 TJ (Statistik Austria 2008) corresponds to a factor of 1.02556, which is used for the recalculation. Moreover, since the load data is given for every quarter-hour, it has been re-approximated to match the corresponding data of the weather station, that is, with an accuracy of half an hour. The processed data is finally used as basis for modeling communities of different sizes. For the small settlements considered here, the change of the load profile characteristics that occurs as the number of households grows, is assumed to be negligible.

The load profiles are given for winter and summer, as well as for workdays, Saturday and Sunday. These options are suitably combined in the models, assuming that the period April to September is equivalent to “summer” and October to March to “winter”.

Table 11. Load profile for 100 households 1.1.1991–31.12.1991, without a night tariff (Energie AG Oberösterreich 2000).



ENERGIE AG Oberösterreich

11.05.2000 / EU / Dr.St

Lastprofilanalyse

Haushalt ohne Nachtstrom, Messung 1.1.1991 - 31.12.1991
(~100 Haushalte)

Leistung in kWel

	Winter			**Sommer**			**Übergang**		
Uhrzeit	Samstag	Sonntag	Werktag	Samstag	Sonntag	Werktag	Samstag	Sonntag	Werktag
0:15	30.40	34.20	27.87	27.33	29.28	23.86	28.71	29.55	24.12
0:30	29.40	31.60	26.24	25.44	27.75	22.78	26.43	28.15	22.80
0:45	27.40	30.10	25.61	24.22	25.75	21.73	24.71	27.15	22.70
1:00	26.85	28.40	24.46	22.94	24.34	21.34	23.50	25.82	22.07
1:15	25.55	28.05	24.17	22.00	23.99	20.47	23.29	24.15	21.79
1:30	24.90	26.40	23.80	22.17	23.22	19.97	23.07	23.68	21.54
1:45	27.50	29.00	26.34	23.72	25.34	22.81	24.57	25.08	23.75

8.1.4. Energy storage model

The main concept of the energy storage model is presented in the block diagram in Figure 15. First, the difference between the generation and the load is calculated. Surplus energy is stored, and if the capacity of the storage is exceeded, the exceeding share is dissipated. On the other hand, if the generation and storage cannot supply the required load, the energy shortage is registered as deficit.

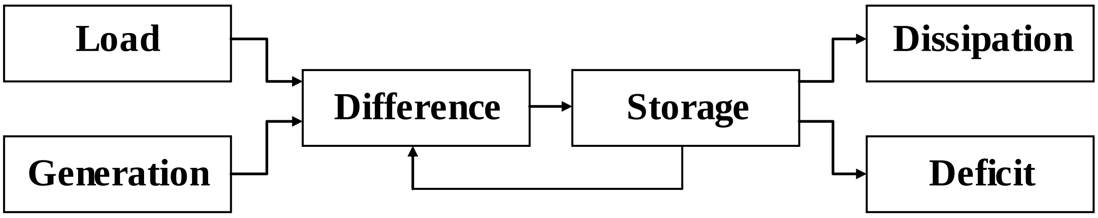


Figure 15. Block diagram of the energy storage model.

Initially, the model calculates the difference between the generated and the consumed power for every half-hour and converts it into energy, in accordance with

$$E_{\mathrm{diff}_\mathrm{n}} = (P_{\mathrm{gen}_\mathrm{n}} - P_{\mathrm{load}_\mathrm{n}})t_{\mathrm{interval}}, \tag{24}$$

where $E_{\mathrm{diff}_\mathrm{n}}$ is the energy difference, $P_{\mathrm{gen}_\mathrm{n}}$ is the generated power and $P_{\mathrm{load}_\mathrm{n}}$ is the consumed power during the interval n, and t_{interval} is the duration of the interval.

After receiving a possible starting capacity E_0, the status of the energy storage system is computed so that the energy difference for the previous period is continuously added

$$E_{\mathrm{storage}_{\mathrm{n+1}}} = E_{\mathrm{storage}_\mathrm{n}} + E_{\mathrm{diff}_{\mathrm{n+1}}}, \tag{25}$$

where $E_{\mathrm{storage}_\mathrm{n}}$ is the status of the storage system.

This occurs under the condition that the obtained result is not negative, in which case the storage status is set to zero and the negative sum is exported and categorized as energy deficit

$$E_{\mathrm{storage}_\mathrm{n}} + E_{\mathrm{diff}_{\mathrm{n+1}}} \le 0 \Rightarrow \begin{cases} E_{\mathrm{storage}_{\mathrm{n+1}}} = 0 \\ E_{\mathrm{deficit}_{\mathrm{n+1}}} = E_{\mathrm{storage}_\mathrm{n}} + E_{\mathrm{diff}_{\mathrm{n+1}}} \end{cases}. \tag{26}$$

Moreover, if the result exceeds the preset storage capacity, the storage status is fixed to the value of this and the difference between the sum and the storage capacity is exported and categorized as dissipated energy, in accordance with

$$E_{\mathrm{storage}_\mathrm{n}} + E_{\mathrm{diff}_{\mathrm{n+1}}} \ge E_{\mathrm{cap}} \Rightarrow \begin{cases} E_{\mathrm{storage}_{\mathrm{n+1}}} = E_{\mathrm{cap}} \\ E_{\mathrm{diss}_{\mathrm{n+1}}} = E_{\mathrm{storage}_\mathrm{n}} + E_{\mathrm{diff}_{\mathrm{n+1}}} - E_{\mathrm{cap}} \end{cases}, \tag{27}$$

where E_{cap} is the preset capacity of the storage.

For all other cases, the attained sum is the current storage status. The efficiency of a specific storage technology is not considered yet.

8.2. Wind power system

8.2.1. Generation model

The features of a three-bladed Enercon E-40 are used for modeling the wind generation. The turbine parameters which are essential for the model are listed in Table 12.

Table 12. Parameters of the Enercon E-40 turbine (Austrian Wind Power 2007).

Rated power	500 kW
Rotor diameter	44 m
Hug height	78 m
Cut-in wind speed	2.5 m/s
Cut-out wind speed	28 m/s
Turbine concept	Gearless / variable speed / variable pitch control

Since the wind speeds provided by the weather station are measured close to ground level, they are recalculated for the altitude of the turbine hub, in accordance with (Brauner 2004)

$$v_{\mathrm{H}} = v_{10}\left(\frac{H}{10}\right)^{g}, \tag{28}$$

where v_H is the speed at the requested height, v_{10} the speed at 10 meters height, H the requested height and g the exponential factor. This describes the surroundings of the site and is chosen according to Table 13.

Table 13. Considerations and values for the exponential factor g (Brauner 2004).

Surroundings	***g***
Open areas with few obstacles, flat farmlands, coasts, seas and deserts	0.16
Areas with regularly scattered obstacles in the range of 10 to 15 m: residential areas, forests and coppices	0.28
Areas with large randomly scattered obstacles: city centers, very uneven areas with considerable amounts of obstacles, e.g. trees	0.40

Since Burgenland is a typical example of the first category, the value 0.16 is chosen for the calculations.

The power output of the turbine is calculated according to (Brauner 2004)

$$P = P_{\max} c_{\mathrm{p}}, \tag{29}$$

where c_{p} is the coefficient of performance[5] and $P_{\max}$ the maximum available power flow. The former can be obtained as (Brauner 2004)

$$c_{\mathrm{p}} = \frac{1}{2}\left(1+\frac{v_2}{v_1}\right)\left(1-\left[\frac{v_2}{v_1}\right]^2\right), \tag{30}$$

provided that the wind speed v_1 in front of the rotor and the wind speed v_2 behind it are known. As this is not case, the parameter is set to 0.5, which is representative for a modern rotor (Nørgaard & Holttinen 2007: 1). Hereafter, P_{max} is substituted with equation 27 (Brauner 2004)

$$P_{\max} = \frac{1}{2}\rho A v_1^3, \tag{31}$$

where ρ is the air density and A the area of the cross section swept by the rotor. The density ρ is set to the standard value 1.2 kg/m^3 in the model. The area A is calculated in accordance with the specific rotor diameter and is hence approximately 1521 m^2.

Next, the computed power values are filtered so that all values received for corresponding wind speeds below the cut-in speed and above the cut-out speed are set to zero, as follows

$$\begin{cases} v_{1_{\mathrm{n}}} < v_{\mathrm{cut-in}} \\ v_{1_{\mathrm{n}}} > v_{\mathrm{cut-out}} \end{cases} \Rightarrow P_{\mathrm{n}} = 0, \tag{32}$$

---

[5] The teoretical limit on energy extraction from the wind, using the concept of a wind turbine, is known as the Betz limit: c_{pmax}=16/27≈0.593.

where $v_{\text{cut-in}}$ is the cut-in speed of the turbine, $v_{\text{cut-out}}$ is the cut-out speed and P_n is the power output.

Moreover, all power outputs exceeding the rated power are fixed to this value (the rated wind speed is not utilized since the available data sheets provide different information and sheets from the producer are not available for this turbine type), in accordance with

$$P_\text{n} \geq P_\text{rated} \Rightarrow P_\text{n} = P_\text{rated}. \tag{33}$$

Thus, the values used in the model are finally obtained.

8.2.2. Modeling the system

Energy balance

The community, which is to be supported by the wind turbine and the storage system, consists of 120 households. This corresponds to an annual load of 517 MWh, calculated in accordance with the load profiles used. The employed turbine generates a total of 534 MWh in the considered year. Hence, on an annual basis, the energy balance is positive.

Full-load hours

Correspondingly, the number of full-load hours, calculated as

$$\frac{\sum P(t)}{P_\text{rated}}, \tag{34}$$

is 1067 h. Figure 16 illustrates the relationship between generated power and the number of hours the concerned power out is attained during the year. As seen in the figure, the turbine reaches its full capacity only 111 hours and a power output exceeding 400 kW only 188 h. Thus, it can already be concluded that an energy storage system suited for storing all of the energy otherwise dissipated, is not economically feasible since the gains of such a large system would be comparatively small. On the other hand, the turbine is not operating at all for 1306 h and generating less than 100 kW for 7186 h, which creates a need for additional energy supply during this time.

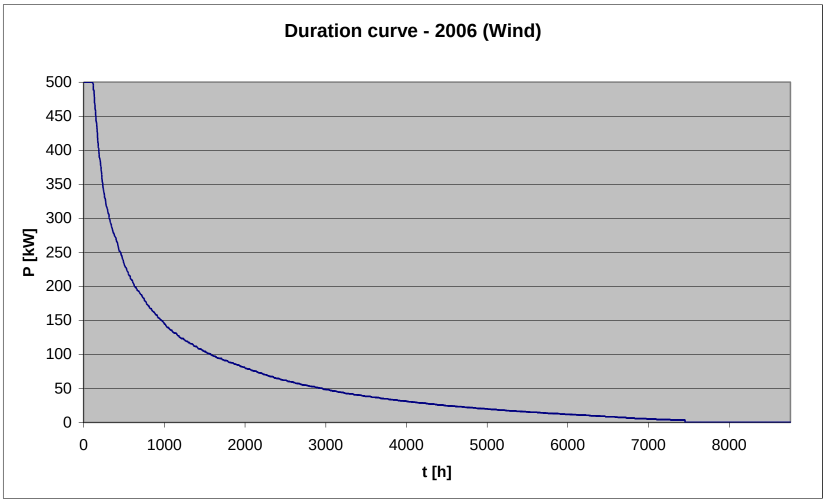


Figure 16. Duration curve of the modeled wind power system, year 2006.

Seasonal situation

Figure 17 illustrates the seasonal variations of the power output (the blue curve) and the load (the green curve) of the considered system. Even though the total generation matches the total load, the intermittent nature of wind leads to continuous differences, which are plotted in Figure 18.

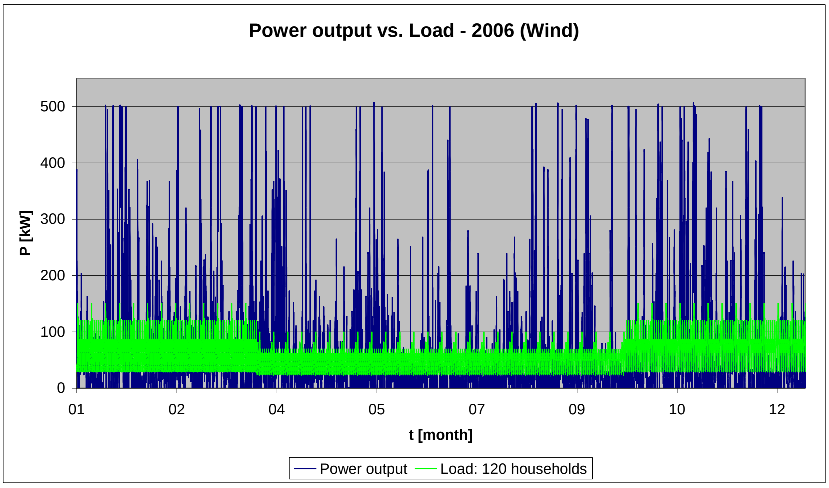


Figure 17. The power output and the load during the whole year.

The corresponding energy disparity between the generation and the demand over the year is illustrated in Figure 18. Also interesting are the considerable seasonal differences; even though the generation increases in winter, the corresponding rise in demand is greater, wherefore seasonal energy storage would be of interest. In total in this stand-alone system, 276.7 MWh of the generated energy is not utilized, whereas a shortage of 260.5 MWh arises, in a scenario without energy storage.

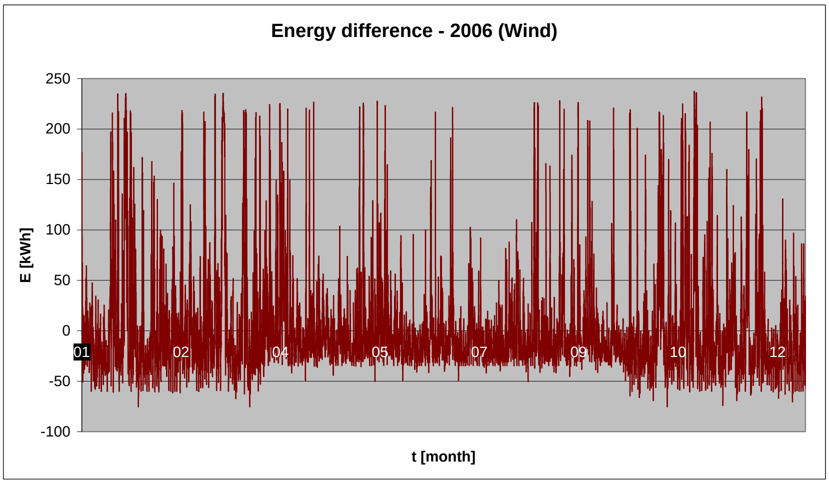


Figure 18. Difference between generated and consumed energy.

Employment of energy storage - assessments

This disparity has to be addressed and an effective solution is the employment of energy storage. In order to assess the need for and use of storage, different periods are chosen for analysis. First, monthly assessments are made and these are then complemented with corresponding analyses for periods of three days. To provide a versatile view, one winter and one summer month are chosen. Moreover, the months with the highest and the lowest generations, i.e. March (74.0 MWh) and July (22.1 MWh), are selected.

Assessment: March

The variations of the power output and the load during March are plotted in Figure 19. As seen, the generation repeatedly exceeds the load by more than threefold during this period. Nevertheless, the load cannot be fully covered for most of the days during the month.

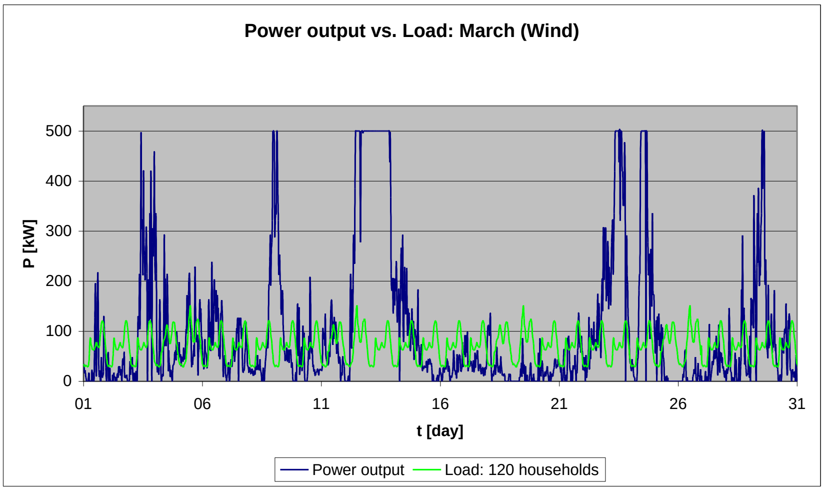


Figure 19. Power output vs. load during March.

