ENERGY STORAGES

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# Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>CONTENTS</td>
<td>2</td>
</tr>
<tr>
<td>1. ELECTRICITY STORAGE TECHNOLOGIES</td>
<td>3</td>
</tr>
<tr>
<td>1.1. Parameters of an Energy Storage Device</td>
<td>5</td>
</tr>
<tr>
<td>1.2. Load Management</td>
<td>6</td>
</tr>
<tr>
<td>1.3. Life Cycle Costing</td>
<td>6</td>
</tr>
<tr>
<td>2. PUMPED HYDROELECTRIC ENERGY STORAGE (PHES)</td>
<td>7</td>
</tr>
<tr>
<td>2.1. Underground Pumped Hydroelectric Energy Storage (UPHES)</td>
<td>8</td>
</tr>
<tr>
<td>3. COMPRESSED AIR ENERGY STORAGE (CAES)</td>
<td>9</td>
</tr>
<tr>
<td>4. FLYWHEEL ENERGY STORAGE (FES)</td>
<td>12</td>
</tr>
<tr>
<td>5. SUPERCAPACITOR ENERGY STORAGE (SCES)</td>
<td>15</td>
</tr>
<tr>
<td>6. SUPERCONDUCTING MAGNETIC ENERGY STORAGE (SMES)</td>
<td>17</td>
</tr>
<tr>
<td>7. HYDROGEN ENERGY STORAGE (HESS)</td>
<td>19</td>
</tr>
<tr>
<td>8. BATTERY ENERGY STORAGE (BES)</td>
<td>23</td>
</tr>
<tr>
<td>8.1. Lead Acid (LA) Battery</td>
<td>23</td>
</tr>
<tr>
<td>8.2. Nickel Cadmium (NiCd) Battery</td>
<td>24</td>
</tr>
<tr>
<td>8.3. Sodium Sulphur (NAS) Battery</td>
<td>25</td>
</tr>
<tr>
<td>8.4. Flow Battery Energy Storage (FBES)</td>
<td>26</td>
</tr>
<tr>
<td>8.5. Vanadium Redox (VR) Flow Battery</td>
<td>27</td>
</tr>
<tr>
<td>8.6. Polysulphide Bromide (PSB) Flow Battery</td>
<td>28</td>
</tr>
<tr>
<td>8.7. Zinc Bromine (ZnBr) Flow Battery</td>
<td>29</td>
</tr>
<tr>
<td>9. THERMAL ENERGY STORAGE SYSTEM (TESS)</td>
<td>31</td>
</tr>
<tr>
<td>10. CONCENTRATED SOLAR POWER (CSP)</td>
<td>35</td>
</tr>
<tr>
<td>11. COST/LIFE CYCLE CHARACTERISTICS OF STORAGE TECHNOLOGIES</td>
<td>37</td>
</tr>
<tr>
<td>12. FIGURES FROM ELECTRICITY STORAGE ASSOCIATION HOMEPAGE</td>
<td>41</td>
</tr>
<tr>
<td>13. EXAMPLE - DIMENSIONING OF ENERGY STORAGE FOR SMALL SCALE PV-SYSTEM IN ESTONIA</td>
<td>43</td>
</tr>
<tr>
<td>Balance between generation and load</td>
<td>45</td>
</tr>
<tr>
<td>Electricity surplus and shortage</td>
<td>45</td>
</tr>
<tr>
<td>Dimensioning of electricity reserve</td>
<td>46</td>
</tr>
<tr>
<td>14. REFERENCES</td>
<td>49</td>
</tr>
</tbody>
</table>
1. Electricity storage technologies

Flourishing use of electric grid needs permanent online balancing of supply and demand including grid losses. Correctly chosen electricity storage technology, will smooth out this surges and allow electricity to be dispatched at a later time.

The simplest definition of a storage device is one that is specifically designed to accept electrical energy from the grid, convert it into an energy form suitable for storage, subsequently convert it back into electricity and, apart from any losses due to inefficiencies, return it to the grid [1]. Energy storages have wide spectrum of using in the different scope of applications. Mainly, it is caused by their special storage capacities and energy power that can be received from a various range of devices. Figure 1 shows topology of energy storages with classifications by sectors. PHES abbreviation means Pumped Hydroelectric Energy Storage, UPHES - Underground Pumped Hydroelectric Energy Storage, CAES - Compressed Air Energy Storage, TES - thermal energy storage, CHP - Combined Heat and Power and CSP - Concentrated Solar Power energy storages. These storages are not described in this paper due to their specific power rates and installation difficulties for small households. Other abbreviations from figure will be described later. Despite that energy storages have own assorted properties and features, all of them have general base parameters also. The most significant is energy storage capacity - the total of electrical energy that storage can accumulate, official units of measure are megawatt-hours (MWh) or kilowatt-hours (kWh) for small applications. The second significant parameter is power capacity - the highest immediate productivity that an energy storage system can supply, the units of measure are megawatts (MW) or kilowatts (kW). The efficiency parameter should be considered at calculations of a recoupment of system during projecting - shows the sum of electricity on output with difference in the percents from device charge electricity.

Power quality property is ability of energy storage to transfer to demand the energy with good quality without harmonics, spikes or other problems. Round-Trip efficiency parameter same as efficiency property, same indicates in the percents the quantity of electricity which can be recovered from the electricity used to charge and discharge the device. And the last main property is response time which shows the time which goes from request and energy storage power output response.

Back to consumption and supplier relation, there are two main load management features. Load levelling: applying off-peak electricity to charge the energy storage system and after that
permit it to discharge during peak demand (energy storage devices can be charged during off-peak hours and then used to provide electricity when it is the most expensive, during short peak production periods). Therefore, the overall power production requirements become flatter and thus cheaper base load power production can be increased. Another is load following: energy storage device works as a sink when power falls on demand below production level and works as a source when power required is above production levels [2].

Due to the complicated design of some energy storage systems it is important to bear in mind that initial investments in developing and installation usually have higher costs than their alternatives. As a result, on the stage of calculation, the life cycle costing (LCC) analysis could be applied, in which all costs associated with the alternative approaches are defined over a certain time period, usually 10 or 30 years. These costs are discounted to a net present value, so that they can be directly compared.

![Fig. 1 The main groups of energy storage and their abbreviations](image)

Task to make a fair description and comparison among the energy storage technologies, requires grouping them together with based on the size of power and storage capacity that they have. We can theoretically create three groups: energy storage capacities with either medium power 5-100 MWh or medium storage capacities 5-100 MWh; storages with average power 1-50 MW and storage capacities 5-100 MWh; finally storages with large power >50 MW and storage >100 MWh capacities.

Successful operation of electric grid requires continuous real-time balancing of supply and demand including losses. Electricity storage technologies, when properly designed and integrated, can smooth out this variability and allow electricity to be dispatched at a later time.
1.1. Parameters of an Energy Storage Device

- Power Capacity: is the maximum instantaneous output that an energy storage device can provide, usually measured in kilowatts (kW) or megawatts (MW).
- Energy Storage Capacity: is the amount of electrical energy the device can store usually measured in kilowatt-hours (kWh) or megawatt-hours (MWh).
- Efficiency: indicates the quantity of electricity which can be recovered as a percentage of the electricity used to charge the device.
- Response Time: is the length of time it takes the storage device to start releasing power.
- Round-Trip Efficiency: indicates the quantity of electricity which can be recovered as a percentage of the electricity used to charge and discharge the device.
- Power quality: energy storage, when properly engineered and implemented, can provide electricity to the customer without any secondary fluctuation or disruptions and overcome the power quality problems such as swells/sags, spikes, or harmonics.

Energy storage technologies can be classified broadly into three categories: short-term (a few seconds or minutes), long term (minutes or hours) and real long-term (many hours to days). The classification is basically a measure of the amount of MWh that storage system can provide. Both discharge duration (time), and the storage system capacity (MW) can be varied in order to design a suitable energy storage system.

A. Short Term Response Energy storage Technology
Technologies with high power density (MW/m3) and with the ability to respond in short time frame belongs to this category. Short-term response energy storage technologies are usually applied to improve power quality, particularly to maintain the voltage stability during transients (few seconds or minutes).

B. Long-Term Response Energy Storage Technology
Long-term response energy storage technologies for power system applications can usually absorb and supply electrical energy for minutes or hours. They are usually deployed to contribute on the energy management, frequency regulation and grid congestion management.