The situation without storage

Figure 20 shows the amount of energy which cannot be provided by the turbine (pink curve) and the amount of generated energy which is not utilized (yellow curve) and thus has to be dissipated. Without storage, the deficit is 22.5 MWh, whereas the dissipation is 44.9 MWh. Hence, the employment of an energy storage system has good potential.

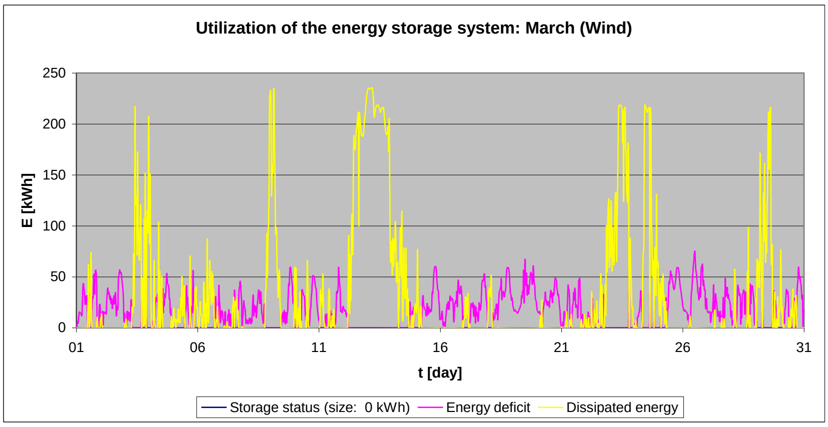


Figure 20. Energy deficit vs. energy dissipation during March, without energy storage.

Employment of a 200 kWh storage capacity

The result of installing a small energy storage system of 200 kWh is displayed in Figure 21. The blue curve illustrates the energy content of the storage system. Through the deployment of such a system, an additional 5.25 MWh of the generated energy can be utilized.

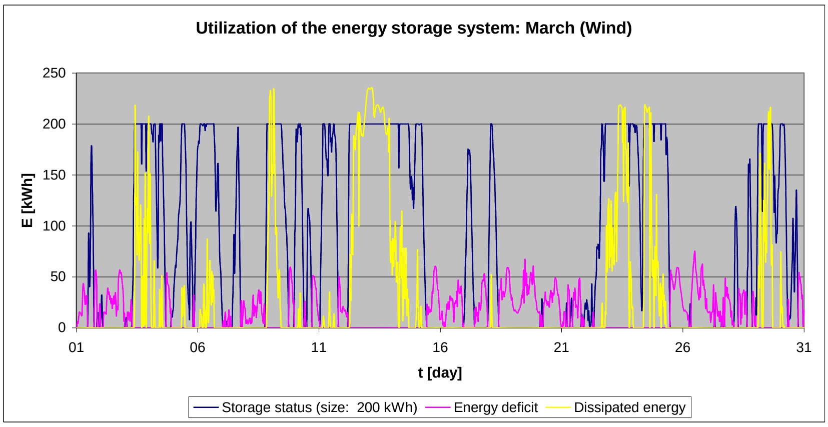


Figure 21. Status of an energy storage system of 200 kWh during March.

Employment of a 1000 kWh storage capacity

The impact of an energy storage system with a capacity of 1000 kW is displayed in Figure 22. As seen, the contribution of such a system is considerable. However, the five-fold increase of the storage size only decreases the dissipation and the deficit by approximately a factor of two, i.e. by 10.4 MWh and by 10.0 MWh, respectively. Thus, from an economic point of view, this is not likely to be a sustainable concept. Moreover, not even a system this size is capable of eliminating the entire deficit. Consequently, further measures are at all events necessary in order to secure the energy supply.

Assessment: 23rd to 25th March

The variations of the power output and the load during 23rd to 25th March are plotted in Figure 23. During this period, the generation is most of the time able to provide the required energy.

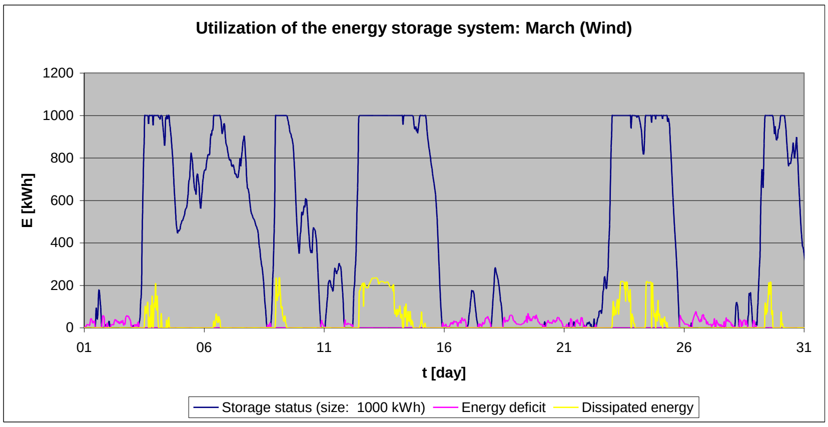


Figure 22. Status of an energy storage system of 1000 kWh during March.

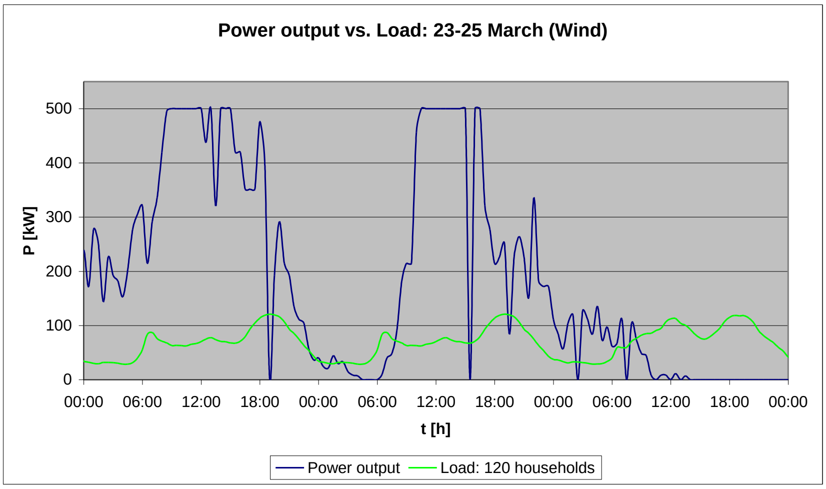


Figure 23. Power output vs. load during 23rd to 25th March.

The situation without storage

As illustrated in Figure 24, there is still a need for energy which cannot be supplied by the wind turbine, even though this is one of the most advantageous periods of the year. The deficit is here only 1.68 MWh, but the dissipation is 10.3 MWh. Hence, an energy storage system has good potential in this scenario.

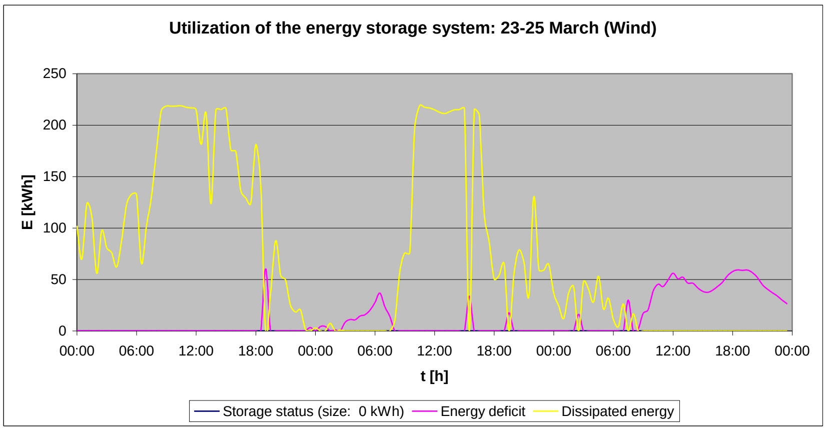


Figure 24. Energy deficit vs. energy dissipation during 23rd to 25th March, without energy storage.

Employment of a 200 kWh storage capacity

The employment of an energy storage system of 200 kWh would eliminate the entire deficit, with the exception of that during the evening of the 25th. This entails a reduction of the deficit of 0.539 MWh and concurrently of the dissipation of 0.641 MWh. Such a scenario is plotted in Figure 25.

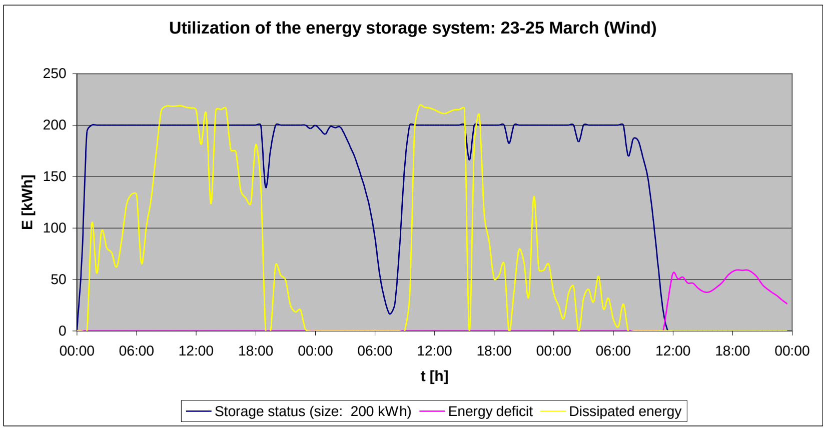


Figure 25. Status of an energy storage system of 200 kWh during 23rd to 25th March.

Employment of a 1000 kWh storage capacity

Installing an even bigger system of 1000 kWh involves further reductions: totally 1.34 MWh of the deficit and 1.44 MWh of the dissipation. However, as seen in Figure 26, the actual additional contribution in comparison to the smaller system is still rather marginal, since the need for additional energy during the end of the period persists.

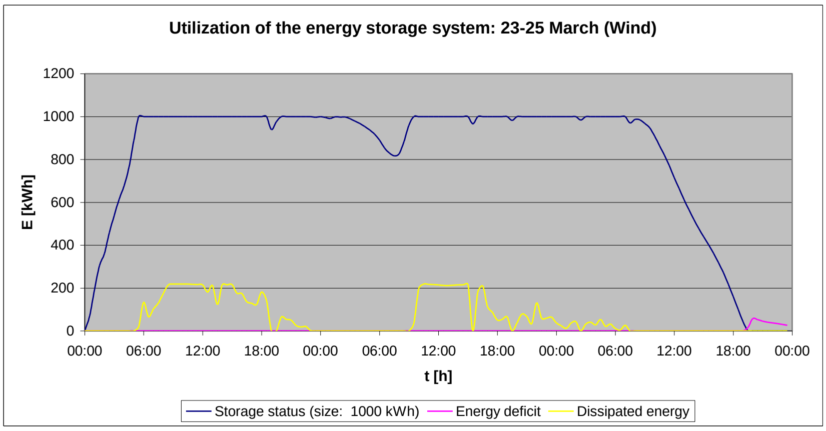


Figure 26. Status of an energy storage system of 1000 kWh during 23rd to 25th March.

Assessment: July

The variations of the power output and the load during July are illustrated in Figure 27. During this period, there is almost constantly an energy deficit.

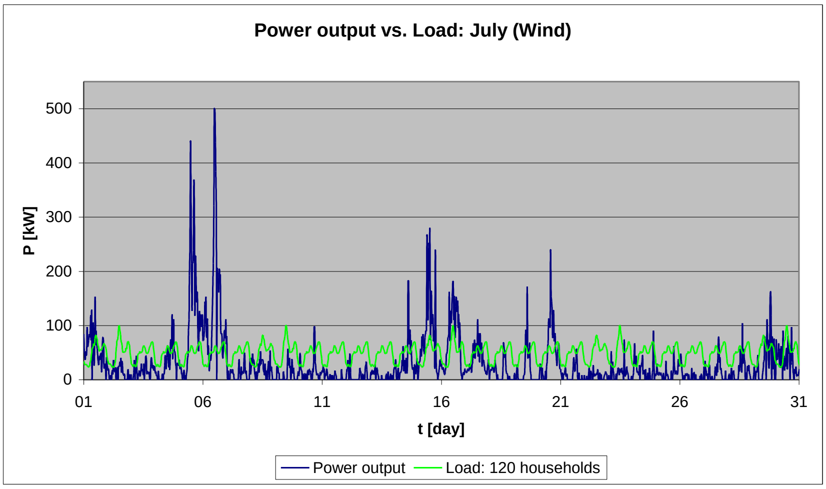


Figure 27. Power output vs. load during July.

The situation without storage

The situation without energy storage is displayed in Figure 28. Although the generation is comparatively small during this period, 7.93 MWh is still dissipated. Since the deficit, 22.2 MWh, is greater, storage alone will not be sufficient for this month.

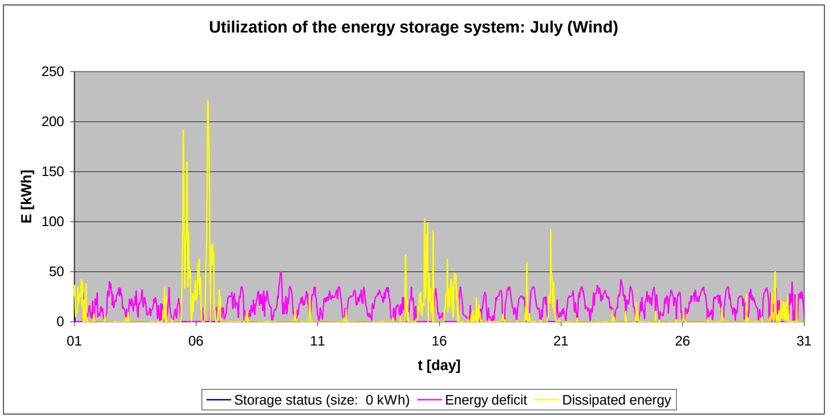


Figure 28. Energy deficit vs. energy dissipation during July, without energy storage.

Employment of a 200 kWh storage capacity

Nevertheless, an energy storage system of 200 kWh is capable of reducing the deficit with 2.45 MWh and the dissipation with 2.48 MWh. The impact of such a system is seen in Figure 29.

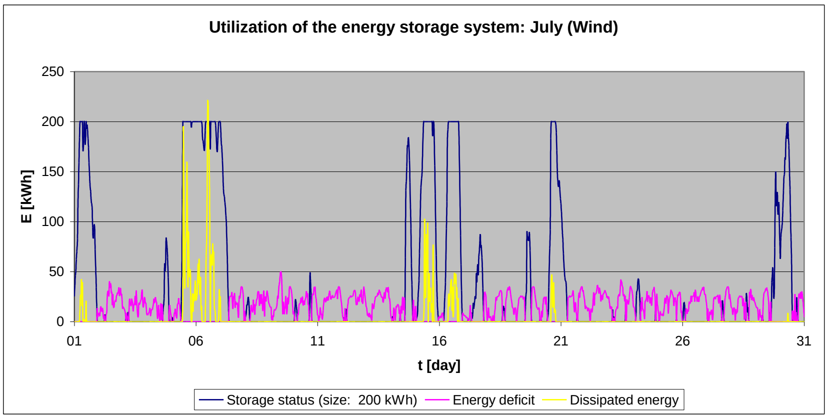


Figure 29. Status of an energy storage system of 200 kWh during July.

Employment of a 1000 kWh storage capacity

A further increase of the storage size to 1000 kWh reduces the deficit with 4.53 MWh and the dissipation with 4.56 MWh. However, the need for additional energy supply remains rather constant, in accordance with Figure 30.

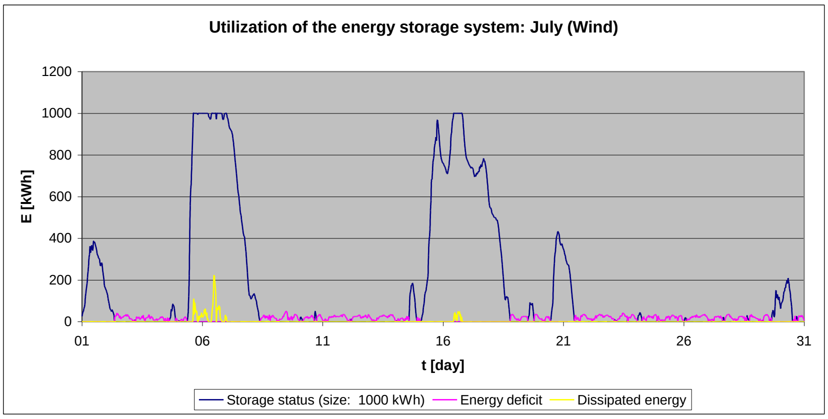


Figure 30. Status of an energy storage system of 1000 kWh during July.

Assessment: 9th to 11th July

The variations of the power output and the load during 9th to 11th July are plotted in Figure 31. During this period, the load is almost constantly larger than the generation, which only briefly produces surplus energy.

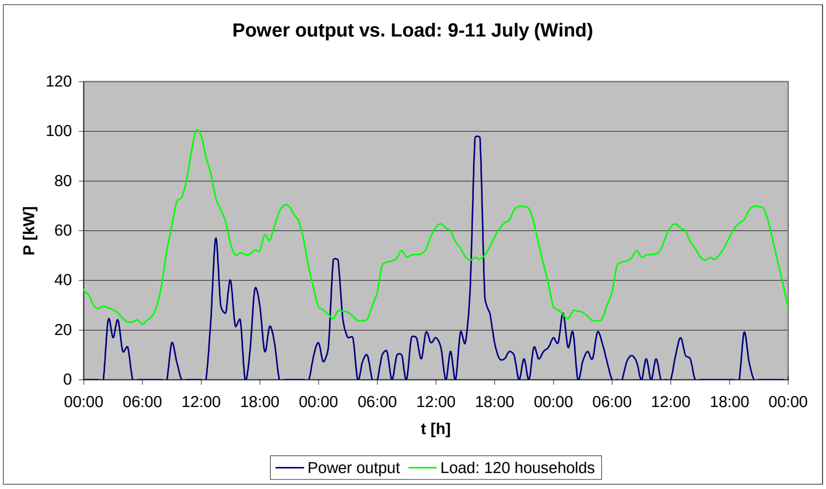


Figure 31. Power output vs. load during 9th to 11th July.

The situation without storage

The dissipation, which could be stored, is in this scenario only 70.6 kWh. Hence, as seen in Figure 32, the employment of energy storage is not economically feasible during this period.

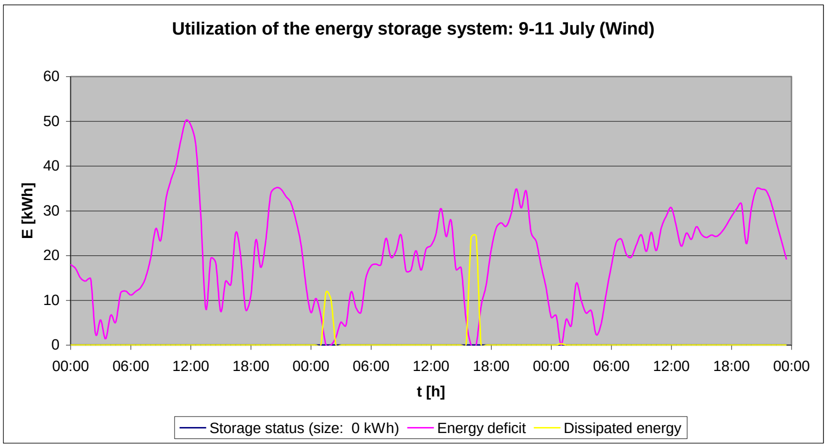


Figure 32. Energy deficit vs. energy dissipation during 9th to 11th July, without energy storage.

8.2.3. Economic assessment

In order to assess the profitability of storage depending on the size, an analysis utilizing the parameters of lead-acid batteries is made. Batteries are the natural chose for a small-scale system like this, and lead-acid batteries are chosen for the modeling due to their inexpensiveness. The analysis is limited to the profitability of the storage, whereas the investment costs for the wind turbine are not considered. Moreover, compensations are not paid for undeliverable energy.

The main concept of the economic assessment procedure is displayed in the block diagram in Figure 33. The decrease in dissipation and the cost of the storage system are calculated in accordance with the storage size. Depending on the storage parameters and the electricity price, the financial gains obtained through storage are obtained. Finally, considering the investments costs, the net gains are calculated.

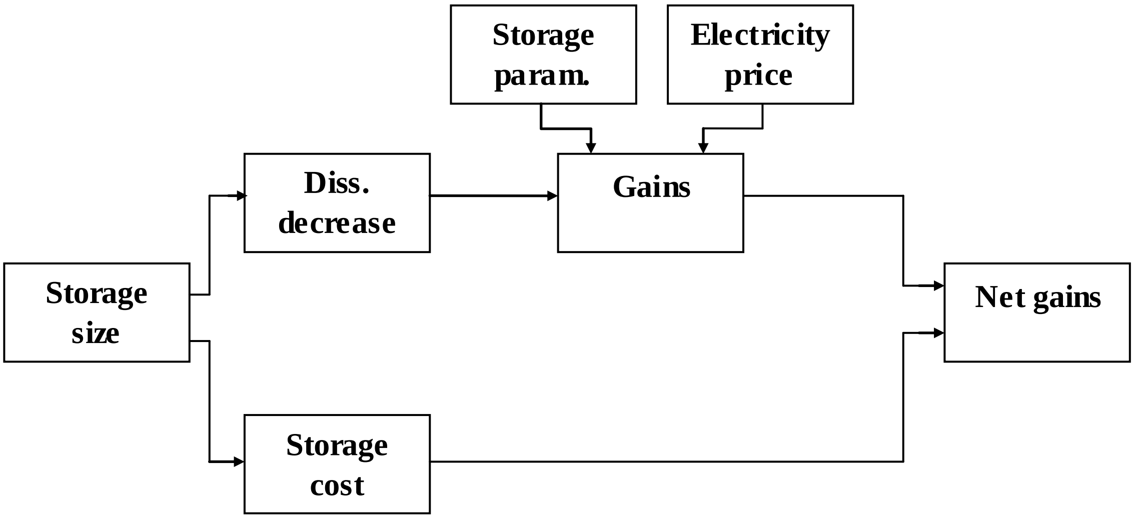


Figure 33. Block diagram of the economic assessment procedure.

The employment of such batteries for bulk storage at a cost of 152 €/kWh serves as basis for the following calculation of the discount factor β (Brauner 2004):

$$\beta = \frac{q^n - 1}{(q-1)q^n}, \tag{35}$$

where the q is the interest factor and n is the lifetime. In the model, the interest is set to 5 % and the lifetime is estimated to be 5 years. Thus, a discount factor of 4.33 is obtained. Under these conditions, the relationship between the storage size and the capital costs is obtained as

$$y_{\mathrm{cost_n}} = \frac{E_\mathrm{n} x_{\mathrm{cost_n}}}{\beta}, \tag{36}$$

where $y_{\mathrm{cost_n}}$ is the cost of the energy storage system, E_n is the capacity of the energy storage system and x_{cost} is the investment cost of the storage technology. The blue line in Figure 34 displays the relationship.

Furthermore, with a battery efficiency of 90 % and a sales price of the stand-alone electricity of 30 cent/kWh, the financial gains obtained through the additional available energy are calculated as

$$y_{\mathrm{gain}_n} = (E_{\mathrm{diss}_0} - E_{\mathrm{diss}_n})\eta_{\mathrm{storage}} x_{\mathrm{cost}}\,, \tag{37}$$

where y_{gain_n} is the gain from the stored energy, E_{diss_0} is the dissipation without storage, E_{diss_n} is the dissipation with the energy storage system and η_{storage} is the efficiency of the storage technology. The plotted in the figure as the turquoise curve.

Finally, the red curve displays the actual gains y_{net_n} made through energy storage, considering the corresponding investment costs

$$y_{\mathrm{net}_n} = y_{\mathrm{gain}_n} - y_{\mathrm{cost}_n}\,. \tag{38}$$

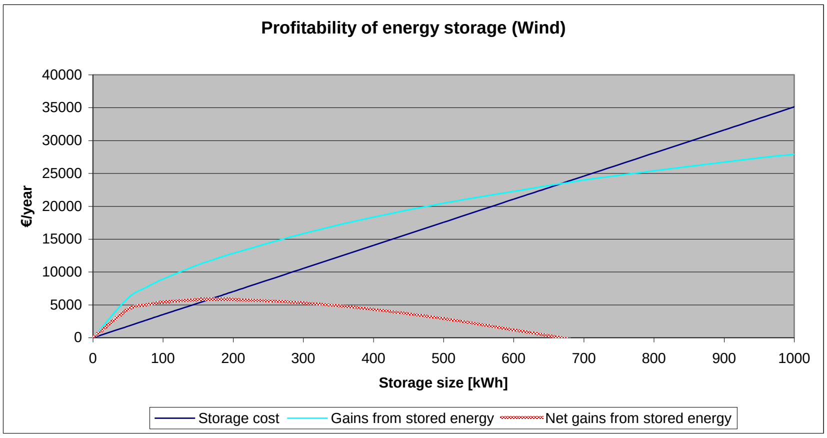


Figure 34. Profitability of energy storage.

Hence, the costs for a storage system with a capacity exceeding 650 kWh surpass the obtained gains. If 650 kWh is installed, the deficit is reduced to 33.8 % and the dissipation to 35.8 %.

On the other hand, an optimal profitability is achieved with a capacity of approximately 175 kWh, which to a cost of 6144 € generates incomes of 11990 €, which results in a profit of 5846 € for the considered year. Consequently, the payback of such a storage system would only be 1.05 year.

Therefore, it can be concluded that storage can offer considerable benefits for the system, but rather in the form of financial gains than as a single solution for backup power.

Furthermore, if the energy, which cannot be delivered to the customers, would have to be compensated, the gains would be even greater.

8.2.4. Conclusions and discussion

Figure 35 illustrates the quotient between the energy deficit and the load (pink curve) over the year, as a function of the storage size. Correspondingly, the quotient between the dissipated and the generated energy is plotted with a yellow curve.

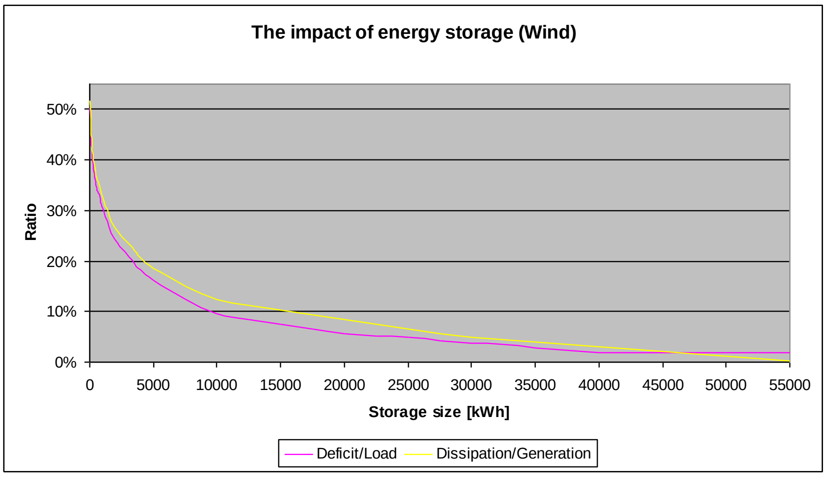


Figure 35. The impact of energy storage.

The initial gains of an energy storage system are considerable. However, the profitability decreases exponentially. For the above described system of 200 kWh, the reduction of the deficit and dissipation is 47.5 MWh, respectively, over the year. Concurrently, the deficit and dissipation ratios are decreased by 9.1 % and 8.9 %, respectively.

Correspondingly, for the system of 1000 kWh the reductions are both 103.4 MWh and the ratios are decreased by 19.9 % and 19.3 %. Assuming a linear cost increase for storage systems this size, this means that the latter system, which merely doubles the decrements of the deficit and dissipation ratios, would increase the costs by fivefold.

Considering larger concepts, a system of 2000 kWh would reduce both the deficit and dissipation with 134.2 MWh. Concomitantly, the ratios are decreased with 25.9 % and 25.1 %, respectively. The installation of a system with a capacity of 10 MWh would bring reductions of 210.9 MWh, corresponding to additional reductions of 14.8 % and 14.3 %. Hence, the latter system only decreases the deficit and dissipation another half, at a fivefold increase in costs.

Any energy gains acquired through larger systems than 10 MWh are marginal in relationship to the additional capacity required: a storage size of 30 MWh would only result in further reductions of 30.0 MWh and 39.5 MWh, respectively, and concurrently in 5.8 % and 7.5 % ratio decreases.

Thus, storage can play an important role in increasing the efficiency of stand-alone wind systems, but complete independency solely through storage is not economically possible. The financial gains of properly dimensioned storage can, however, be considerable. In a scenario where the wind turbine, on a yearly basis, is clearly overdimensioned in relation to the load, the contribution of storage would be of greater significance. Moreover, as part of a solution, either together with demand side management or additional back-up generation, storage remains an attractive option.

8.3. Photovoltaic generation system

8.3.1. Generation model

A simplified arrangement is used for modeling a photovoltaic generation system. The power output is calculated as

$$P = SA\eta, \qquad (39)$$

where S is the solar radiation, A the total area of the solar panels and η the efficiency of the system.

A system with a generation capacity equivalent to that of the previously analyzed wind system is modeled. This entails 368 kW_p (875 kWh/kW_p). Assuming 8 m^2/kW_p, the total area of the panels needed in the model is calculated to 2944 m^2. As the efficiencies of the commercially available solar cells are in the range of 8.5 % to 19 % (Brauner 2004), an average of 15 % is used.

8.3.2. Modeling the system

Energy balance

The community, which is to be supported by the photovoltaic plant and the storage system, consists of 120 households. This corresponds to an annual load of 517 MWh, calculated in accordance with the load profiles used. The employed photovoltaic system generates a total of 534 MWh in the considered year. Hence, over the year, the energy balance is positive.

Full-load hours

Figure 36 illustrates the relationship between generated power and the number of hours the concerned power out is attained during the year. As seen in the figure, the highest outputs exceeding 325 kW are only reached 282 h of the year. Hence, similarly to wind power, as this share is so marginal, it is not economically feasible to install a storage system capable of storing all of the energy otherwise dissipated. On the other hand, the PV plant is not operating at all for 4111 h and generating less than 75 kWh for 6365 h, wherefore storage can play an important role in the system.

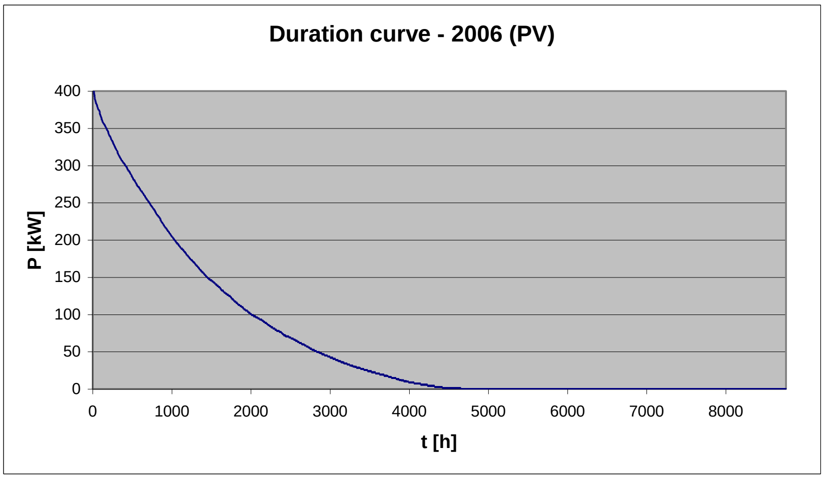


Figure 36. Duration curve of the modeled PV system, year 2006.

Seasonal situation

Figure 37 illustrates the seasonal variations of the power output and the load of the considered system. Even though the total generation matches the total load, the intermittent nature of the sun radiation leads to continuous differences, which are plotted in Figure 38. The seasonal variations of the generation are clearly greater as for wind power, wherefore a seasonal storage system would be of interest.