C. Real Long Term Response Energy Storage Technology
Real Long-term (days, weeks, or months) response energy storage technologies are usually applied to match supply and demand over 24 hours or longer

1.2. Load Management

There are two different aspects to load management:
1. Load levelling: using off-peak power to charge the energy storage device and subsequently allowing it to discharge during peak demand (energy storage devices can be charged during off-peak hours and then used to provide electricity when it is the most expensive, during short peak production periods). As a result, the overall power production requirements becomes flatter and thus cheaper base load power production can be increased.

2. Load following: energy storage device acts as a sink when power required falls below production levels and acts as a source when power required is above production levels.

1.3. Life Cycle Costing

The normal tool for making these cost justifications is a life cycle costing (LCC) analysis, in which all costs associated with the alternative approaches are defined over a certain time period, often 10 or 20 years. These costs are discounted to a net present value, so that they can be directly compared. The LCC approach is important, because energy rage systems often have higher initial costs than their alternatives, and this is the best way to judge whether this represents a sound investment.
2. Pumped Hydroelectric Energy Storage (PHES)

Pumped or conventional hydro-power plant is the most developed and practiced utility storage and/or power control option. Hydroelectric pumped storage is the only method of large scale electrical energy storage in widespread use today. The basic concept is simple. Energy is stored as hydraulic potential energy by pumping water from a low-level into a high-level reservoir. When recovery of the energy is required, the water is returned to the lower reservoir through turbines which drive electrical generators.

The energy used in pumping a volume \( V \) of water through a height \( h \) with a pumping efficiency \( \eta_p \), mass density of water in \( \text{kg m}^{-3} \) and \( g \) acceleration due to gravity in \( \text{m s}^{-2} \)

\[
E_1 = \frac{\rho g h V}{3600 \eta_p} \text{ MW h}
\]

and the energy recoverable with a regeneration efficiency \( \eta_g \) is

\[
E_2 = \frac{\rho g h V \eta_g}{3600} \text{ MW h}
\]

For example, for \( E_2 = 10000 \text{ MWh}, h = 300 \text{ m}, \rho = 1000 \text{ kg m}^{-3} \) and \( \eta_g = 0.87 \), each reservoir would require a storage volume of 14 million \( \text{ m}^3 \) or an area of, say 1 km\(^2\) for a water level variation of 14 m. Typically, the overall efficiency \( E_2/E_1 = \eta_g/\eta_p \) is in the range 70—80%. The possibilities of developing storage systems of this type clearly depend on the availability of sites having suitable physical characteristics. These are often in areas of scenic importance. Massive civil engineering works are required and great care has therefore to be taken over the environmental effects of such schemes [3].

**Applications**

As well as large storage capacities, PHES also has a fast reaction time, hence identifying load levelling as an ideal application. Facilities can have a reaction time as short as 10 minutes or less from complete shutdown (or from full reversal of operation) to full power. In addition, if kept on standby, full power can even be reached within 10 to 30 seconds. Also,
with the recent introduction of variable speed machines, PHES systems can now be used for frequency regulation in both pumping and generation modes (this has always been available in generating mode). This allows PHES units to absorb power in a more cost-effective manner that not only makes the facility more useful, but also improves the efficiency by approximately 3% and the life of the facility. PHES can also be used for peak generation and black starts due to its large power capacity and sufficient discharge time. Finally, PHES provides a load for base-load generating facilities during off-peak production, hence, cycling these units can be avoided which improves their lifetime as well as their efficiency.

**Cost**

Cost ranges from $600/kW to upwards of $2,000/kW, depending on a number of factors such as size, location and connection to the power grid [4].

**Features**

Advantages: Very high energy and power capacity; moderate access time; long life time.
Disadvantages: Special site requirements; adverse impact on environment; moderate efficiency

### 2.1. Underground Pumped Hydroelectric Energy Storage (UPHES)

An UPHES facility has the same operating principle as PHES system: two reservoirs with a large hydraulic head between them. The only major difference between the two designs is the locations of their respective reservoirs. In conventional PHES, suitable geological formations must be identified to build the facility. However, UPHES facilities have been designed with the upper reservoir at ground level and the lower reservoir deep below the earth’s surface. The depth depends on the amount of hydraulic head required for the specific application.
3. Compressed Air Energy Storage (CAES)

This is an established energy storage technology in grid operation since the late 1970s. With this technology, energy is stored mechanically by compressing air. When the air is expanded again, energy is released to the grid. If the heat that develops during compression is conserved, this mechanical process is theoretically 100% efficient. However, in large-scale systems, that is not likely to be the case and combined with the losses occurring during the conversion from electrical to mechanical energy and back, the round-trip efficiency is very low. Other disadvantages include slow response and fewer environmentally acceptable siting opportunities [25].

Air is assumed to perfect gas which specific heat is constant. Use an ideal gas, which relates temperature \(T\), pressure \(P\) and volume \(V\) of gas as shown by \(PV = nRT\), where \(n\) is the number of mole and \(R\) is the gas constant. The work for producing the compressed air as polytrophic process is shown as

\[
W = \frac{\gamma}{\gamma - 1} \cdot P_1 V_1 \left[ \left( \frac{P_2}{P_1} \right)^{\frac{\gamma}{\gamma - 1}} - 1 \right]
\]

where \(P_1, P_2\) and \(V_1, V_2\) are the pressure and volume of the initial state and the final state that are atmospheric state and compressed air state, respectively. However, power is work per unit time and air flow \((Q)\) is volume per unit time \((Q=V/t)\), so the compression power \((Pc)\) is

\[
Pc = \frac{\gamma}{\gamma - 1} \cdot P_1 Q \left[ \left( \frac{P_2}{P_1} \right)^{\frac{\gamma}{\gamma - 1}} - 1 \right]
\]

where \(\gamma\) is the ratio of specific heat, \(\gamma = C_p/C_v\), \(\left( \frac{P_2}{P_1} \right)\) is the compression ratio [5].

Figure below depicts the potential energy stored if 250, 500 or 1000 liters of air is slowly compressed into a pressure container of varying size under isothermal condition. To put this into a context, a fully charged average 12 V lead acid battery of 40 Ah contains 480 Wh of energy [6].
Applications
CAES is the only very large scale storage technique other than PHES. CAES has a fast reaction time with plants usually able to go from 0% to 100% in less than ten minutes, 10% to 100% in approximately four minutes and from 50% to 100% in less than 15 seconds. As a result, it is ideal for acting as a large sink for bulk energy supply and demand and also, it is able to undertake frequent start-ups and shutdowns. CAES use compressed air so they do not suffer from this effect. Also, traditional gas turbines suffer from excessive heat when operating on partial load, while CAES facilities do not. These flexibilities mean that CAES can be used for ancillary services such as frequency regulation, load following, and voltage control. As a result, CAES has become a serious contender in the wind power energy storage market. A number of possibilities are being considered such as integrating a CAES facility with a number of wind farms within the same region. The excess off-peak power from these wind farms could be used to compress air for a CAES facility.

Cost
The cost of CAES facilities are $425/kW to $450/kW. Maintenance is estimated between $3/kWh and $10/kWh. Costs are largely dependent on the reservoir construction [2].
**Features**

Advantages: Very high energy and power capacity; long life time;

Disadvantages: Low efficiency; adverse environmental impact; low efficiency; difficulty of siting [4].
4. Flywheel Energy Storage (FES)

Main
With advances of power electronics technology, high strength/lightweight composite materials, and high performance magnetic bearings, flywheel energy storage systems are being intensively studied recently.

The “Flywheel Energy Storage” or “Flywheel batteries” describes a system, which consist of three parts:
- flywheel,
- motor/generator,
- power electronic system.

The electric energy from the source, store as a kinetic energy of rotation, and delivers it to the load (as electric energy). The machine (working as motor) spins up the flywheel and stores energy mechanically. When the machine works as generator, the electrical energy is delivered to the load. Modern high-speed flywheels differ from their forebears in being lighter and spinning much faster. Today’s system operate somewhere between atmospheric pressure (100 kPa) and 0.1 Pa, with the highest speed devices operating at the lowest pressure. Lower speed flywheels are larger, but can be operated in air with acceptable losses [7][23].