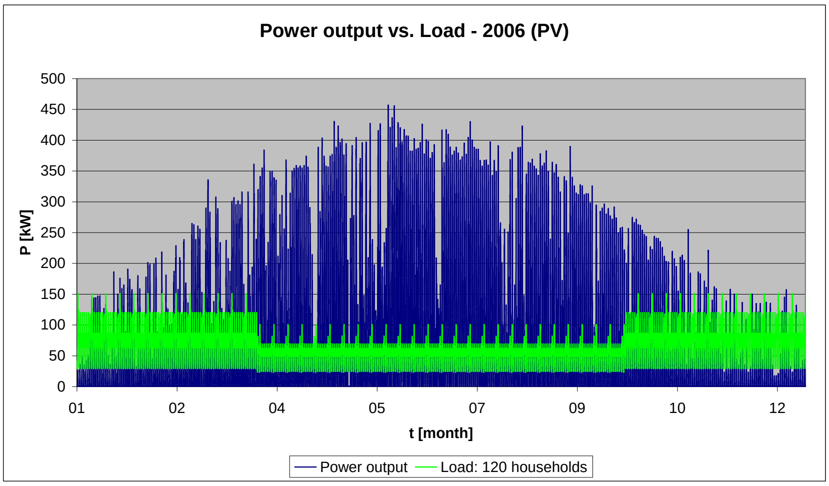


Figure 37. The power output and the load during the whole year.

The corresponding energy disparity between the generation and the demand over the year is illustrated in Figure 38. In opposite to wind power, the seasonal periods of high generation and high consumption do not coincide, which makes energy storage even more important. In total, over the year 331.5 MWh of the energy generated by the stand-alone system is not utilized, whereas 315.1 MWh of the load cannot be supplied, in a scenario without energy storage.

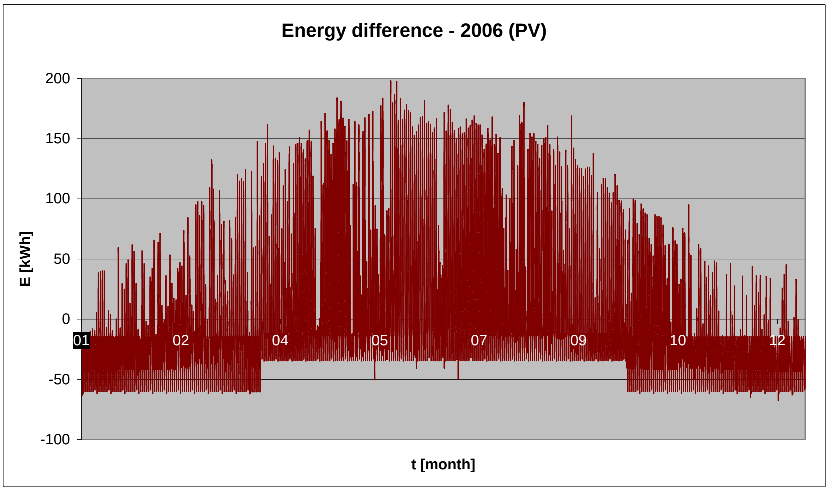


Figure 38. Difference between generated and consumed energy.

Employment of energy storage - assessments

The months with the highest and lowest generations, i.e. July (89.3 MWh) and December (9.68 MWh), are chosen for the evaluation of the potential of energy storage. These assessments are then supported by corresponding analyses of periods of three days.

Assessment: July

The variations of the power output and the load during July are plotted in Figure 39. As seen, daytime the generation almost constantly exceeds the load by more than sixfold during this period. However, the complete lack of generation nighttime has to be addressed.

The situation without storage

The situation without energy storage is displayed in Figure 40. The amount of dissipated energy forms 74 % (66.5 MWh) of the total generation during this period. Nevertheless, due to the nights, there is a shortage of 13.6 MWh, which has to be covered.

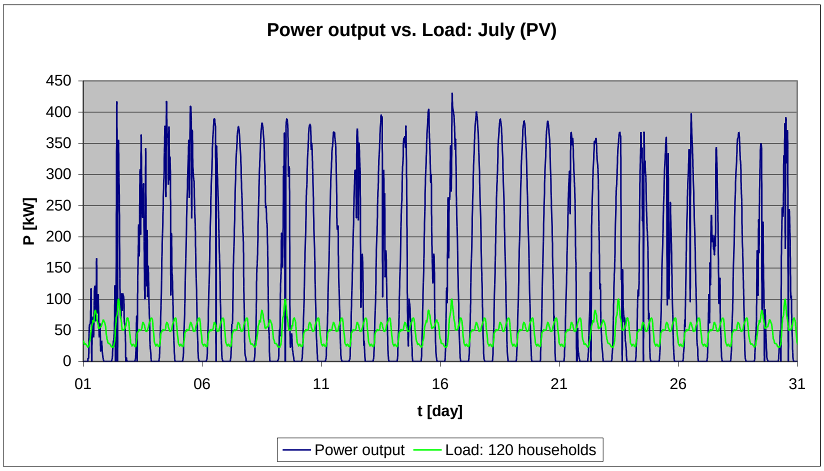


Figure 39. Power output vs. load during July.

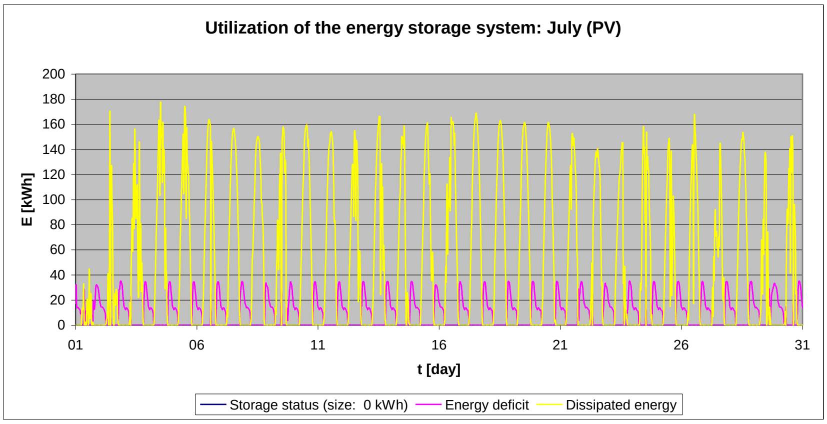


Figure 40. Energy deficit vs. energy dissipation during July, without energy storage.

Employment of a 450 kWh storage capacity

Through the deployment of an energy storage system of 450 kWh, the surplus energy produced daytime can be utilized to essentially fully cover the nighttime demand, which is seen in Figure 41. The deficit is hereby reduced to only 0.659 MWh and is concentrated to the beginning and the end of the month.

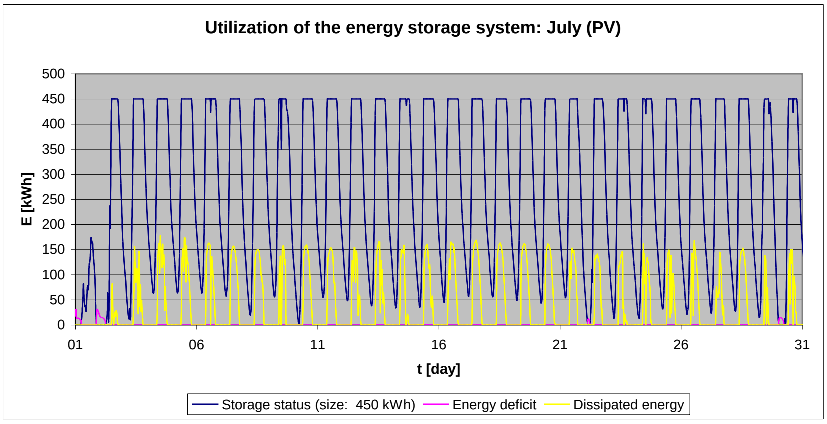


Figure 41. Status of an energy storage system of 450 kWh during July.

Assessment: 15th to 17th July

The variations of the power output and the load during 15th to 17th July are plotted in Figure 42. During these days, the generation clearly exceeds the load daytime, but for regular periods of approximately 9 h there is a need for storage.

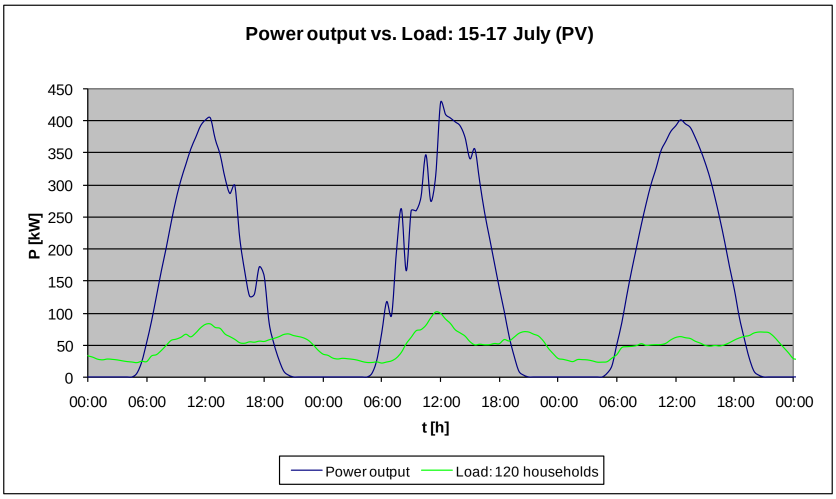


Figure 42. Power output vs. load during 15th to 17th July.

The situation without storage

Figure 43 displays the situation without any storage. In this case, 7.92 MWh would be dissipated and the deficit would concurrently be 1.20 MWh.

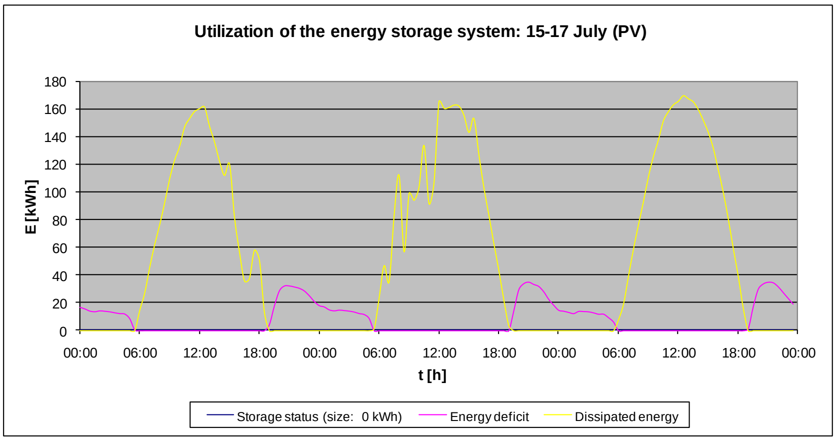


Figure 43. Energy deficit vs. energy dissipation during 15th to 17th July, without energy storage.

Employment of a 450 kWh storage capacity

The utilization of an energy storage system of 450 kWh would be sufficient to supply the nighttime demand, as displayed in Figure 44. The remaining deficit (148 kWh) exists only because the chart starts at nighttime, but in practice it would be covered by the stored energy from the previous day.

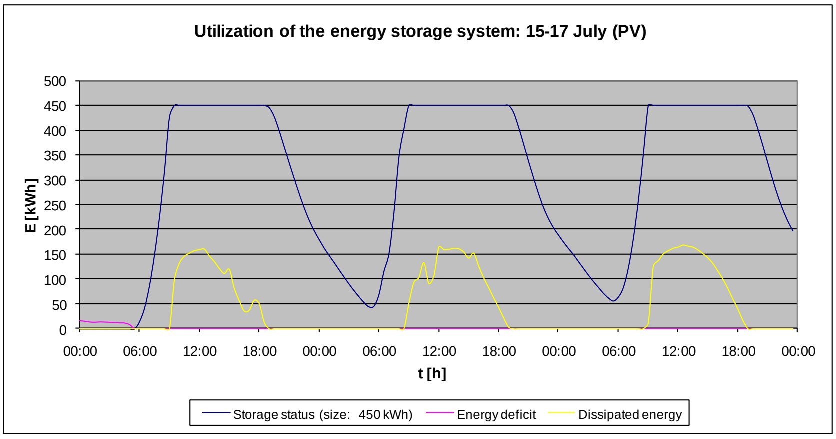


Figure 44. Status of an energy storage system of 450 kWh during 15th to 17th July.

Assessment: December

The variations of the power output and the load during December are plotted in Figure 45. During this period, the load is almost constantly larger than the generation, which only briefly produces surplus energy.

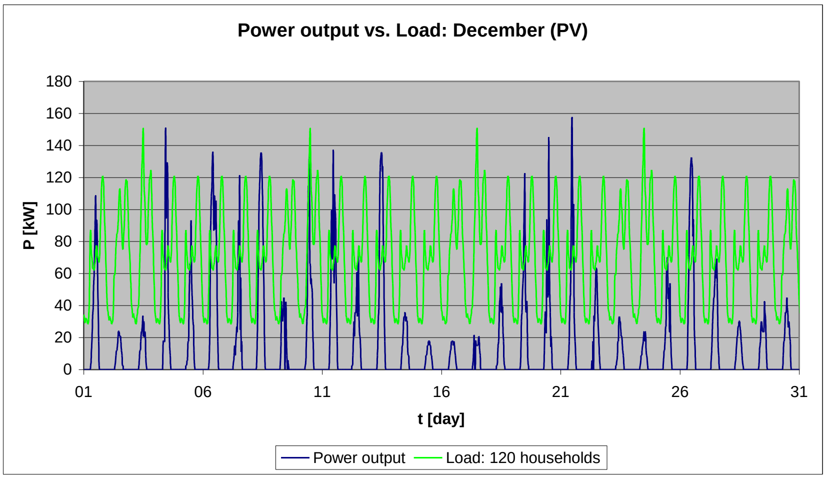


Figure 45. Power output vs. load during December.

The situation without storage

Figure 46 illustrates the situation without energy storage. The energy deficit is 43.9 MWh, but with a dissipation of only 1.51 MWh, employment of energy storage is not economically feasible.

Assessment: 2nd to 4th December

Figure 47 displays the variations of the power output and the load during 2nd to 4th December. During this period, the generation only briefly exceeds the load.

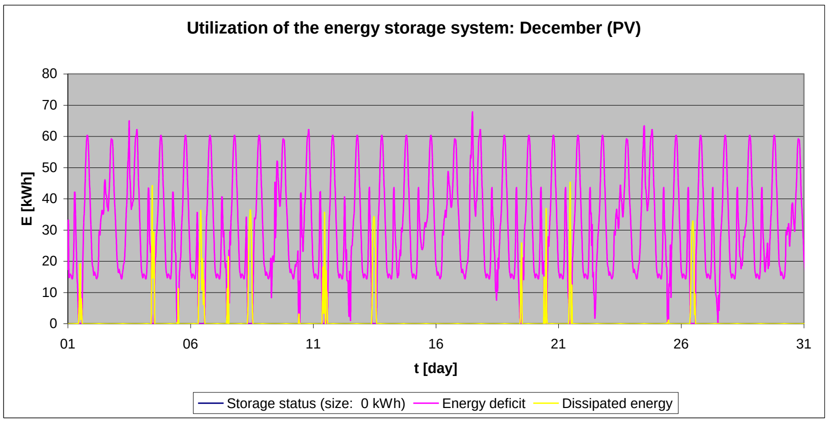


Figure 46. Energy deficit vs. energy dissipation during December, without energy storage.

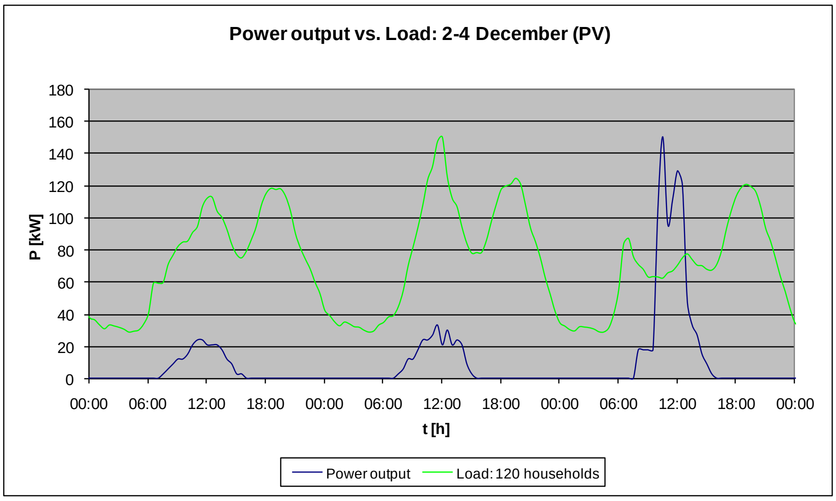


Figure 47. Power output vs. load during 2nd to 4th December.

The situation without storage

Figure 48 illustrates the situation without energy storage. The energy deficit is 3.90 MWh, but with a dissipation of only 123 kWh, employment of energy storage is not economically feasible.

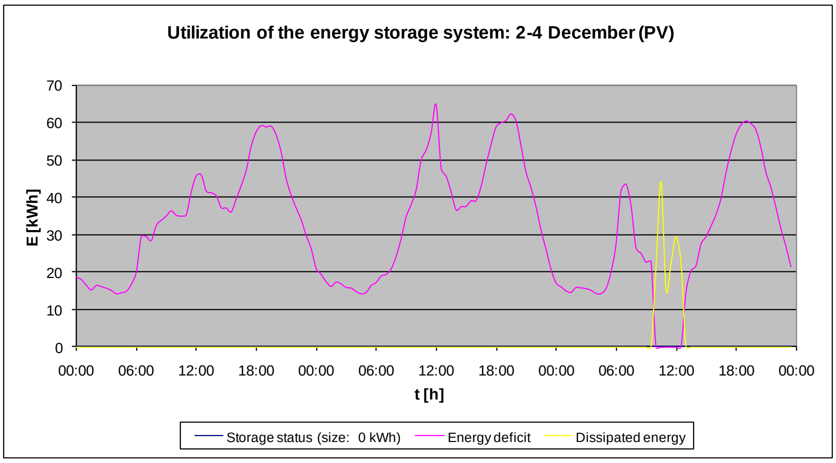


Figure 48. Energy deficit vs. energy dissipation during 2nd to 4th of December, without energy storage.

8.3.3. Economic assessment

In order to assess the profitability of storage depending on the size, a similar analysis as for the wind power system is carried out (see chapter 3.1.3). Figure 49 is obtained employing the equivalent conditions, i.e.

- Storage cost: 152 €/kWh
- Battery lifetime: 5 years
- Battery efficiency: 90 %
- Interest: 5 %
- Electricity price: 30 cent/kWh

Under these conditions, the relationship between the storage size and the capital costs is displayed in Figure 49 (blue line). Moreover, the financial gains of the stored energy are plotted in the figure (turquoise curve). Finally, the red curve displays the actual gains made through energy storage, considering the corresponding investment costs.

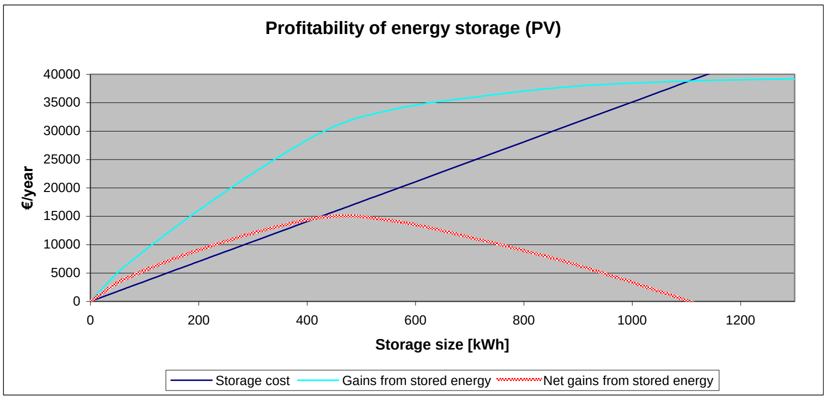


Figure 49. Profitability of energy storage.

Hence, the costs for a storage system with a capacity exceeding 1100 kWh surpass the obtained gains. A capacity of 1100 kWh would entail a deficit ratio of 33.1 % and concomitantly a dissipation of 35.2 %.

On the other hand, an optimal profitability is achieved with a capacity of approximately 475 kWh, which to a cost of 16676 € generates additional incomes of 31715 €, which results in a further profit of 15038 € for the considered year. Consequently, the payback of such a storage system would only be 1.11 year.

Therefore, it can be concluded that storage can offer considerable benefits for the system, but rather in the form of financial gains than as a single solution for backup power. Moreover, if the energy which cannot be delivered would have to be compensated, the gains would be even greater.

8.3.4. Conclusions and discussion

Figure 50 displays the quotient between the energy deficit and the load (pink curve) over the year, as a function of the storage size. Correspondingly, the quotient between the dissipated and the generated energy is plotted with a yellow curve. As for the wind power system, the initial gains are significant, but for the photovoltaic system the profitability decreases even faster.

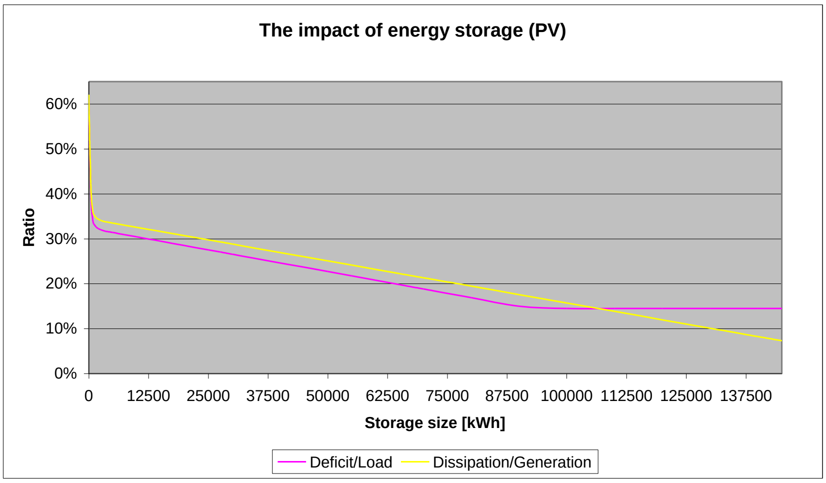


Figure 50. The impact of energy storage.

As viewed in Figure 51, a considerable change of the character of both curves can be noticed by a storage size of 700 kWh. The underlying reason is that 700 kWh is summertime essentially adequate for storing the amount energy required nighttime, whereas this capacity wintertime is sufficient to store the small amounts of surplus energy generated. Hence, any gains made hereafter are small in relation to the required increase of the storage capacity.

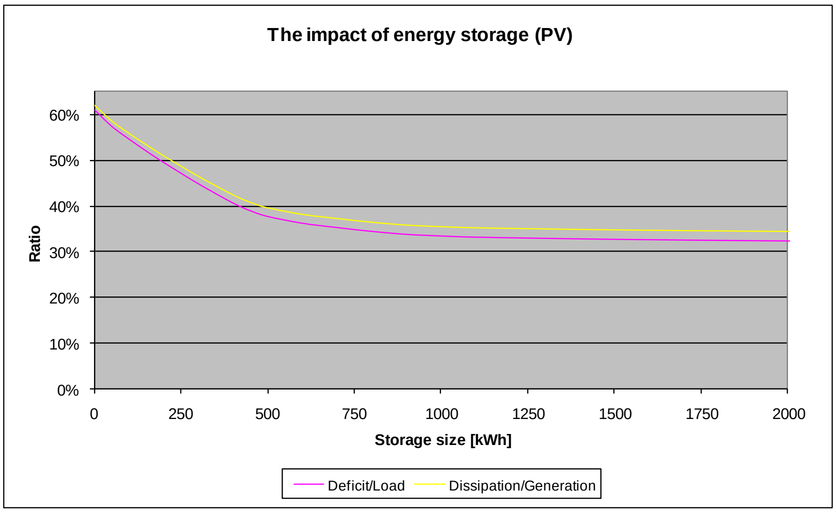


Figure 51. The impact of energy storage.

Another alteration of the deficit/load curve occurs by a storage size of 92.3 MWh. After this point, an increase of the storage capacity will no longer affect the energy deficit.

This is due to the generation profile of the PV plant, in accordance with which there is a significant deficit during the beginning of the year, and assuming that the storage starts empty, these 74.9 MWh remains uncompensatable. If the storage would contain a starting capacity this could be reduced. This is, however, not a sustainable long-term concept, since even the remarkably oversized system above would be emptied at the end of the year.

For comparison, a theoretical storage capacity, which would be sufficient throughout the year, is modeled in Figure 52. The size of such a seasonal system would be 167.5 MWh which results in a storage status of 74.9 MWh at the end of the year. When this amount of energy is set as starting capacity, a system is obtained, which delivers the required amount of energy necessary to fully cover the load during the whole year. However, storage of this size is obviously not sensible.

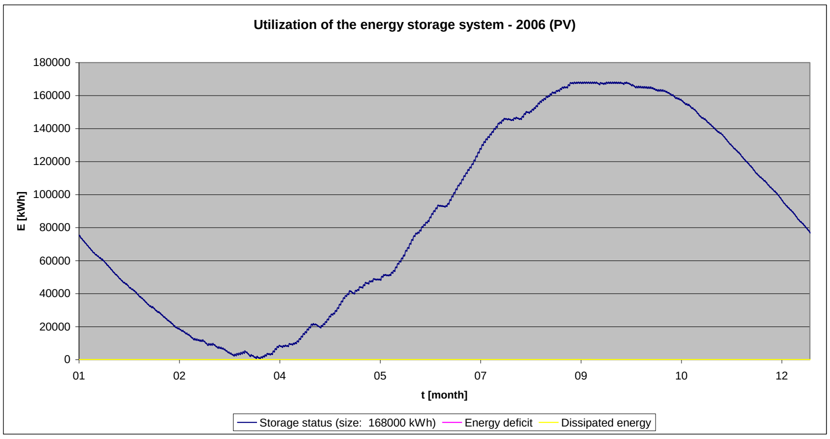


Figure 52. Theoretical sizing of an adequate seasonal storage.

For the previously considered system of 450 kWh, the reduction of both the deficit and the dissipation is 113.9 MWh, which corresponds to ratio decreases of 20.1 % and 23.2 %. For comparison, a system with a capacity of 2000 kWh would bring an additional reduction of 34.06 MW and concurrently reduce the deficit ratio with 8.5 % and the dissipation ratio with 4.5 %. Still assuming a linear cost increase for the storage systems, a cost increment of 500 % only result in an improvement of 30 %.

The benefit of systems larger than 2000 kWh is negligible in relationship to size increases required. For instance, the employment of a system of 40 MWh would only result in an additional improvement of 73.6 MWh, corresponding to ratio reductions of 7.6 % and 7.4 %.

Thus, storage can play an important role in increasing the efficiency of stand-alone photovoltaic systems, but complete independency solely through storage is not economically possible. In a scenario where the PV plant, on a yearly basis, is clearly overdimensioned in relation to the load, the contribution of storage would be of greater importance. Furthermore, as part of a solution, either together with demand side management or additional back-up generation, storage remains an attractive option.

8.4. Comparison of energy storage for the wind and PV systems

Assessment from an energy perspective

Figure 53 illustrates the quotient between the energy deficit and the load (pink) over the year, as a function of the storage size. Correspondingly, the quotient between the dissipated and the generated energy is plotted with a yellow curve. Significant differences can be discerned between the wind power (solid curves) and the photovoltaic system (dashed curves). As seen in the figure, the initial gains of energy storage are similar, but sizes exceeding 700 kWh are noticeably more beneficial for the wind system.

For wind power, storage of 1050 kWh is necessary to reduce the deficit ratio to 30 %. Correspondingly, to obtain ratios of 20 % and 10 %, storage capacities of 3300 kWh and 9600 kWh, respectively, would be necessary. Concomitantly, the PV system would need a storage of 12.5 MWh for a ratio of 30 %, whereas 20 % would require 64 MWh.

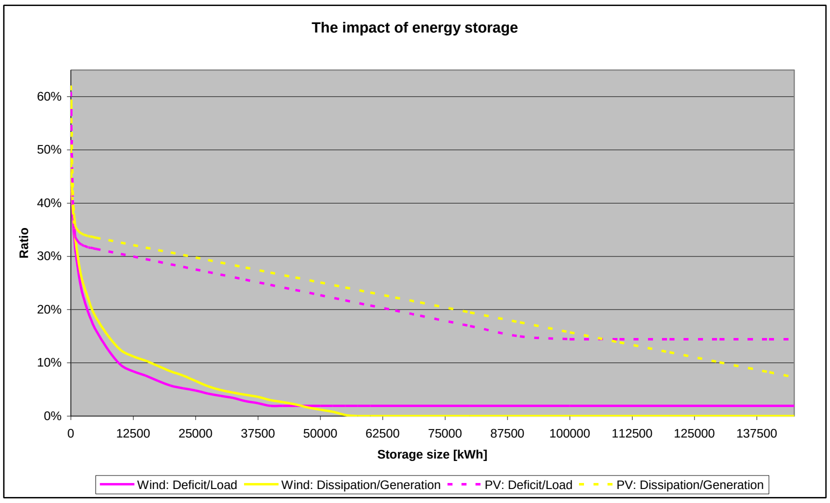


Figure 53. Comparison of the impact of energy storage for wind and PV.

Assessment from a profitability perspective

Moreover, the gains obtainable trough energy storage are clearly different for a wind power system and a photovoltaic plant. Figure 54 shows the net gains, in relationship to the storage size, for both systems. As indicated in the figure, the potential profits of storage are almost three times greater in the PV system (red curve) than in the wind system (violet curve).

Interesting is, however, that the initial gains (storage capacities up to 90 kWh) are larger for the wind system. For capacities exceeding this value, the worth of energy storage increases fast in the PV system, whereas it soon starts to decline in the wind system.

Final conclusions

Hence, it can be concluded that for the given conditions energy storage is considerably more profitable in combination with a PV plant than together with a wind power system. Also from an energy point of view, the PV system benefits significantly more from storage within the economical range: the economically optimal storage (475 kWh) reduces the deficit and dissipation ratios with 22.7 % and 22.0 %, respectively. Correspondingly, the most profitable storage (175 kWh) for the wind system is only capable of reducing the ratios with 8.5 % and 8.3 %.

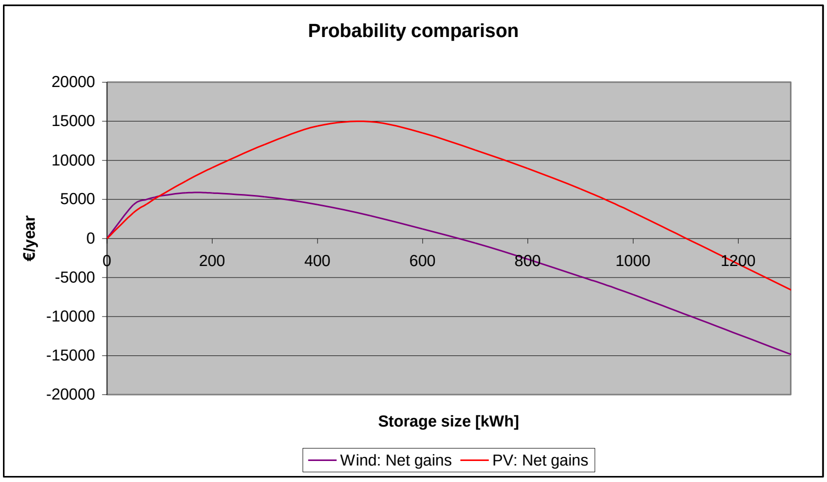


Figure 54. Profitability of energy storage for wind and PV.

On the other hand, when only considering the situation from an energy perspective, the contribution of large-scale storage is greater in the wind system. In order to achieve a reduction of the deficit by 30 %, a capacity of 3200 kWh is sufficient for the wind system, whereas the PV plant would require storage of 7700 kWh. This difference grows even more when larger deficit reductions are examined. To obtain a decrease of 40 %, the storage for the wind system would have to be 9300 kWh, while the PV system would necessitate 59.4 MWh.

Finally, depending on the conditions (electricity price, storage costs, lifetime of the storage etc.), the optimal size of the storage changes, and the obtained gains will alter in accordance with Figure 52.