The rotational energy stored in the flywheel is defined as

$$E = \frac{1}{2}I\omega^2$$

Where $I$ is the moment of inertia that is directly proportional to the mass of the rotor by means of a constant that depends on the shape factor. $\omega$ is the angular velocity. For a cylinder
flywheel, the moment of inertia is determined by:

\[ I = \frac{1}{2} \pi \rho h (r_0^4 - r_i^4) \]

Where the outer diameter and inner diameter are represented by \( r_0 \) and \( r_i \), respectively. \( h \) is length and \( \rho \) is mass density.

Thus

\[ E = \frac{1}{4} \pi \rho h \omega^2 (r_0^4 - r_i^4) \]

The energy scales as \( \omega^2 \). The flywheel with a larger angular velocity can store much more energy. But a small and light flywheel is preferable because it can operate at high stress levels [8].

**Applications**

Flywheels have an extremely fast dynamic response, a long life, require little maintenance, and are environmentally friendly. They have a predicted lifetime of approximately 20 years or tens of thousands of cycles. As the storage medium used in flywheels is mechanical, the unit can be discharged repeatedly and fully without any damage to the device. Consequently, flywheels are used for power quality enhancements such as Uninterruptable Power Supply (UPS), capturing waste energy that is very useful in electric vehicle applications and finally, to dampen frequency variation, making FES very useful to smooth the irregular electrical output from wind turbines.

**Cost**

At present, FES systems cost between $200/kWh to $300/kWh for low speed flywheels, and $25,000/kWh for high-speed flywheels. The large cost for high-speed flywheels is typical for a technology in the early stages of development. Battery technology such as the Lead-Acid battery is the main competitor for FES. These have similar characteristics to FES devices, and usually cost 33% less. However, FES have a longer life span, require lower maintenance, have a faster charge/discharge, take up less space and have fewer environmental risks [2].
Features
Advantages: High power capacity; short access time; long life time; low maintenance effort; high efficiency; small environmental impact.
Disadvantages: Low energy density [4]
5. Supercapacitor Energy Storage (SCES)

Main

The double-layer capacitors (ultracapacitors, supercapacitors) are made of carbon, which have huge effective surface so the capacitance could attain several farad even thousands farad. The supercapacitors doesn’t have electrochemical reaction and only have electric charges absorption and desorption when charge and discharge. It has many merits such as high charge/discharge current, less maintenance, long life and some other perfect performance. At the same time its small leakage current enables it has long time of energy storage and the efficiency could exceed 95%.

The maximum amount of energy \( W_{\text{max}} \) that can be stored in a supercapacitive bank of total capacitance \( C_T \) and maximum voltage \( U_{\text{max}} \) is

\[
W_{\text{max}} = \frac{1}{2} C_T U_{\text{max}}^2
\]

Because of the losses in the supercapacitors and the minimum voltage \( U_{\text{min}} \) required by the interface converter, this energy cannot be restored totally. If we consider a discharge ratio \( d \)

\[
d = \frac{U_{\text{min}}}{U_{\text{max}}} \times 100
\]

We can get the value of \( C_T \) as

\[
C_T = \frac{2TP_{\text{max}}}{\eta_d U_{\text{max}}^2 \left[1 - \left(\frac{d}{100}\right)^2\right]}
\]

Where \( P_{\text{max}} \) load power. So a total discharge efficiency \( \eta_d \) and the maximum useful energy is [9]

\[
W_{\text{useful}} = \frac{1}{2} \eta_d C_T U_{\text{max}}^2 \left[1 - \left(\frac{d}{100}\right)^2\right]
\]
Applications
The main attraction of SCES is its fast charge and discharge, combined with its extremely long life of approximately 1 x 10^6 cycles. This makes it a very attractive replacement for a number of small scale (<250 kW) power quality applications. In comparison to batteries, supercapacitors have a longer life, do not suffer from memory effect, show minimal degradation due to deep discharge, do not heat up, and produce no hazardous substances. As a result, although the energy density is smaller, SCES is a very attractive option for some applications such as hybrid cars, cellular phones, and load levelling tasks. SCES is primarily used where pulsed power is needed in the millisecond to second time range, with discharge times up to one minute.

Cost
SCES costs approximately $12,960/kWh to $28,000/kWh. Therefore, large scale applications are not economical using SCES.

Features
Advantages: High efficiency; long life cycle.
Disadvantages: Low energy density; few power system applications [4]
6. Superconducting Magnetic Energy Storage (SMES)

**Main**
A SMES device is made up of a superconducting coil, a power conditioning system, a refrigerator and a vacuum to keep the coil at low temperature.

Energy is stored in the magnetic field created by the flow of direct current in the coil wire. In general, when current is passed through a wire, energy is dissipated as heat due to the resistance of the wire. However, if the wire used is made from a superconducting material such as lead, mercury or vanadium, zero resistance occurs, so energy can be stored with practically no losses. In order to obtain this superconducting state within a material, it must be kept at a very low temperature. There are two types of superconductors; low-temperature superconductors that must be cooled from 0 K to 7.2 K, and high-temperature superconductors that have a temperature range of 10 K to 150 K, but are usually in the 100±10K region. The energy stored within the coil (in Joules), \( E_c \), can be obtained from

\[
E_c = \frac{1}{2} LI^2
\]

where \( L \) is the inductance of the coil, and \( I \) is the current passing through it.
[The energy densities which can be achieved in magnetic fields (e.g. 1-6MJ/m³ for 2T) are an order of magnitude or more greater than those attainable in electric fields [3]. Therefore, material properties are extremely important as temperature, magnetic field, and current density are pivotal factors in the design of SMES. The overall efficiency of SMES is in the region of 90% to 99%. SMES has very fast discharge times, but only for very short periods of time, usually taking less than one minute for a full discharge. Discharging is possible in milliseconds if it is economical to have a PCS that is capable of supporting this. Storage capacities for SMES can be anything up to 2 MW, although its cycling capability is its main attraction. SMES devices can run for thousands of charge/discharge cycles without any degradation to the magnet, giving it a life of 20+ years.

**Applications**

Due to the high power capacity and instantaneous discharge rates of SMES, it is ideal for the industrial power quality market. It protects equipment from rapid momentary voltage sags, and it stabilizes fluctuations within the entire network caused by sudden changes in consumer demand levels, lightening strikes or operation switches. As a result, SMES is a very useful network upgrade solution with some sources claiming that it can improve the capacity of a local network by up to 15%. However, due to high energy consumption of the refrigeration system, SMES is unsuitable for daily cycling applications such as peak reduction, renewable applications, and generation and transmission deferral.

**Cost**

SMES cost approximately $300/kW to $509/kW. It is worth noting that it is difficult to compare the cost of SMES to other storage devices due to its scales and purpose. In practical terms SMES should be compared to other network upgrade solutions where it is often very competitive or even less costly. Finally, the cost of storing electricity within a superconductor is expected to decline by almost 30% which could make SMES an even more attractive option for network improvements [2] [4].

**Features**

Advantages: High power capacity; short access time; long life time; high efficiency
Disadvantages: Low energy density; high production cost; potential adverse health impact
7. Hydrogen Energy Storage (HESS)

**Main**

HESS is the one of the most immature but also one of the most promising energy storage techniques available. As an energy storage system, HESS acts as a bridge between all three major sectors of an energy system: the electricity, heat and transport sectors. It is the only energy storage system that allows this level of interaction between these sectors and hence it is becoming a very attractive option for integrating large quantities of intermittent wind energy [10][11].

There are three stages in HESS:
1. Create hydrogen
2. Store hydrogen
3. Use hydrogen (for required application)
Hydrogen has a very high enthalpy of 120MJ/kg, which is about 3 times that of Gasoline. Therefore, hydrogen is a good candidate as an energy carrier and methods for its storage have been investigated intensively. Five basic methods are proposed in the literature for hydrogen storage: compressed and stored in a pressure tank; cooled to a liquid state and kept cold in an insulated tank; physisorbed in carbon; metal hydrides and complex compounds. Metal hydrides and complex compounds occupy a smaller volume to store the same amount of hydrogen; however, this method is not suitable for this application due to its high ad/absorption temperature. Both liquid hydrogen and compressed gas at high pressure were better candidates for suitable methods for this project, however, liquid hydrogen requires more expensive equipments and very low temperature.