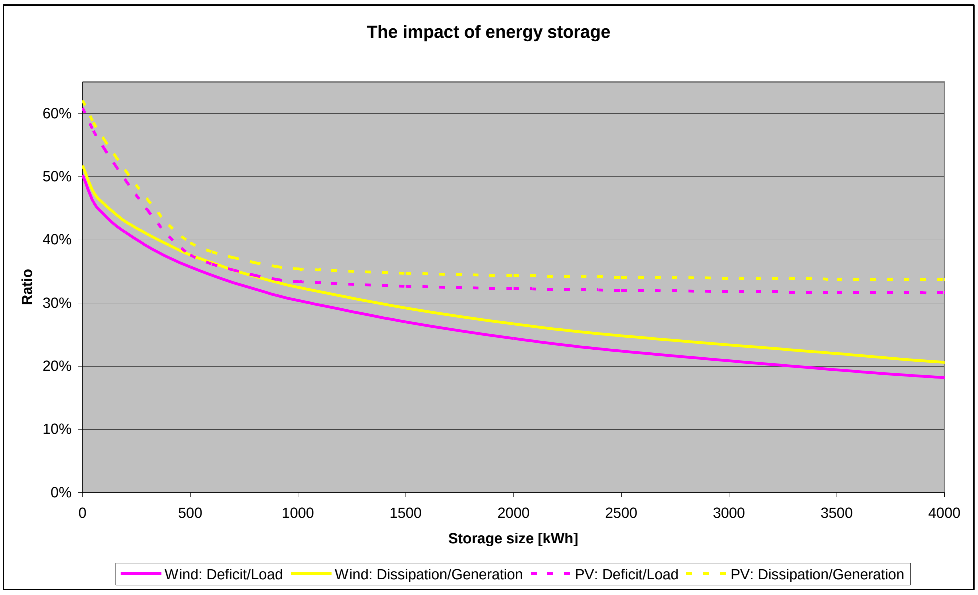


Figure 55. Comparison of the impact of small-scale energy storage for wind and PV.

9. DISCUSSION AND FUTURE TRENDS

In accordance with the second law of thermodynamics, a process in an isolated system can only occur if it increases the total entropy of the system. Hence, the employment of energy storage systems will inevitably result in energy losses to some extent. However, even without truly lossless technology, if carefully chosen, energy storage is clearly able to provide considerable support for the renewable energy generation.

According to Ter-Gazarian (1994: 8), the intricate issue of combining generation with suitable storage is to be approached from two perspectives: through a consideration of the power system requirements for energy storage, and through an analysis of the technical and economical parameters of the storage equipment.

A definite universal comparison is, however, impossible due to the number of factors. Not only all the parameters of the storage technology have to be taken into consideration, but also the requirements of the specific generating unit and the load. Every technology has its own field of applications for which it is suitable. Moreover, such a comparison is further complicated by the fact that the development, technically as well as economically, of the emerging technologies progresses rapidly. Thus, no “ideal technology” exists and the selection of the optimal storage method always remains case-specific.

However, Figure 56, which shows the relationship between energy capacity and power output, provides the possibility to compare which of the common technologies are more likely to be suitable for a certain range of applications. The area of the shapes represents the typical range of appropriateness for the technologies. Additionally, the lines highlight the range of the main fields of applications and the possible storage times.

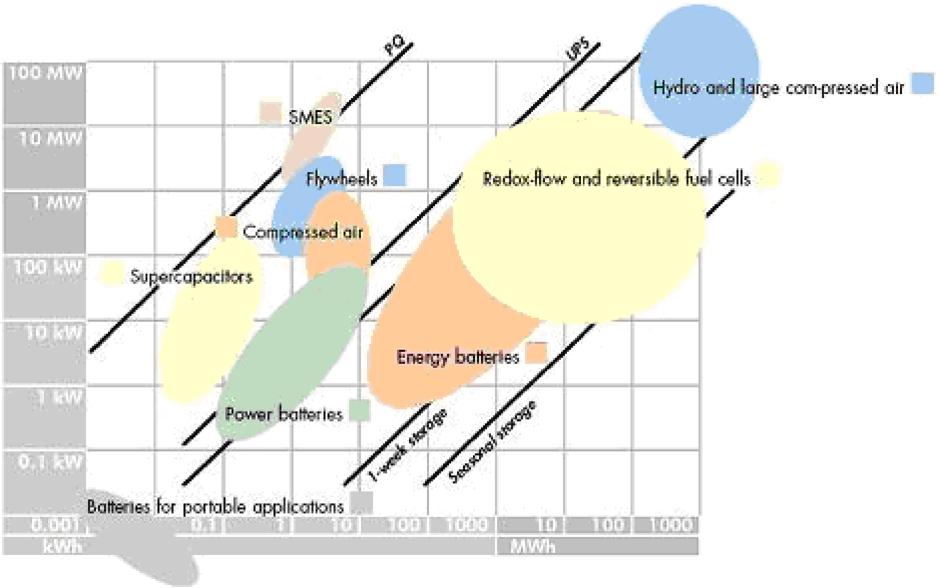


Figure 56. Energy capacity and power output of the storage technologies (EC 2001: 5).

From an economic point of view, the considerations are likewise complex. Figure 57 (left) provides a useful insight in the capital costs of the different storage technologies, related to the power output as well as to the energy capacity. However, it should still only serve as a guideline since the impact of lifetime, and operation and maintenance costs is substantial. Hence, e.g. the lead-acid battery is in reality not a profitable choice at all for applications which require long lifetime.

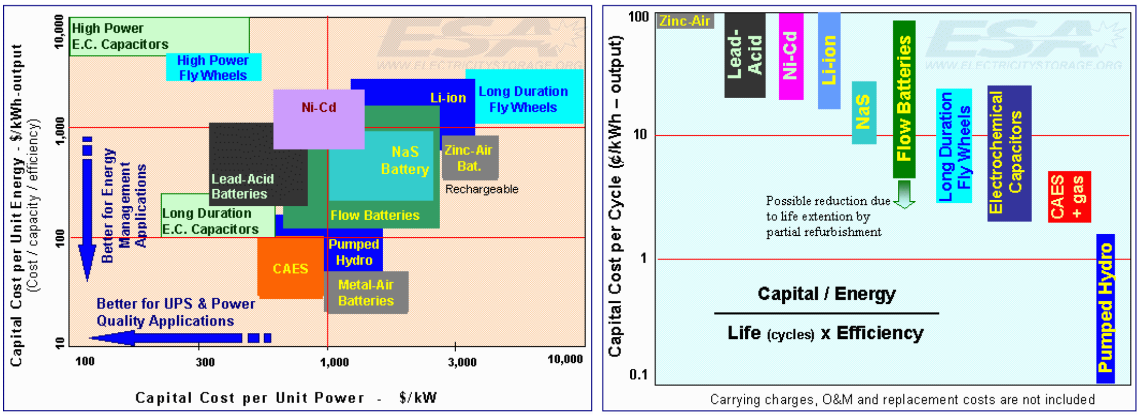


Figure 57. Capital and per-cycle costs of the storage technologies (ESA 2008).

On the right, the costs per-cycle are plotted. When considering applications for which frequent charging and discharging is characteristic, this perspective is valuable. Still, the previously mentioned factors are necessary for a realistic evaluation.

Despite the numerous benefits of storage, with the exception of pumped hydro storage, the exploitation of utility scale energy storage is still in its infancy. From a technical point of view, many of the technologies are already applicable, but have due to unprofitability not been utilized. However, energy storage for portable applications has been successfully implemented for decades. Hence, what specifically has to be addressed, are the unique needs of renewable energy systems. Rather than specific power, specific energy and rate of recharge, the key factors are here costs, lifetime, efficiency, and for mid- and long-term storage self-discharge.

Another reason for the so far limited use of energy storage is that the systems have to compete against peaking power plants, which represent well established technology. However, rising fuel prices and growing concern regarding emissions will inevitably restrict their further use.

Moreover, intermittent renewable energy is often perceived as not being an adequate option to conventional generation in utility scale systems. This view mostly owes to an underestimation of the potential of large-scale storage systems (Cavallo 2001: 389). Hence, further demonstration projects and site surveys would be expedient for enlightening and promotion purposes. Moreover, governmental measures ought to be taken, e.g. in the form of beneficial legislation in a similar way as for renewable energy generation.

Still, the research and development in the field is clearly accelerating. Massive studies are undertaken even on government and international level. Examples are the Energy Storage Systems Research Program of the U.S. Department of Energy and the Framework Programme 5 of the European Commission.

Regarding standards for energy storage technologies, with the exception of secondary batteries, the process is still in its infancy. However, The IEEE Standards Association –

Stationary Batteries Committee has scheduled a standard covering all technologies for December 2009: *PAR1679 — Recommended Practice for the Characterization and Evaluation of Emerging Energy Storage Technologies in Stationary Applications*. The document will provide an objective evaluation of the potential of all the emerging energy storage technologies for explicitly stationary applications, including both standby and cycling operation. (Cotton 2006; IEEE-SA Standards Board 2006.)

Continuous development parallel with declining costs constantly increases the market penetration. The so-called new energy storage technologies (flywheels, SMES and supercapacitors) continually grow in importance. The share in the European market is expected to rise from €90.5 million in 2002 to €187 million in 2009. Holding a share of approximately 95 %, flywheel technology is dominating the group. (Ruddell 2003: 5.)

The lead-acid battery will, however, remain dominant in the near future and its market is even predicted to grow. For large-scale applications, pumped hydro storage is likewise going to remain in a key position, even though the alternative technologies will enter the market. Primarily, these two options are preferred due to their cost-efficiency: lead-acid batteries have very favorable investment costs, whereas pumped hydro storage offers extremely low per cycle costs. Moreover, they are the most well-known, reliable and safe choices.

As the importance of the renewable energy sources steadily grows, the prospects of the closely related energy storage market are also bright. The Energy Storage Council even considers storage to be a potential “sixth dimension”, as illustrated in Figure 58, in addition to the conventional electricity value chain with an energy source, generation, transmission, distribution, and customer energy services. The interaction of the bulk storage with the other levels of the chain is moreover considered to be one of the most promising new areas of the whole electricity industry.

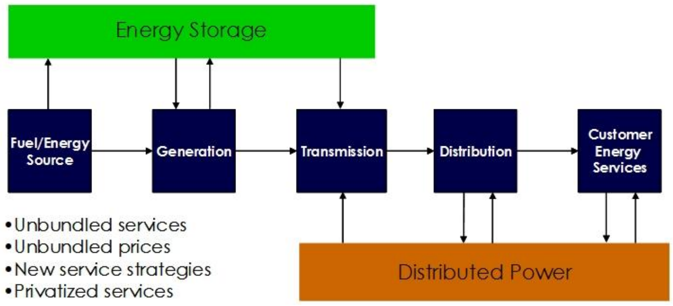


Figure 58. New electricity value chain with energy storage as the “sixth dimension” (ESC 2007).

10. SUMMARY

The purpose of this thesis was to investigate the different possibilities of energy storage for renewable energy generation. The dominating storage technologies are currently lead-acid batteries for small-scale applications and pumped hydro storage for bulk storage. Through a comparison of the characteristics, present use, costs and state-of-the-art situation of emerging storage technologies, the possibilities of finding near-future superior successors have been assessed. In parallel, their suitabilities for renewable energy generation and the directions of development were analyzed. The study is primarily based on comprehensively examining and reviewing application specific literature and applying it to the field of renewable energy generation.

Because of the intermittent nature of the commonly utilized renewable energy sources, energy storage is of central importance. Basically, short-term storage is used for frequency and voltage regulation, as well as for providing ride through during momentary power outages. During longer periods, storage offers sophisticated energy management in the form of load leveling and as rapid reserve.

When considering storage in the lower power range, up to a size of approximately 10 kW, secondary batteries and primarily lead-acid batteries, whose popularity foremost derives from inexpensive capital costs, are employed. Secondary batteries in general are capable of addressing all application areas. However, the price for this flexibility is consistently mediocre performance. Until now, the primary alternative has been the nickel-cadmium battery, which, however, is expected to decrease in importance due to environmental restrictions. Lithium batteries are considerably further developed and held as the most likely near-future successor, but extensive employment is still limited by the higher expenses. For extremely short durations, supercapacitors form an attractive alternative, but further cost decreases are necessary. In the future, fuel cells will be an important option, but are currently not economically feasible.

All the above mentioned technologies are also applicable for a mid-power range, 10 kW to 100 MW. Additionally, flow batteries, SMES and flywheels constitute potential alternatives. Flow batteries are mainly interesting due to decoupled power and energy ratings, which makes them highly versatile. Owing to recent commercialization progress, SMES holds great future potential for high power applications. Flywheels are suitable for energy as well as power applications and grow fast in popularity, but are still the most expensive alternative for short-term storage.

In the upper power range, above 100 MW, there are only three systems which can be considered: CAES, pumped hydro storage and technologies based on sensible heat storage. CAES is an economically competitive alternative to the dominating pumped hydro storage. Especially the pollution-free, adiabatic modification is likely to increase in importance due to its flexible siting. This attractive quality is also one of the key characteristics of the thermal storage, which still is in an early phase of development.

Table 13 provides an overview of the most important advantages and disadvantages of the considered technologies for energy storage. In addition, an outline of the primary application field – high power or high energy – is given for each technology. This recommendation is based on the general characteristics of each storage concept and hence not representative for every available product. The division is made into entirely capable (green), plausible (chequers), feasible but not practical or economical (yellow) and finally not feasible or economical.

Common for almost all of the energy storage technologies is that the concepts are old and well-known, but yet they have not been taken extensively into use for large-scale applications. Although the investments in energy storage are increasing considerably, it has still remained a niche solution on this level, with the exception of lead-acid batteries and pumped hydro storage. However, this is about to change due to the growing importance of renewable energy generation.

Table 14. Summary of the considered energy storage technologies.

	Advantages	Disadvantages	Power	Energy
Lead-acid	Capital cost, reliability, self-discharge	Cycle life, specific energy, degradation, toxicity	🟩	🟨
Nickel	Cycle life, low temp.performance	Cost, self-discharge, toxicity (NiCd)	🟩	▨
Lithium	Specific energy & power, efficiency	Cost, charging circuitry	🟩	🟨
Sodium-sulfur	Self-discharge, cycle life, energy density	Cost, safety	🟩	🟩
Metal-air	Specific energy, cost	Cycle life, efficiency, specific power	🟩	🟨
Fuel cells	Specific energy & power, variety	Cost, complexity, safety	▨	▨
Flow batteries	Independent power & energy ratings, lifetime, self-discharge	Specific energy	▨	🟩
Supercapacitors	Specific power, cycle life, efficiency	Cost, self-discharge, specific energy	🟩	▨
SMES	Specific power, cycle life, efficiency	Cost, complexity, safety	🟩	⬜
Flywheels	Specific power, cycle life	Cost, self-discharge	🟩	🟨
CAES	High capacity, €/kWh-cost	Fossil fuel combustion, capital cost, site dependence	⬜	🟩
AA-CAES	Environmentally benign, efficiency	Cost, complexity	⬜	🟩
CAS	Environmentally benign	Efficiency, cost	🟨	🟩
PHS	High capacity, €/kWh-cost	Capital cost, site dependence	⬜	🟩
TES	High capacity, efficiency, flexible siting	Complexity	🟨	🟩

🟩	Entirely capable
▨	Plausible
🟨	Feasible, but not practical/economical
⬜	Not feasible/economical

An excellent energy storage system should have long lifetime, negligible self-discharge, high efficiency, a rapid response time, high power and energy densities, and a low level of maintenance. Furthermore, the investment costs and the expenses over life must be reasonable, and the system should not be restricted by geographical factors. Moreover, the system ought to be environmentally benign, and possible recycling must be efficient. A technology meeting all these criterions does not exist and will not be available in the foreseeable future.

Nevertheless, energy storage is clearly able to provide considerable support for the renewable energy generation. Careful case-specific analyses are, however, necessary in order to find the most suitable system.

In order to assess the concrete benefits of energy storage for renewable generation, two fictive scenarios, featuring a wind turbine and a photovoltaic based system, respectively, were devised. Both were stand-alone systems modeled with data from a weather station located in Burgenland, Austria, and were completed with a typical Austrian load profile.

Both scenarios featured a positive energy balance and the generation was completed with energy storage. Due to the intermittent nature of the renewable energy sources, the generation and the load are not in balance. Due to this power imbalance, the deficit, as well as the dissipation, was in the range of 50─60 % for the systems without storage. The energy storage systems which were proved profitable maximally had capacities of 650─1100 kWh, which still entails deficits and dissipation ratios of approximately 35 %.

Thus, it can be concluded that storage can play an important role in increasing the efficiency of such island systems, but complete independency solely through storage is not economically possible at current assumptions. In a scenario where the generation, on a yearly basis, is clearly overdimensioned in relation to the load, the contribution of storage would be of greater importance. Furthermore, as part of a solution, either together with demand side management or additional back-up generation, storage remains an attractive option.

Hence, it can be concluded that storage can offer considerable benefits for such systems, but rather in the form of financial gains than as a single solution for backup power. For the given conditions, the profitability of storage proved to be considerably greater in combination with a PV plant, than together with a wind power system. On the other hand, when only considering the situation from an energy perspective, the contribution of large-scale storage is greater in the wind system. Moreover, if the energy which cannot be delivered would have to be compensated, the gains would be even greater.