There are various inefficiencies involved with storage and recovery of electrical energy via the use of hydrogen. Energy is consumed to place the hydrogen in storage. This varies with the different energy storage approaches, the efficiency of each method is summarized in Table 1. From this we see that the energy lost to compress the gas is relatively low and therefore yields higher conversion efficiency. Activated carbon also has a high efficiency; however, a very low temperature is required during the process. During the storage period, the hydrogen leakage rate should also be considered because it is part of systems dynamic efficiency. As shown in Table 1, the compressed gas method has a very low leakage rate compared to the other methods. Without considering the operational losses, the main loss in compressed gas is permeation. Fick’s first law for diffusion provides the relationship between the hydrogen flux $J$ and the concentration gradient across the plate (container wall). Sievert’s law states that the concentration $C$ is proportional to the square root of the pressure. Combining these relationships at steady state provides an expression for the rate of permeation of hydrogen by diffusion:

$$ J = D \frac{\Delta C}{t} = DS \sqrt{P} $$

Where $J$ is the permeation rate (mol H2.s-1.m-2), $D$ is the diffusivity of hydrogen in the plate material, and $S$ is the solubility of hydrogen in the plate material (also called Sievert’s parameter), there is a parameter table for $DS$. The following equation can be used to design the cylinder wall thickness $l$. The wall thickness of a cylinder capped with two hemispheres is given by the following equation:
$l = \frac{\Delta p \cdot d}{2 \cdot \sigma_p + \Delta p}$

Where $d$ is the outer diameter of the cylinder, $\Delta p$ is the overpressure, and $\sigma_p$ is the tensile strength of the material.

**TABLE I**

THE ENERGY REQUIRED TO PLACE THE HYDROGEN IN STORAGE VARIES BETWEEN THE VARIOUS ENERGY STORAGE APPROACHES AND THE CORRESPONDING EFFICIENCY.

<table>
<thead>
<tr>
<th>Hydrogen storage approaches</th>
<th>Energy intensity [MJ/kg]</th>
<th>Efficiency</th>
<th>Leakage rate (/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressed gas</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>300 bar</td>
<td>0.915</td>
<td>0.915</td>
<td>0.000024%</td>
</tr>
<tr>
<td>700 bar</td>
<td>0.905</td>
<td>0.905</td>
<td>0.000033%</td>
</tr>
<tr>
<td>Liquid</td>
<td>28-45</td>
<td>0.625-0.77</td>
<td>1% [14]</td>
</tr>
<tr>
<td>Activated carbon (77 K)</td>
<td>8-10</td>
<td>0.917-0.933</td>
<td>0.2% [13]</td>
</tr>
<tr>
<td>Hydrides</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low temperature (&lt;100°C)</td>
<td>0.9-0.933</td>
<td>0.9-0.933</td>
<td>---</td>
</tr>
<tr>
<td>High temperature (&gt;300°C)</td>
<td>0.79-0.83</td>
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</tbody>
</table>

Thus 1kg hydrogen can produce energy about 120 MJ = 33.3 KWh. Also, 1kg hydrogen occupies 44 L at a pressure of 35 MPa. [12][13].
**Application**
The use of hydrogen within the transport and electricity generation industries is expected to grow rapidly as electrolysis, storage techniques, and fuel cells become more commercially available. Car manufacturers are driving research in hydrogen for both the transport and infrastructure divisions. The automotive industry has engaged in setting up a strategy for the introduction of hydrogen to the transport sector with a number of single prototype projects advancing to fleet demonstrations. Hydrogen is a serious contender for future energy storage due to its versatility. Once hydrogen can be produced effectively, it can be used for practically any application required. Consequently, producing hydrogen from renewable resources using electrolysis is currently the most desirable objective available.

**Cost**
The estimated costs to produce power using an electrolyser are extremely varied. Predictions are as low as €300/kW up to €1,100/kW. *ITM Power* in the UK claim to have produced an electrolyser that can operate with renewable sources, at a cost of $164/kW, and are currently planning to begin mass production in 2008. Maintenance costs are expected to be 3% of the capital cost.

All fuel cells cost between €500/kW and €8,000/kW which is very high, but typical of an emerging technology. These costs are expected to reduce as the technology ages and commercialisation matures [1][2].

**Features**
Advantages: Less maintenance, low emissions, and low noise.
Disadvantages: Expensive
8. Battery Energy Storage (BES)
There are three important types of large-scale BES. These are:
1. Lead-Acid (LA)
2. Nickel-Cadmium (NiCd)
3. Sodium-Sulphur (NaS)

These operate in the same way as conventional batteries, except on a large scale i.e. two electrodes are immersed in an electrolyte, which allows a chemical reaction to take place so current can be produced when required.

8.1. Lead Acid (LA) battery

This is the most common energy storage device in use at present. Its success is due to its maturity (research has been ongoing for an estimated 140 years), relatively low cost, long lifespan, fast response, and low selfdischarge rate. These batteries are can be used for both short-term applications (seconds) and long term applications (up to 8 hours).

There are two types of lead-acid (LA) batteries; flooded lead-acid (FLA) and valve-regulated lead-acid (VRLA). FLA batteries are made up of two electrodes that are constructed using lead plates which are immersed in a mixture of water (65%) and sulphuric acid (35%). VRLA batteries have the same operating principle as FLA batteries, but they are sealed with a pressure regulating valve. This eliminates air from entering the cells and also prevents venting of the hydrogen. VRLA batteries have lower maintenance costs, weigh less and occupy less space. However, these advantages are coupled with higher initial costs and shorter lifetime.

LA batteries can respond within milliseconds at full power. The average DC-DC efficiency of a LA battery is 75% to 85% during normal operation, with a life of approximately 5 years or 250-1,000 charge/discharge cycles, depending on the depth of discharge.

Applications
FLA batteries have 2 primary applications:
1. Starting and ignition, short bursts of strong power e.g. car engine batteries
2. Deep cycle, low steady power over a long time
VRLA batteries are very popular for backup power, standby power supplies in telecommunications and also for UPS systems.

**Cost**
Costs for LA battery technology have been stated as $200/kW - $300/kW, but also in the region of $580/kW

**Features**
Advantages: High power capacity; low volume energy density; low capital cost; long life time
Disadvantages: Low efficiency; potential adverse environmental impact [4]

### 8.2. Nickel Cadmium (NiCd) battery

A NiCd battery is made up of a positive with nickel oxyhydroxide as the active material and a negative electrode composed of metallic cadmium. These are separated by a nylon divider. The electrolyte, which undergoes no significant changes during operation, is aqueous potassium hydroxide. During discharge, the nickel oxyhydroxide combines with water and produces nickel hydroxide and a hydroxide ion. Cadmium hydroxide is produced at the negative electrode. To charge the battery the process can be reversed. However, during charging, oxygen can be produced at the positive electrode and hydrogen can be produced at the negative electrode. As a result some venting and water addition is required, but much less than required for a LA battery. The DC-DC efficiency of a NiCd battery is 60% - 70% during normal operation although the life of these batteries is relatively high at 10 to 15 years, depending on the application. NiCd batteries with a pocket-plate design have a life of 1,000 charge/discharge cycles, and batteries with sintered electrodes have a life of 3,500 charge/discharge cycles. NiCd batteries can respond at full power within milliseconds.

**Applications**
Sealed NiCd batteries are used commonly in commercial electronic products such as a remote control, where light weight, portability, and rechargeable power are important. Vented NiCd batteries are used in aircraft and diesel engine starters, where large energy per weight and volume are critical. NiCd batteries are ideal for protecting power quality against voltage sags and providing standby power in harsh conditions. Recently, NiCd batteries have become popular as storage for solar generation because they can withstand high temperatures.
However, they do not perform well during peak shaving applications, and consequently are generally avoided for energy management systems.

**Cost**

NiCd batteries cost more than LA batteries at $600/kW. However, despite the slightly higher initial cost, NiCd batteries have much lower maintenance costs due to their environmental tolerance.

**Features**

Advantages: Short access time; high energy density; high efficiency
Disadvantages: Cycling and safety control required; environmental concerns [4]

### 8.3. Sodium Sulphur (NaS) Battery

NaS batteries have three times the energy density of LA, a longer life span, and lower maintenance. These batteries are made up of a cylindrical electrochemical cell that contains a molten-sodium negative electrode and a molten sulphur positive electrode. The electrolyte used is solid β-alumina. During discharging, sodium ions pass through the β-alumina electrolyte where they react at the positive electrode with the sulphur to form sodium polysulfide, see figure below. During charging, the reaction is reversed so that the sodium polysulfide decomposes, and the sodium ions are converted to sodium at the positive electrode. In order to keep the sodium and sulphur molten in the battery, and to obtain adequate conductivity in the electrolyte, they are housed in a thermally-insulated enclosure that must keep it above 270°C, usually at 320°C to 340°C.

A typical NaS module is 50 kW at 360 kWh or 50 kW at 430 kWh. The average round-trip energy efficiency of a NaS battery is 86% to 89%. The cycle life is much better than for LA or NiCd batteries.

**Applications**

One of the greatest characteristics of NaS batteries is its ability to provide power in a single, continuous discharge or else in shorter larger pulses (up to five times higher than the continuous rating). It is also capable of pulsing in the middle of a long-term discharge. This
flexibility makes it very advantageous for numerous applications such as energy management and power quality. NaS batteries have also been used for deferring transmission upgrades.

**Cost**
Currently, NaS batteries cost $810/kW, but it is only a recently commercialized product. This cost is likely to be reduced as production increases, with some predicting reductions upwards of 33%.

**Features**
Advantages: Very high energy and power capacity; high energy density; high efficiency; long life time
Disadvantages: Production cost; safety concerns [4]

**8.4. Flow Battery Energy Storage (FBES)**

There are three primary types of FBES:
1. Vanadium Redox (VR)
2. Polysulphide Bromide (PSB)
3. Zinc Bromine (ZnBr)
They all operate in a similar fashion; two charged electrolytes are pumped to the cell stack where a chemical reaction occurs, allowing current to be obtained from the device when required. The operation of each will be discussed in more detail during the analysis.

8.5. Vanadium Redox (VR) Flow Battery

A VR battery is made up of a cell stack, electrolyte tank system, control system and a PCS (Power Conversion System). These batteries store energy by interconnecting two forms of vanadium ions in a sulphuric acid electrolyte at each electrode. The size of the cell stack determines the power capacity (kW) whereas the volume of electrolyte (size of tanks) indicates the energy capacity (kWh) of the battery.

As the battery discharges, the two electrolytes flow from their separate tanks to the cell stack where H+ ions are passed between the two electrolytes through the permeable membrane. This process induces self separation within the solution thus changing the ionic form of the vanadium as the potential energy is converted to electrical energy. During recharge this process is reversed. VR batteries operate at normal temperature with an efficiency as high as 85%. As the same chemical reaction occurs for charging and discharging, the charge/discharge ratio is 1:1. The VR battery has a fast response, from charge to discharge in 0.001 s and also a high overload capacity with some claiming it can reach twice its rated capacity for several minutes. VR batteries can operate for 10,000 cycles giving them an estimated life of 7-15 years depending on the application. Unlike conventional batteries they can be fully discharged without any decline in performance. At the end of its life (10,000 cycles), only the cell stack needs to be replaced as the electrolyte has an indefinite life and thus can be reused. VR batteries have been designed as modules so they can be constructed on-site.

Applications

As the power and energy capacities are decoupled, the VR flow battery is a very versatile device in terms of energy storage. It can be used for every energy storage requirement including UPS, load levelling, peakshaving, telecommunications, electric utilities and integrating renewable resources. Although the versatility of flow batteries makes it extremely useful for a lot of applications, there are a number of competing devices within each area that perform better for their specific application. Consequently, although capable of performing
for numerous applications, VR batteries are only considered where versatility is important, such as the integration of renewable resources.

**Cost**

There are two costs associated with flow batteries: the power cost (kW), and the energy cost (kWh), as they are independent of each other. The power cost for VR batteries is $1,828/kW, and the energy cost is $300/kWh to $1,000/kWh, depending on system design.

**Features**

Advantages: Unique versatility, specifically their MW power and storage capacity potential. Disadvantages: Low power density, require the most cells, very complicated in relation to conventional batteries

### 8.6. Polysulphide Bromide (PSB) Flow Battery

PSB batteries operate very similarly to VR batteries. The unit is made up of the same components; a cell stack, electrolyte tank system, control system and a PCS (see Figure below). The electrolytes used within PSB flow batteries are sodium bromide as the positive electrolyte, and sodium polysulphide as the negative electrolyte. During discharge, the two electrolytes flow from their tanks to the cell where the reaction takes place at a polymer membrane that allows sodium ions to pass through. Like VR batteries, self-separation occurs during the discharge process and as before, to recharge the battery this process is simply reversed. The voltage across each cell is approximately 1.5 V.

PSB batteries operate between 20°C and 40°C, but a wider range can be used if a plate cooler is used in the system. The efficiency of PSB flow batteries approaches 75%. As with VR batteries, the discharge ratio is 1:1, since the same chemical reaction is taking place during charging and discharging. The life expectancy is estimated at 2,000 cycles but once again, this is very dependent on the application. As with VR batteries the power and energy capacities are decoupled in PSB batteries.

**Applications**

PSB flow batteries can be used for all energy storage requirements including load levelling, peak shaving, and integration of renewable resources. However, PSB batteries have a very fast response time; it can react within 20 milliseconds if electrolyte is retained charged in the
stacks (of cells). Under normal conditions, PSB batteries can charge or discharge power within 0.1 s. Therefore, PSB batteries are particularly useful for frequency response and voltage control.

Cost
The power capacity cost of PSB batteries is $1,094/kW and the energy capacity cost is $185/kWh.

Features
Advantages: High power capacity; long life time.
Disadvantages: Low energy density; low efficiency

8.7. Zinc Bromine (ZnBr) Flow Battery

These flow batteries are slightly different to VR and PSB flow batteries. Although they contain the same components: a cell stack, electrolyte tank system, control system, and a PCS they do not operate in the same way. During charging the electrolytes of zinc and bromine ions (that only differ in their concentration of elemental bromine) flow to the cell stack. The electrolytes are separated by a microporous membrane. Unlike VR and PSB flow batteries, the electrodes in a ZnBr flow battery act as substrates to the reaction. As the reaction occurs, zinc is electroplated on the negative electrode and bromine is evolved at the positive
electrode, which is somewhat similar to conventional battery operation. An agent is added to the electrolyte to reduce the reactivity of the elemental bromine. This reduces the self-discharge of the bromine and improves the safety of the entire system. During discharge the reaction is reversed; zinc dissolves from the negative electrode and bromide is formed at the positive electrode. ZnBr batteries can operate in a temperature range of 20°C to 50°C. Heat must be removed by a small chiller if necessary. No electrolyte is discharged from the facility during operation and hence the electrolyte has an indefinite life. The membrane however, suffers from slight degradation during the operation, giving the system a cycle life of approximately 2,000 cycles. The ZnBr battery can be 100% discharged without any detrimental consequences and suffers from no memory effect. The efficiency of the system is about 75% or 80%. Once again, as the same reaction occurs during charging and discharging, the charge/discharge ratio is 1:1, although a slower rate is often used to increase efficiency. Finally, the ZnBr flow battery has the highest energy density of all the flow batteries, with a cell voltage of 1.8 V.

Applications
The building block for ZnBr flow batteries is a 25 kW, 50 kWh module constructed from three 60-cell battery stacks in parallel, each with an active cell area of 2500 sq. cm. ZnBr batteries also have a high energy density of 75 Wh/kg to 85 Wh/kg. As a result, the ZnBr batteries are relatively small and light in comparison to other conventional and flow batteries such as LA, VR and PSB. Consequently, ZnBr is currently aiming at the renewable energy backup market. It is capable of smoothing the output fluctuations from a wind farm, or a solar panel [24], as well as providing frequency control. Installations currently completed have used ZnBr flow batteries for UPS, load management and supporting microturbines, solar generators, substations and T&D grids.

Cost
The power capacity cost is $639/kW and the energy capacity cost is $400/kWh.