A final word: successfully integrating energy storage and renewable energy generation on a utility scale will enable the intermittent power to be dispatched in a similar way to conventional power plants. Thus, renewables could create a credible alternative to fossil fuel and nuclear generation to a larger extent than previously possible.

LIST OF REFERENCES

ABB (2001). *ABB-led Group to build World's largest Battery Storage System*. [online]. ABB [cited 2008-04-08]. Available from Internet: <URL:http://www.abb.com/cawp/seitp202/c1256c290031524bc1256af40027567c.aspx>.

ABB (2004). *ABB Constructs World's Largest Battery Energy Storage System in Fairbanks, Alaska* [online]. ABB [cited 2008-04-07]. Available from Internet: <URL:http://search.abb.com/library/Download.aspx?DocumentID=9AKK101130D0196&LanguageCode=en&DocumentPartID=&Action=Launch&IncludeExternalPublicLimited=True>.

ABB. *BESS, World's Largest Battery Energy Storage System, Fairbanks, Alaska, USA* [online]. ABB [cited 2008-04-10]. Available from Internet: <URL:http://library.abb.com/GLOBAL/SCOT/scot232.nsf/VerityDisplay/FAF8B33A47F7EF21C1256D94002A24A7/$File/PRS%20BESS%20GVEA_rev1.pdf>.

Alanen, Raili, Tiina Koljonen, Sirpa Hukari & Pekka Saari (2003). *Energian varastoinnin nykytila* (In Finnish). Espoo, Finland: VTT. ISBN 951-38-6160-0.

Austrian Wind Power (2007). *Austrian Wind Power — Windkraft Burgenland* [online]. [cited 2008-06-06]. Available from Internet: <URL:http://www.austrian-wind-power.at>.

Bauer, S.J. & M. Lee (2004). *CAES Monitoring to Support RMRCT* [online]. Sandia National Laboratories [cited 2008-05-06]. Available from Internet: <URL:http://www.netl.doe.gov/technologies/oil-gas/publications/Storage/Final_41296.pdf>.

Baxter, Richard (2002). Energy storage - enabling a future for renewables? *Renewable Energy World Review Issue* 5:4, 108–117.

Bito, Akihiro (2005). Overview of the sodium-sulfur battery for the IEEE Stationary Battery Committee. *Power Engineering Society General Meeting, 2005. IEEE* 2, 1232—1235. San Francisco, USA.

Bitterly, Jack G. (1998). Flywheel technology: past, present and 21st century projections. *IEEE Aerospace and Electronic Systems Magazine* 13:8, 13—16.

Blomgren, George E. (2000). Current status of lithium ion and lithium ion polymer secondary batteries. *Battery Conference on Applications and Advances, 2000. The Fifteenth Annual*, 97–100. Long Beach, USA.

Boulanger, Pascal & Marion Perrin (2003). *WP ST 5 – Electrolyser, Hydrogen Storage and Fuel Cell* [online]. Investire-Network [cited 2008-04-21]. Available from Internet: <URL:http://www.itpower.co.uk/investire/pdfs/fuelcellrep.pdf>.

Boyes, John D. & Nancy Clark (2000). *Flywheel Energy Storage and Super Conducting Magnetic Energy Storage Systems* [online]. Sandia National Laboratories [cited 2008-04-02]. Available from Internet: <URL:http://www.electricitystorage.org/pubs/2000/summer2000/SMES-FES.pdf>.

Bradshaw, Dale T. (2000). Pumped hydroelectric storage (PHS) and compressed air energy storage (CAES). *IEEE Power Engineering Society Summer Meeting, 2000* 3, 1551—1573. Seattle, Washington.

Brauner, Günther (2004). *Energieversorgung* (In German). Vienna, Austria: Technische Universität Wien. Lecture notes.

Brauner, Günther (2008). Heutige und zukünftige Aufgaben der Speicher-Wasserkraft (In German). In: *Speicher und Pumpspeicherkraftwerke – Energiewirtschaftliche und Umwelt relevante Bedeutung*. Vienna, Austria: Technische Universität Wien.

Bullough, Chris, Christoph Gatzen, Christoph Jakiel, Martin Koller, Andreas Nowi & Stefan Zunft (2004). Advanced adiabatic compressed air energy storage for the integration of wind energy. *Proceedings of the European Wind Energy Conference (EWEC 2004)*. London, United Kingdom.

Butler, Paul, Jennifer L. Miller & Paula A. Taylor (2002). *Energy Storage Opportunities Analysis Phase II Final Report – A Study for the DOE Energy Storage Systems Program* [online]. Washington D.C.: Sandia National Laboratories [cited 2008-03-17]. Available from Internet: <URL:http://www.prod.sandia.gov/cgi-bin/techlib/access-control.pl/2002/021314.pdf>.

Cavallo, Alfred J. (2001). Energy Storage Technologies for Utility Scale Intermittent Renewable Energy Systems. *Journal of Solar Energy Engineering* 123, 387–389.

Cheung, Kenny Y.C., Simon T.H. Cheung, R.G. Navin De Silva, Matti P.T. Juvonen, Roopinder Singh & Jonathan Woo (2003). *Large-Scale Energy Storage Systems* [online]. London, UK: Imperial College London [cited 2008-05-06]. Available from Internet: <URL:http://q-m.org/academic/ise2grp/energystorage_report/ storage.pdf >.

Cobasys (2007). *NiGen Renewable Battery Systems* [online]. Orion, USA.: Cobasys [cited 2008-04-11]. Available from Internet: <URL:http://www.cobasys.com/ pdf/stationary/NiGen%20Renewable%20Spec%20Sheet.pdf>.

Cobasys. *Considerations for the Utilization of NiMH Battery Technology in Stationary Applications* [online]. Orion, USA: Cobasys [cited 2008-04-11]. Available from Internet: <URL:http://www.cobasys.com/pdf/presentations/Considerations_for_NiMH_in_Stationary_Apps_TechPaperFormat.pdf>.

CORDIS (Community Research and Development Information Service). 73. Advanced adiabatic compressed air energy storage (AA-CAES). *FP5 Project Record* [online]. European Commission [cited 2008-05-15]. Available from Internet: <URL:http://cordis.europa.eu/data/PROJ_FP5/ACTIONeqDndSESSIONeq112362005919ndDOCeq73ndTBLeqEN_PROJ.htm>.

Cotton, Bart (2006). *The IEEE Standards Association Stationary Batteries Committee* [online]. [cited 2008-05-20]. Available from Internet: <URL:http://www.infobatt.com/zip/06/8%20Cotton_IEEE_Standards_Association_Battery_Committe.pdf>.

Crotogino, Fritz (2003). Einsatz von Druckluftspeicher-Gasturbinen-Kraftwerken beim Ausgleich fluktuierender Windenergie-Produktion mit aktuellem Strombedarf (In German). In: *Fortschrittliche Energiewandlung und –anwendung*.

Cyphelly, Ivan (2002). *WP ST8-Pneumatic Storage* [online]. Investire-Network [cited 2008-04-29]. Available from Internet: <URL:http://www.itpower.co.uk/investire/pdfs/compairrep.pdf>.

Dahlen, Magnus (2003). *Nickel Batteries* [online]. Investire-Network [cited 2008-04-04]. Available from Internet: <URL:http://www.itpower.co.uk/investire/pdfs/ nickelbattrep.pdf>.

De Boer, Petra & Jillis Raadschelders (2007). Flow Batteries. *EPQU Magazine* 3:1 [online] [cited 2008-03-10], 1–9. Available from Internet: <URL:http://www.leonardo-energy.org/drupal/disknode/get/783/Briefing%2520paper%2520-%2520Flow%2520batteries.pdf?download>.

De Doncker, Rik W., Christoph Meyer, Robert U. Lenke & Florian Mura (2007). Power electronics for future utility applications. *7th International Conference on Power Electronics and Drive Systems, 2007. PEDS '07*, 1–8. Bangkok, Thailand.

De Vries, Tim, Jim McDowall, Niklaus Umbricht & Gerhard Linhofer (2003). A solution for stability. Power Engineering International [online] [cited 2008-04-08]. Available from Internet: <URL:http://pepei.pennnet.com/display_article/193173/17/ARTCL/none/none/1/A-solution-for-stability/>.

De Vries, Tim, Jim McDowall, Niklaus Umbricht & Gerhard Linhofer (2004). *Cold Storage – Battery Energy Storage for Golden Valley Electric Association* [online]. ABB [cited 2008-04-10]. Available from Internet: <URL:http://library.abb.com/global/scot/scot271.nsf/veritydisplay/627968be8161966fc1256e3f004e0366/$File/38-43%20M848.pdf>.

Dell, R.M. & D.A.J. Rand (2001). Energy storage – A key technology for global energy sustainability. *Journal of Power Sources* 100:1–2, 2–17.

Dell, R.M. & D.A.J. Rand (2004). *Clean Energy*. Cambridge: Royal Society of Chemistry. 323 p. ISBN 0 85404 546 5.

Denholm, Paul (2006). Improving the technical, environmental and social performance of wind energy system using biomass-based energy storage. *Renewable Energy* 31:9 [online] [cited 2008-05-06], 1355—1370. Available from Internet: <URL:http://www.nrel.gov/docs/fy06osti/38270.pdf>.

EC (European Commission) (2001). *Energy Storage – A Key Technology for decentralised power, power quality and clean transport* [online]. Luxembourg: Office for Official Publication of the European Communities [cited 2008-03-03]. Available from Internet: <URL:ftp://ftp.cordis.europa.eu/pub/eesd/docs/db_energy_storage_eur19978.pdf>.

Energie AG Oberösterreich (2000). Lastprofilanalyse — Haushalte ohne Nachtstrom, Messung 1.1.1991—31.12.1991 (~100 Haushalte) (In German).

Englander, Daniel (2007). *The 2008 Greentech Market Taxonomy* [online]. Greentech Media [cited 2008-03-11]. Available from Internet: <URL:http://www.greentechmedia.com/articles/greentech-market-taxonomy-342. html>.

ESA (Electricity Storage Association) (2008). *Technologies & Applications* [online]. [cited 2008-02-22]. Available from Internet: <URL:http://electricitystorage.org/technologies.htm>.

ESC (Energy Storage Council) (2007). *Sixth Dimension of the Electricity Value Chain* [online]. [cited 2008-06-30]. Available from Internet: <URL:http://www.energy storagecouncil.org/storage_valuechain.html>.

European Union (2006). *2003/0282 COD – Directive 2006/.../EC of the European Parliament and of the Council of on Batteries and Accumulators and Waste Batteries and Accumulators and repealing Directive 91/157/EWG* [online] [cited 2008-04-25]. Brussels, Belgium. Available from Internet: <URL:http://register.consilium.europa.eu/pdf/en/06/st03/st03615-re02.en06.pdf>.

Gibbard, Frank (1993). Nickel metal hydride battery technology. *WESCON/'93. Conference Record*, 215–219. San Francisco, USA.

IEA (International Energy Agency) (2004). *Evaluation of Energy Storage Devices in Stand-Alone PV Power Systems* [online]. [cited 2008-02-22]. Available from Internet: <URL:http://www.re.e-technik.uni-kassel.de/iea/Publications/Evaluation %20 of%20energy%20storage%20devices.pdf >.

IEEE-SA Standards Board (2006). *New Standards Committee (NesCom) Recommendations* [online]. [cited 2008-05-20]. Available from Internet: <URL:http://standards. ieee.org/board/nes/0609nesrec.rtf>.

IEEE Std 1013 (2007). *IEEE Recommended Practice for Sizing Lead-Acid Batteries for Stand-Alone Photovoltaic (PV) Systems*. ISBN 0-7381-5593-4.

Iwakura, Chiaki, Hiroki Murakami, Shinji Nohara, Naoji Furukawa & Hiroshi Inoue (2005). Charge-discharge characteristics of nickel/zinc battery with polymer hydrogel electrolyte. *Journal of Power Sources* 152, 291–294.

IWEI (Iowa Wind Energy Institute) (2001). *Wind Hybrid Electricity Applications* [online]. [cited 2008-02-22]. Available from Internet: <URL:http://www.iowadnr.com/energy/news/files/hybrid.pdf>.

Jewell, Ward, Phanikrishna Gomatom, Lokendra Bam & Rudra Kharel (2004). *Evaluation of Distributed Electric Energy Storage and Generation* [online]. Wichita State University [cited 2008-05-08]. Available from Internet: <URL:http://www.pserc.org/cgi-pserc/getbig/publicatio/reports/2004report/jewell_der_final_report_2004.pdf>.

Joseph, Arni & Mohammad Shahidehpour (2006). Battery storages systems in electric power systems. *IEEE Power Engineering Society General Meeting 2006*. Montreal, Canada.

Jossen, Andreas & Jürgen Garche. *Lithium Batteries* [online]. Investire-Network [cited 2008-04-03]. Available from Internet: <URL:http://www.itpower.co.uk/investire/pdfs/lithiumrep.pdf>.

Kim, Dong-Won (1999). Electrochemical characterization of polynext term (ethylene-co-methyl acrylate)-based gel polymer electrolytes for lithium-ion polymer batteries. *Journal of Power Sources* 87:1—2, 78—83.

Kondoh, J., I. Ishii, H. Yamaguchi, A. Murata, K. Otani, K. Sakuta, N. Higuchi, S. Sekine & M. Kamimoto (2000). Electrical energy storage systems for energy networks. *Energy Conversion and Management* 41:17, 1863–1874.

Kötz R. & M. Carlen (2000). Principles and applications of electrochemical capacitors. *Electrochimica Acta* 45:15─16, 2483─2498.

Lailler, Patrick (2003). *WP ST1 – Lead Acid Systems Storage Technology Report* [online]. Investire-Network [cited 2008-04-03]. Available from Internet: <URL:http://www.itpower.co.uk/investire/pdfs/leadacidrep.pdf>.

Laine, Jerri (2007). *Global Markets for Wärtsilä Fuel Cells* [online]. Wärtsilä [cited 2008-06-02]. Available from Internet: <URL:http://akseli.tekes.fi/opencms/opencms/OhjelmaPortaali/ohjelmat/DENSY/fi/Dokumenttiarkisto/Viestinta_ja_aktivointi/Loppuseminaari/web/Laine.pdf>.

Ledran, Josette (1993). New electrochemical couples to meet the requirement for mobile terminal miniaturization. *Telecommunications Energy Conference, 1993. INTELEC '93. 15th* 1, 71–78..

Lee, Sang-Seung, Young-Min Kim, Jong-Keun Park, Seung-Il Moon & Yong-Tae Yoon (2007). Compressed air energy storage units for power generation and DSM in Korea. *IEEE Power Engineering Society General Meeting, 2007*, 1─6. Tampa, USA.

Levine, Jonah, Gregory Martin & Richard Moutoux (2007). *Large Scale Electrical Energy Storage in Colorado* [online]. CERI [cited 2008-05-20]. Available from Internet: <URL:http://www.ceri-mines.org/documents/LargeScaleElectricalEnergyStorageinColorado-BarnesgroupCU_000.pdf>.

Li, Ling-Feng, Fuyuan Ma, Boris Kukovitskiy & Sadeg M. Faris (2007). Polyelectrolyte membranes as separator for battery and fuel cell applications. In: *United States Patent*. Patent No. 20070020501.

Luongo, César A. (1996). Superconducting energy storage systems: an overview. *IEEE Transactions on Magnetics* 32:4, 2214—2223.

Martin, Gregory (2001). *Aquifer Underground Pumped Hydroelectric Energy Storage* [online]. Madison, USA: University of Wisconsin-Madison [cited 2008-05-27]. Available from Internet: <URL:http://www.colorado.edu/engineering/ energystorage/files/GDM_thesis_final.pdf>.

Martynyuk, Valeriy (2007). Supercapacitor data acquisition systems. *4th IEEE Workshop on Intelligent Data Acquisition and Advanced Computing Systems: Technology and Applications 2007. IDAACS 2007*, 24—28. Dortmund, Germany.

McDowall, Jim (2003). Memory effect in stationary Ni-Cd batteries? Forget about it! In: *The Battcon 2003 Proceedings*, 22/1–22/8. Marco Island, USA.

McKeogh, E.J. (2003). *Electricity Storage Options* [online]. University College Cork [cited 2008-04-02]. Available from Internet: <URL:http://www.eurec.be/ component/option,com_docman/task,doc_download/gid,344/>.

Meyer, Franz (2007). *Projektinfo 05/07 — Compressed air energy storage power plants* [online] Eggenstein-Leopoldshafen, Germany: FIZ Karlsruhe [cited 2008-05-16]. Available from Internet: <URL:http://www.bine.info/pdf/publikation/projekt0507englinternetx.pdf>.