Features
Advantages: High power capacity; long life time.
Disadvantages: Low energy density; low efficiency [2]
9. Thermal Energy Storage System (TESS)

The thermal energy storage system can also be used very effectively to increase the flexibility within an energy system. As mentioned previously in this chapter, by integrating various sectors of an energy system, increased wind penetrations can be achieved due to the additional flexibility created. Unlike the hydrogen energy storage system which enabled interactions between the electricity, heat and transport sectors, thermal energy storage only combines the electricity and heat sectors with one another. By introducing district heating into an energy system, then electricity and heat can be provided from the same facility to the energy system using Combined Heat and Power (CHP) plants. This brings additional flexibility to the system which enables larger penetrations of intermittent renewable energy sources. To illustrate the flexibility induced by thermal energy storage on such a system, a snapshot of the power during different scenarios is presented below. The system in question contains a CHP plant, wind turbines, a thermal storage, a hot water demand, and an electrical demand as illustrated in Figure 5.19. During times of low wind power, a lot of electricity must be generated by the CHP plants to accommodate for the shortfall power production. As a result, a lot of hot water is also being produced from the CHP plant as seen in Figure 5.19a. The high production of hot water means that production is now greater than demand, and consequently, hot water is sent to the thermal storage. Conversely, at times of high wind power, the CHP plants produce very little electricity and hot water. Therefore, there is now a shortage in of hot water so the thermal storage is used to supply the shortfall, as seen in Figure 5.19b.

This system has been put into practice in Denmark which has the highest wind penetration in the world. Also, Lund has outlined a roadmap for Denmark to use this setup in achieving a 100% renewable energy system [2].

Table - Losses and turnaround efficiencies of thermal energy-storage systems

<table>
<thead>
<tr>
<th>Storage system</th>
<th>Losses of available energy</th>
<th>Turnaround efficiency¹</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Charging</td>
<td>Discharging</td>
</tr>
<tr>
<td>Internal steam generation (varying pressure)</td>
<td>A, B</td>
<td>B, F</td>
</tr>
<tr>
<td></td>
<td>C, D</td>
<td>C/B, F, D</td>
</tr>
<tr>
<td>External steam generation</td>
<td>Displacement</td>
<td>Expansion</td>
</tr>
<tr>
<td></td>
<td>C, E</td>
<td>C/B, F</td>
</tr>
<tr>
<td></td>
<td>D</td>
<td>D, F</td>
</tr>
<tr>
<td></td>
<td>C, E</td>
<td>C, E, F</td>
</tr>
<tr>
<td>Feedwater Storage</td>
<td>Displacement*</td>
<td>Indirect with oil/rock</td>
</tr>
</tbody>
</table>

¹ Turnaround efficiency is the ratio of the energy available for use to the energy stored.
Figure 5-19: Thermal energy storage system during (a) a low-wind scenario and (b) a high-wind scenario

*storage of water used directly in the boiler/turbogenerator cycle
†includes a thermal insulation loss for the accumulator
A Pipe friction
B Throttling
C Heat transfer or mixing
D Recirculation power
E Pumping power
F Peaking turbine efficiency difference

Here the turnaround efficiency is chosen as a primary measure of performance and is defined as the ratio of the peaking electrical energy generated during the discharge cycle to the reduction of electrical energy during the charge cycle. This becomes simply

$$\eta_T = \frac{(\frac{P}{P_N} - 1)\xi_D}{(1 - \frac{P}{P_N})\xi_L}$$
Where $P_D$, $P_C$, $P_N$ = power generation during discharge, charge and normal operation, respectively, $\frac{t_D}{t_C}$ = discharge to charge time ratio $\frac{P_D}{P_N}$ ~ 1 = peaking power swing.

**Application**

Allow enable the utilization of more intermittent renewable energy (such as wind), but it also maximizes the use of fuel within power plants, something that will become critical as biomass becomes more prominent. This system has been put into practice in Denmark which has the highest wind penetration in the world. In addition, Lund has outlined a roadmap for Denmark to use this setup in achieving a 100% renewable energy system at a lower cost than a conventional energy-system. Therefore, it is evident this technology can play a crucial role in future energy-systems.

**Cost**

The total cost charged to a TESS project should be based on the cost of the components of the TESS itself, together with costs of a peaking turbine and the required modification to the main turbine and heat rejection system. The sum of all increments of capital cost divided by the increment in peaking capacity that is provided (Ct in £/kW) is used as a cost comparison of systems and is independent of the size of plant and the magnitude of the peaking swing added to the reference plant. Ct may be written as $Ct(\text{£}/\text{kW}) = C_p + C_e$ Here the system cost is divided into two portions. $C_p$ is the power-related cost and includes peaking turbine and heat exchangers, i.e. components that are energy- and mass-flow dependent. $C_e$ is the portion that is energy related where cost is proportional to the energy stored, for example, storage media and containment. $C_e$ also embodies a component which expresses the energy loss from the turnaround efficiency as a capital cost term. Except for storage cycles with poor turnaround efficiencies (< 70%), this energy loss cost is only a small component of the total cost $Ct$ [1].

**Features**

Advantages: The energy system efficiency is improved with the implementation of a thermal energy storage system. CHP production is approximately 85% to 90% efficient while conventional power plants are only 40% efficient.
Disadvantages: Large investments required to build the initial infrastructure, thermal energy storage does not improve flexibility within the transport sector like the hydrogen energy storage system [2].
10. Concentrated Solar Power (CSP)

In the concentrated solar power (CSP) system, energy from the sunlight is converted into heat. The heat energy is stored and eventually used in a conventional power plant to generate electricity. The plants consist of two parts: one that collects solar energy and converts it to heat, and another that converts heat energy to electricity. Unlike solar photovoltaic (PV) technologies, the CSP has an inherent capacity to store heat energy for short periods of time (thermal storage) for later conversion to electricity. When combined with thermal storage capacity, the CSP plants can continue to produce electricity even when clouds block the sun or after sundown. The CSP has power capacity ranges between 10kW for small applications to 200MW (or even higher) for grid connection applications. The storage technique in the CSP plant is shown in figure A. The extra heat collected in the solar field is moved to the heat exchanger and heats the molten salt going from the cold tank to the hot tank. At peak period, the stored heat can be sent to the steam generator to produce the steam. The typical output power of the combined storage and solar system during the day is shown in figure B.

![Figure A. Storage system in a trough CSP plant.](image)

The thermal storage of the CSP plants is classified as long-term response energy storage (several hours). The storage and backup capabilities of the CSP plants offer significant benefits for electricity grids. Losses in thermal storage cycles are much less than those in...
other existing electricity storage technologies (including pumped hydro and batteries), making the thermal storage available in the CSP plants more effective and less costly.

Figure B. Output of Combination of Storage and CSP.
11. Cost/Life cycle characteristics of storage technologies

There is a tough task, to pick up the best technology from the large range of energy storage techniques. Because as they are individually ideal for certain applications, but no technology is perfect for everything. Large variation of power ranges and installations makes this choice even harder. If we forget about such criteria’s for example like: energy density, environmental issues or efficiency, and will choose only accordingly to the energy storage capacity cost, then we will like the PHES or CAES options with very long life cycles. But we must bear in mind that these systems have such drawbacks like: special site requirements, adverse impact on environment and moderate efficiency. The same situation is with another cheap pretender HESS, which could be used in only some niche and specific applications. Finally, there are tables below specifying the applications that each storage technology is suitable for and outlining the detailed characteristics of each storage technology, depending on particular requirements.

Nowadays the simplest opportunity for shifting load and using consumption pattern for average apartment is possible with use of batteries. The cheapest kWh of LA type has actually cost-effective recycle process. Also it has many disadvantages in use and not friendly to environment. To find the best energy storage from investment payback and features, it is necessary to create summarizing table with different power groups. The differentiation by power and storage capacities gives opportunity quickly separate using divisions without deep analyzing. Since the only devices capable of large power (>50 MW) and energy capacities (>100 MWh) are PHES, UPHES and CAES, this group is mainly suitable for complete satisfying heavy industry demands not residential and small commercial power requirements less than 10 kW and 50 kW respectively, table 1 still shows all storages with congenial features and costs calculations. The wide cost ranges in FES rows are specified by common calculation for low speed and high speed FES devices. The table parameter Self-discharge is rate in percentage that shows lost of the energy over time (1 day in this case) when the storage is charged but unused. The Specific energy variable is defined as the energy per unit mass (1 kilogram); Specific power describes the rate of available energy but on the basis of weight (1 kilogram); Energy density is the amount of energy, on the basis of volume (1 liter), which can be taken from an energy source and parameter Power density combines the energy density with the speed that the energy can be delivered to the load. Energy Storage System Costs is the capital cost of the storage device itself, and is usually given in two parts: Power Capacity
Cost [$/kW] and Energy Capacity Cost [$/kWh]. By dividing the cost this way, there is statement that the energy capacity and power capacity are independent, which is not always true. By way of example, this assumption is true for flow batteries and pumped hydroelectric storage, but not true for traditional secondary batteries and flywheels. However, since most systems can be scaled up by interconnecting multiple units in series/parallel combinations, it will be assumed that this methodology correctly approximates the system costs. The kWh is cost based on system capital cost per unit of rated energy capacity, as measured by duration (hours) at rated power (kW) [15][16]