Mikkonen, R (2002). Highlights of SC power applications in Europe. *IEEE Transactions on Applied Superconductivity* 12:1, 782—787.

MPower (2006). *Comparisons* [online]. [cited 2008-04-18]. Available from Internet: <URL:http://www.mpoweruk.com/contacts.htm>.

Nichols, D.K. & Steve Eckroad (2003). Utility-scale application of sodium sulfur battery. In: *The Battcon 2003 Proceedings*, 10/1–10/9. Marco Island, USA.

Nitta, Iwao (2008). *Inhomogeneous Compression of PEMFC Gas Diffusion Layers* [online]. Espoo, Finland: Helsinki University of Technology [cited 2008-04-22]. Available from Internet: <URL:http://lib.tkk.fi/Diss/2008/isbn9789512292332/isbn9789512292332.pdf>. ISBN 978-951-22-9233-2.

Nørgaard, Per & Hannele Holttinen (2004). A multi-turbine power curve approach. *Nordic Wind Power Conference* [online] [cited 2008-06-10]. Gothenburg, Sweden: Chalmers University of Technology.

Paish, Oliver (2002). Small hydro power: technology and current status. *Renewable and Sustainable Energy Reviews* 6:6, 537—556.

Parker, Carl D. (2001). Lead-acid battery energy-storage systems for electricity supply networks. *Journal of Power Sources* 100:1–2, 18–28.

Parker, C.D. & J. Garche (2004). Battery energy-storage systems for power-supply networks. In: *Valve-Regulated Lead-Acid Batteries*, 295–326. Ed. D.A.J. Rand, P.T. Moseley, J.Garche & C.D. Parker. Saunders Ltd. ISBN 0 44450 746 9.

PhenoScience. *Flow Battery* [online]. [cited 2008-03-11]. Available from Internet: <URL:http://www.phenoscience.com/climate_change/Flow_Battery.html>.

Piller. *Drehmassenspeicher Powerbridge — Aufbau und Technische Daten* (In German). RWE Solutions.

Price, Anthony (2000). Technologies for energy storage – present and future: flow batteries. *IEEE Power Engineering Society Summer Meeting 2000* 3, 1541–1545.

REN21 (Renewable Energy Policy Network for the 21st Century) (2007). *Renewables 2007 ─ Global Status Report* [online]. [cited 2008-05-09]. Available from Internet: <URL:http://www.ren21.net/pdf/RE2007_Global_Status_Report.pdf>.

Rose, M.F., S.A. Merryman & C.R. Johnson (1991). Comparative analysis of energy storage media and techniques. *IEEE Aerospace and Electronic Systems Magazine* 6:12, 26–32.

Ruddell, Alan (2003). *WP ST 6_Flywheel* [online]. Investire-Network [cited 2008-04-28]. Available from Internet: <URL:http://www.itpower.co.uk/investire/pdfs/flywheelrep.pdf>.

Ruer, Jacques (2007). *Thermal Storage of Electricity* [online]. Saint-Quentin-en-Yvelines Cedex, France: Saipem SA [cited 2008-05-27]. Available from Internet: <URL:http://www.ecrin.asso.fr/system/files?file=THESEprocess.pdf>.

Sauer, Dirk Uwe (2007). Optionen zur Speicherung elektrischer Energie in Energieversorgungssystemen mit regenerativer Stromerzeugung (In German). In: *Kooperationsforum PV – Elektrische Energiespeicher im Niederspannungsnetz*. Aachen, Germany.

Schoenung, Susan M. & William V. Hassenzahl (2003). *Long- vs. Short-Term Energy Storage Technologies Analysis ─ A Life Cycle Cost Study* [online]. Albuquerque & Livermore: Sandia National Laboratories [cited 2008-06-02]. Available from Internet: <URL:http://www.prod.sandia.gov/cgi-bin/techlib/access-control.pl/2003/032783.pdf>.

Staffell, I. (2007). *Review of Alkaline Fuel Cell Performance* [online]. Birmingham, England: University of Birmingham [cited 2008-04-22]. Available from Internet: <URL:http://www.fuelcells.bham.ac.uk/documents/Review_of_AFC.pdf>.

Statistik Austria (2008). *Entwicklung der Energieintensität der Haushalte (ohne Traktion)* (In German) [online]. [cited 2008-06-06]. Available from Internet: <URL:http://www.statistik.at/web_de/statistiken/energie_und_umwelt/energie/energieeffizienzindikatoren/031069.html>.

Surmann, Hartmut (1996). Genetic optimization of a fuzzy system for charging batteries. *IEEE Transactions on Industrial Electronics* 43:5 [online] [cited 2008-04-04], 541–548. Available from Internet: <URL:http://ieeexplore.ieee.org/iel1/41/11565/00538611.pdf>.

Tekes (2007). *DENSY – Distributed Energy Systems 2003–07: Technology Programme Report 11/2007 (Final Report)* [online]. Helsinki, Finland: Tekes [cited 2008-04-10]. Available from Internet: <URL:http://www.tekes.fi/julkaisut/DENSY_Final_Report.pdf>.

Ter-Gazarian, Andrei G. (1994). *Energy Storage for Power Systems*. London, United Kingdom: Peter Peregrinus Ltd. 232 p. ISBN 0 86341 264 5.

TVA (Tennessee Valley Authority). *Hydroelectric Power* [online]. [cited 2008-05-08]. Available from Internet: <URL:http://www.tva.gov/power/hydro.htm>.

Vechy, Stephen L. (2006). Advanced electrochemical storage technologies for stationary power applications. In: *The Battcon 2006 Proceedings*, 2/1–2/4. Orlando, USA.

Venere, Emil (2001). *Engineer Brings Costs of Experiment down to Earth* [online]. West Lafayette, USA: Purdue University [cited 2008-05-29]. Available from Internet: <URL:http://news.uns.purdue.edu/html4ever/010607.Revankar.solar.html>.

Vepakomma, Sivakumar V. (2003). *Carron Valley – A Case Study for Community Wind Power* [online]. Glasgow, Scotland: University of Strathclyde [cited 2008-03-14]. Available from Internet: <URL:http://www.esru.strath.ac.uk/Documents/ MSc_2003/vepakomma.pdf>.

Wen, Zhaoyin (2006). Study on energy storage technology of sodium sulfur battery and it's application in power system [sic]. *International Conference on Power System Technology. PowerCon 2006*, 1─4. Chongqing, China.

Whitehead, Adam H. & Marta Schreiber (2007). *A Comparison of Lead-Acid and Redox Flow Batteries* [online]. Eisenstadt, Austria: Funktionswerkstoffe Forschungs- und Entwicklungs GmbH [cited 2008-03-11]. Available from Internet: <URL:http://ecsmeet6.peerx-press.org/ms_files/ecsmeet6/2007/05/15/00000604/00 /604_0_art_0_ji2pz7.pdf>.

Will, Fritz G. (1998). Recent advance in zinc/air batteries. *Battery Conference on Applications and Advances, 1998. The Thirteenth Annual*, 1–6. Long Beach, USA.

Willer, Bernd (2003). *WP ST 3_Supercaps* [online]. Investire-Network [cited 2008-04-23]. Available from Internet: <URL:http://www.itpower.co.uk/investire/pdfs/ capacitorsrep.pdf>.

Worth, Brian, Adolfo Perujo, Kevin Douglas, Noelle Tassin & M. Brüsewitz (2002). *WP-ST 9-Metal/Air* [online]. Investire-Network [cited 2008-04-15]. Available from Internet: <URL:http://www. itpower.co.uk/investire/pdfs/zincrep.pdf>.

Xue, X.D., K.W.E. Cheng & D. Sutanto (2005). Power system applications of superconducting magnetic energy storage systems. *Conference Record of the 2005 Industry Applications Conference, 2005. Fourtieth IAS Annual Meeting.* 2, 1524–1529. Hong Kong.

APPENDICES

APPENDIX 1. Summary of application specific requirements of energy storage (Butler et al. 2002: 14).

Application	Power [MW]	Storage duration [min]	AC voltage [kV]	Floor space (importance)	Portability (importance)	Number/Distribution of duty cycles	Special demands of the operating environment
Rapid reserve	10–100	10–100	10–100	Medium	Low	10/year, random, discharge only	Unremarkable
Area control and frequency responsive reserve	10–100	Charge–discharge cycles of <10	10–100	Low	Low	Random, continous changes charge / discharge cycles clustered in2-hour blocks daily	Unremarkable
Commodity storage	1–100	100–1 000	10–1000	Medium	Negligible	100/year, regular, periodic, weekday block discharge, increased use in shoulder months	Harmonics are more important than in other generation applications
Transmission stability	10–100 [MVA]	0.001–0.1	10–100	Medium	Low	100/year, random, charge and discharge cycles	Unremarkable
Transmission voltage regulation	1–10 [MVAR]	10–100	10–100	Medium	High	100/year, random charge and discharge cycles, more likely on weekdays, seasonal by region – at least 6–7 months	Safety concerns are important
Transmission facility deferral	0.1–1	100	10–100	High	High	100/year, most likely during weekday peaks, charge and discharge	Safety concerns are important
Distribution facility deferral	0.1–1	100	1–10	High	High	100/year, most likely during weekday peaks, charge and discharge	Safety concerns are important
Customer energy management	0.01–10 [MVA]	10–100	0.1–10	High	Varies	100–1 000/year, regular periods	Safety concerns are important
Renewable energy management	0.01–100 [MVA]	0.001–1000	TBD	High	High	100-1000/year, regular periods, discharge only, unpredictable source	Hostile environments including extreme heat and cold, particulates and corrosive atmospheres
Power quality and reliability	0.001–10 [MVAR]	0.001–1	0.1–10	High	Varies	100–1 000/year, irregular periods, charge and discharge	Safety concerns are important

APPENDIX 2. The largest battery storage system in the world (Fairbanks, Alaska)

The largest existing battery storage system is located in Fairbanks, Alaska. The installation was made while a conventional solution with a constantly spinning generator would be too expensive, due to the remote location. Hence, the system that reduces outages by 65 %, yields considerable savings in the cost for providing spinning reserve. (ABB 2001; De Vries, McDowall, Umbricht & Linhofer 2003.)

The construction made by ABB and Saft consists of four battery strings, each containing 344 series connected nickel-cadmium battery modules. An IGCT converter serves as interface between the DC battery voltage and the 60 Hz AC system voltage. The primary function of the storage is to serve as a spinning reserve and, in addition, to provide continuous voltage support. The parameters of the system are given in Table 1. Figure 1 shows the principle diagram of the electric system, whereas Figure 2 provides an overview of the control and protection system. (ABB 2001; ABB 2004; De Vries et al. 2003.)

Table 1. Parameters of the BESS (ABB; ABB 2001; ABB 2004; De Vries 2003).

Installation year	2003
Load capacity	27 MW (40 MW)
Discharge time	15 min (7 min)
Battery modules	344 pieces
Battery cells	13 760 pieces
Transformers	3 x 14.9 MVA
Nominal voltage	138 kV (1.0 pu)
Normal sustained voltage	0.90 pu (min) / 1.1 pu (max)
Normal frequency	60 Hz (+/– 0.1 Hz)
Sustained frequency range	59.0 Hz (min) / 60.5 Hz (max)
Primary supply	187 A
DC link voltage / current	3440–5200 V / 12 000 A
Weight	1 300 000 kg
Area	120 m x 26 m
Temperature range	–51 °C – +32 °C
Price	26 million €
Expected lifetime	20 years

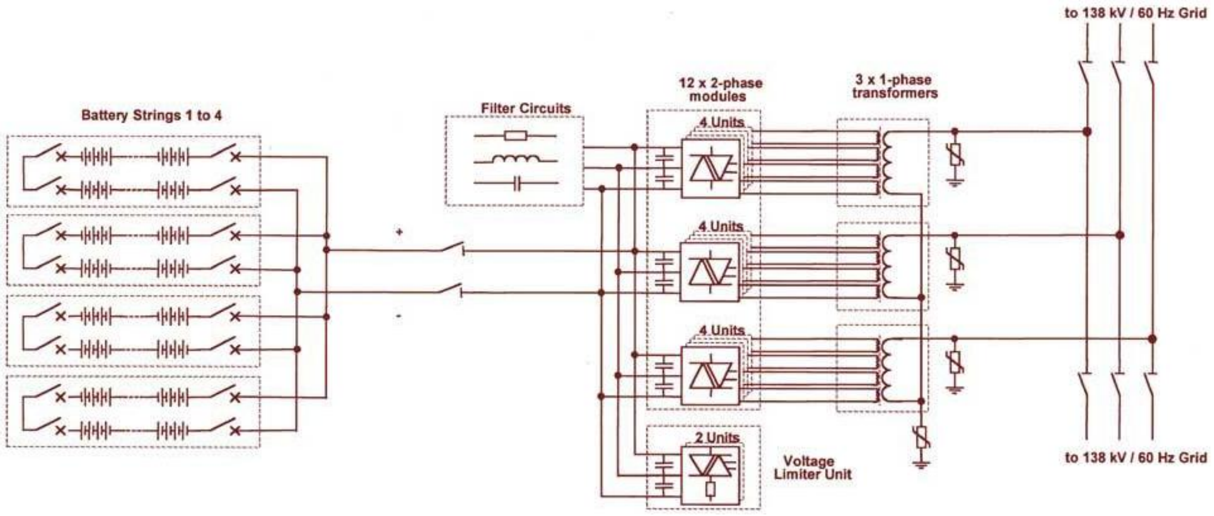


Figure 1. Principle diagram of the BESS electric system (De Vries 2003).

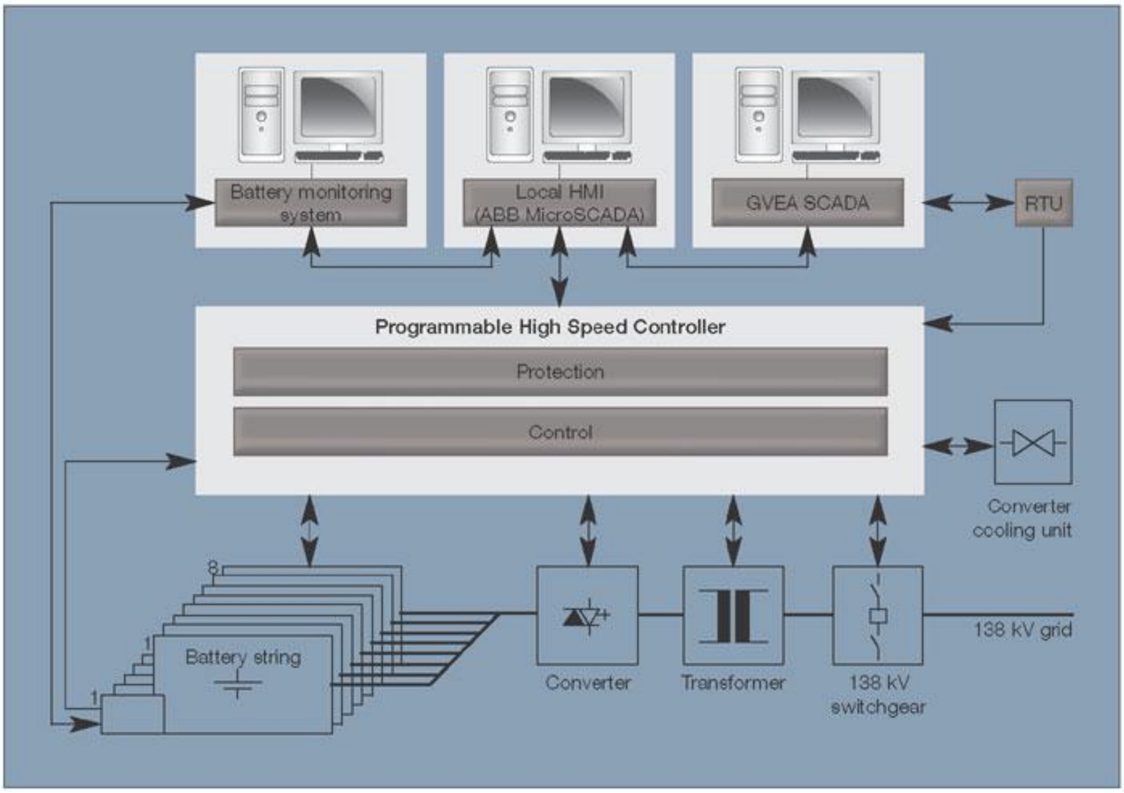


Figure 2. Overview of the BESS control and protection system (De Vries, McDowall, Umbricht & Linhofer 2004: 6).