Power Conversion System Costs (PCS) [$/kW]: This category includes all mechanisms between the storage device and the grid including power conditioning equipment, automatic control systems, power lines, invertors, system isolation equipment, and safety sensors. Balance of Plant Costs (BOP) [$/kW]: This category consists of construction costs and engineering, land, access routes, permits, and fees. Operation and Maintenance (O&M) Fixed Costs [$/kW-yr]: This is an annual costs for the routine maintenance required to keep the system operational. The units for this cost are dollars per kW of installed capacity, per years of operation (so Fixed OM costs of 5$/kW-yr for a 1kW system would cost $5 per year) [16]. The total capital cost of the system $C_{tot}$ can be computed with equation 4 by multiplying the power capacity of the system by the sum of the BOP, PCS, and power capacity costs, then add to it the product of the energy capacity of the system and the energy capacity cost.

\[
C_{tot} = P_{max}(C_{BOP} + C_{PCS} + C_{pc} + C_{OM}) + E_{max}C_{ec}
\]

where $C_{PC}$ Power capacity cost [$/kW]; $C_{EC}$ Energy capacity cost [$/kWh]; $C_{PCS}$ Power conversion system costs

(PCS) [$/kW]; $C_{BOP}$ Balance of plant costs [$/kw]; $C_{OM}$ Operations and maintenance fixed cost [$/kW-yr] multiplied with expected years amount and discount rate %; $P_{max}$ Power capacity of the system [kW] and $E_{max}$ Energy capacity of the system [kWh].

Large scale group members PHES, UPHES and CAES have heavy dependence on the availability of suitable locations (terrain) and practically cannot be applied for using in households, therefore they will not compute in payback table. Due to low energy density values of SCES and SMES, they will not compute also. In its turn FES was not considered, because of relative high discharge cycles [21].
<table>
<thead>
<tr>
<th></th>
<th>PHES</th>
<th>CAES</th>
<th>FES</th>
<th>SCES</th>
<th>SMES</th>
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<th>NiCd</th>
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<td><strong>Technical parameters</strong></td>
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<td>20-40</td>
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<td>800-3.5k</td>
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<td>5-15</td>
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<td>0.5-5</td>
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<td>30-50</td>
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<td>100k</td>
<td>1k-4k</td>
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</tr>
<tr>
<td><strong>Costs</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<td></td>
</tr>
<tr>
<td>Power Cost [$/kW]</td>
<td>600-2k</td>
<td>400-800</td>
<td>250-400</td>
<td>100-360</td>
<td>200-350</td>
<td>150-3000</td>
<td>175-600</td>
<td>150-1500</td>
<td>175-4000</td>
<td>175-2500</td>
<td>330-2500</td>
<td>175-1500</td>
</tr>
<tr>
<td>Energy Cost [$/kWh]</td>
<td>0-23</td>
<td>2-140</td>
<td>230-150k</td>
<td>300-94k</td>
<td>1k-83k</td>
<td>250-500</td>
<td>150-400</td>
<td>600-1500</td>
<td>500-2500</td>
<td>150-1000</td>
<td>120-1000</td>
<td>150-1000</td>
</tr>
<tr>
<td>BOP Cost [$/kW]</td>
<td>270-580</td>
<td>270-580</td>
<td>110-600</td>
<td>180-580</td>
<td>140-650</td>
<td>120-600</td>
<td>120-600</td>
<td>120-600</td>
<td>120-600</td>
<td>120-600</td>
<td>120-600</td>
<td>120-610</td>
</tr>
<tr>
<td>PCS Cost [$/kW]</td>
<td>0-4.8</td>
<td>46-190</td>
<td>0-1200</td>
<td>50-12k</td>
<td>60-12k</td>
<td>0-120</td>
<td>58-180</td>
<td>58-180</td>
<td>0</td>
<td>0-120</td>
<td>60-120</td>
<td>36-120</td>
</tr>
<tr>
<td>O&amp;M Fixed Cost [$/kW-y]</td>
<td>3-4.4</td>
<td>1.6-29</td>
<td>6-22</td>
<td>6-16</td>
<td>9.2-30</td>
<td>23-61</td>
<td>1.8-52</td>
<td>6-32</td>
<td>12-30</td>
<td>15-47</td>
<td>18-96</td>
<td>24-65</td>
</tr>
</tbody>
</table>
Table 2: Cost Characteristics of storage technologies [17][18][19][20]

<table>
<thead>
<tr>
<th>Energy storage</th>
<th>$/kWh</th>
<th>Life cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pumped Hydroelectric Energy Storage (PHES), (UPHES)</td>
<td>12-125</td>
<td>30 years</td>
</tr>
<tr>
<td>Compressed Air Energy Storage (CAES)</td>
<td>3-12</td>
<td>30 years</td>
</tr>
<tr>
<td>Flywheel Energy Storage (FES)</td>
<td>low speed: 200-300, high speed up to 25000</td>
<td>20+ years or 1 000+ cycles</td>
</tr>
<tr>
<td>Supercapacitor Energy Storage (SCES)</td>
<td>12000-28000</td>
<td>110 cycles</td>
</tr>
<tr>
<td>Superconducting Magnetic Energy Storage (SMES)</td>
<td>500 - 2000</td>
<td>20+ years or 1 000+ cycles</td>
</tr>
<tr>
<td>Hydrogen Energy Storage (HESS)</td>
<td>10 - 20</td>
<td>20 years</td>
</tr>
<tr>
<td>Lead Acid (LA) battery</td>
<td>100 -200</td>
<td>5+ years or 250-1000 cycles</td>
</tr>
<tr>
<td>Nickel Cadmium (NiCd) battery</td>
<td>250-500</td>
<td>15+ years or 3500 cycles</td>
</tr>
<tr>
<td>Sodium Sulphur (NaS) Battery</td>
<td>350-500</td>
<td>15+ years or 2500 cycles</td>
</tr>
<tr>
<td>Vanadium Redox (VR) Flow Battery</td>
<td>300-1800</td>
<td>7-15 years or 10 000 cycles</td>
</tr>
<tr>
<td>Polysulphide Bromide (PSB) Flow Battery</td>
<td>185 -1100</td>
<td>2000 cycles</td>
</tr>
<tr>
<td>Zinc Bromine (ZnBr) Flow Battery</td>
<td>150-250</td>
<td>4000 cycles</td>
</tr>
</tbody>
</table>
12. Figures from Electricity Storage Association homepage

System Ratings
Installed systems as of November 2008

Rated Power (MW)

Discharge Time (hr)

0.0001

0.001

0.01

0.1

1

10

100

PSH

CAES
Compressed air
EDLC
Double-layer capacitors
FW
Flywheels
L/A
Lead acid
Li-ion
Lithium-ion
Na-S
Sodium-sulfur
Ni-Cd
Nickel-cadmium
Ni-MH
Nickel-metal hydride
PSH
Pumped hydro
VR
Vanadium redox
Zn-Br
Zinc bromide

Zinc-Air
Lead-Acid
Ni-Cd
Li-Ion
Na-S
Flow Batteries
Long Duration
Flywheels
Electrochemical
Capacitors
CAES
+ gas
Pumped Hydro

Capital Cost per Cycle ($/kWh - output)

100

10

1

0.1

Capital / Energy
Life (cycles) x Efficiency

Possible reduction due to life extension by partial refurbishment

Carrying charges, O&M and replacement costs are not included
13. Example - Dimensioning of energy storage for small scale PV-system in Estonia

Optimal dimensioning of electricity storage according to the energy production of micro-scale renewables (in residential areas and households) and electricity consumption are important topics in the development of micro- and smartGRID technologies to increase system reliability and to reduce the profitability time.

Flourishing use of an electric grid needs permanent online balancing of supply and demand, including grid losses. Correctly chosen electricity storage technologies will smooth out these surges and allow electricity to be dispatched at a later time. Variable nature of solar radiation makes it impossible to deliver energy from a photovoltaic (PV) system at a constant power level, and energy backup and storage are always needed [1].

Solar surface irradiance depends first of all on astronomical factors, but is greatly modified by cloudiness, atmospheric transparency and snow cover. The latter factors show significant spatial and temporal variability, which is reflected in the variability of solar fluxes [2].

The analysis below is based on global irradiance data measured in the Tallinn-Harku Aerological Station (latitude N 59°23’53”; longitude E 24°36’10”; height above sea level 33 m) and average household energy consumption data described in [4].

As a result of the global radiation analysis, the global radiation of an average day in June compared to December is up to 50 times higher. In June at peak hour (11 o’clock) the total radiation is up to 18 times higher than in December. About 85% of the resource is concentrated on the summer season from April until September, when energy generation is over average (Fig. 1).

Today the efficiency ($\eta$) of common PV-panels can be up to 20%. New triple-junction metamorphic cells have an efficiency of about 40% (laboratory tested). Commonly the high efficiency solar cells are used in concentrating photovoltaic systems for solar power stations in the countries with a large fraction of direct solar radiation. In Estonia due to the high share of diffuse radiation, concentrators are not feasible and only flat plate collectors (PV-modules) can be recommended [3]. Also, the high share of diffuse radiation means a lower rate of radiation. As shown in Figure 2, during the last five years about 60% of sunset hours solar radiation was above 200 W/m².h.

Using of a 2-axis solar tracking system (2ASTS) in the winter season, it is very important to take into account apparent altitude of the sun ($\alpha_{aas}$). In December the 2ASTS system produces approximately up to 2.5 times more energy than a horizontal system, but an apparent altitude of the sun is lower and shadows are longer. For example, if an apparent altitude of the sun is 10° (December), the shadow is five times longer than the object length (1).

$$l_{shw} = l_{obj} \frac{\sin(90 - \alpha_{aas})}{\sin(\alpha_{aas})},$$

Fig. 1. Average daily radiation by months (Harku 2005-2009)

Fig. 2. Histogram of global radiation (Harku 2005-2009)

where $l_{shw}$ – length of a shadow; $l_{obj}$ – height of an object; $\alpha_{aas}$ – apparent altitude of the sun.

In June the difference of energy generation of ASTS and horizontal systems is 1.5 times. Using a 2-axis tracking system, the difference found between energy generation in June and December is about 20 times. Using a horizontal PV-system, the difference between energy generation in these months is about 50 times.

**PV-SYSTEM DIMENSIONING FOR TYPICAL ESTONIAN HOUSEHOLDS**

The following calculations (2-3) are simplified and do not take into account the PV-system performance ratio, including system losses. Solar modules based on crystalline cells can even reach a performance ratio of 85 - 95%.
where $A_{pv}$ – PV-module area; $k_{pr}$ – performance ratio; $E_c$ – electricity consumption; $E_{pv}$ – electricity generation of a PV-system; $E_s$ – global irradiance in Wh; $\eta_{pv}$ – efficiency of a PV-system.

Average electricity consumption (about 0.5 kWh per hour) [4], without consumption of an electrical water heater, in June can be covered by flat PV-panels with an area of 10.4 m$^2$ ($\eta = 0.2$). To cover an average electricity consumption in December, PV-panels with an area up to 524 m$^2$ should be installed. Based on annual electricity generation and household consumption, the area of PV panels should be approximately 24 m$^2$. This calculation does not take into account the huge surplus in the summer season and the shortage in the winter season. At least the calculations should be based on average day data of solar radiation and electricity consumption for a month. A PV area calculation for an on-grid system is based on average daily electricity generation and the highest consumption day in the lowest global solar radiation month (in the summer season). As described, about 85% of the resource is concentrated on the summer season from April until September. To use this resource efficiently, during that period the highest consumption day should be found. For a PV area, calculations an average holiday (HD) and workday (WD) electricity consumption (accordingly 0.66 kWh/h and 0.38 kWh/h) should be compared. If the holiday total electricity consumption is greater or equal to the workday electricity consumption, then the PV area calculation is based on the holiday data, otherwise on the workday data (4).

$$E_i = \begin{cases} E_h, E_h \geq E_w \\ E_w, E_h < E_w \end{cases}$$

Here the total electricity consumption of an average holiday is the sum of electricity consumption of 24 hours. Total irradiance of an average day is the sum of each hour in a day (5).

$$E_h = \sum_{i=1}^{n} E_{h,i}; \quad E_w = \sum_{i=1}^{n} E_{w,i} ,$$

where $E_h$ – total electricity consumption of a holiday; $E_w$ – total electricity consumption of a workday; $E_{h,i}$ – holiday electricity consumption at the hour $i$; $E_{w,i}$ – workday electricity consumption at the hour $i$.

The largest average electricity consumption is on holidays. The smallest electricity generation in the summer season is in September. Based on these data the largest area of PV-panels in the summer season should be approximately 34 m$^2$ (holiday in September) (Fig. 3).

Based on the formula (6) below, a PV system with an area of 34 m$^2$ and efficiency of 20% will have theoretically the maximum total day generation of 54 kWh (June) and the minimum 0.1 kWh (December).

$$E_{pv,i} = \eta_{pv} \cdot A_{pv} \cdot E_{s,i}$$

In different seasons of the northern regions the deviation of global solar irradiation and PV-system generated energy is relatively high. The coefficient of variation $V_R$ of monthly generation is 72% (7).
where \( E_{pv,i} \) = generated electricity at the hour \( i \); \( n = 24 \) hours in a day; \( E_{pv} \) = average daily electricity generation.

High variations in annual electricity generation are the main problem to define an optimal PV-system and electricity reserves for an energy storage system for load coverage.

In Northern regions it is not reasonable to plan PV-systems because of the lowest global radiation. If a horizontal PV-system is used, the difference of the calculated areas for September and December is 20 times. Even, if 2ASTS is used, the difference of the calculated areas is 8-10 times.

Next, energy balance of a household PV-system and energy reserve dimensioning for a storage system are analyzed.

**ELECTRICITY RESERVE DIMENSIONING OF A HOUSEHOLD PV-SYSTEM FOR LOAD COVERAGE**

Energy balance of a PV-system can be described according to the following simplified formula:

\[
E_{pv} = E_c + E_{sp} + E_{los} \quad E_{pv} = E_{dir} + E_{res} + E_{sp} + E_{los},
\]

where \( E_{pv} \) = electricity generated by a PV system; \( E_c \) = electricity consumption; \( E_{sp} \) = surplus of generated electricity; \( E_{los} \) = total losses; \( E_{dir} \) = direct consumption of electricity generated by a PV system; \( E_{res} \) = indirect consumption of electricity generated by a PV system (stored energy reserve of PV generated energy).

In the calculations system losses are not taken into account \( (E_{los} = 0) \).

**Balance between generation and load**

The first step to define the dimensions needed for electricity reserve for load coverage of a household PV-system is the analysis of balance between PV generation and load consumption on an average day of each month (9). While the WD and HD have different consumption curves the analysis should be made separately for both days.

\[
E_{bal,i} = E_{c,i} - E_{pv,i},
\]

where \( E_{bal,i} \) = energy balance at the hour \( i \).

According to calculations (9) at WD the surplus of generated energy is very high on midday, when the load is trivial. Load maximum prevails in the evening. This means that direct load coverage is very low and on midday generated energy should be stored for the evening period (Fig. 4).

Measures should be taken to solve this huge surplus problem. At HD the direct load coverage is better than at WD. Balance between generation and load is better. In the summer season also energy reserves are similar to the reserves used in WD. In the winter season main problems are shortage and higher needs for energy reserves (Fig. 5).

\[
V_{r} = \frac{\sum_{i=1}^{n} |E_{pv,i} - E_{pv}|}{n \cdot E_{pv}}.
\]

**Electricity surplus and shortage**

The analysis (10) below shows that PV-systems with an area of 34 m\(^2\) can cover electricity consumption from April to September (Fig. 6).

\[
k_{sp} = \frac{E_{sp}}{E_{c}} = \frac{\sum_{i=1}^{n} (E_{pv,i} - E_{c,i})}{\sum_{i=1}^{n} E_{c,i}}; \quad n = 24,
\]

where \( E_{pv,i} \) = generated electricity at the hour \( i \); \( n = 24 \) hours in a day; \( E_{c,i} \) = electricity consumption at the hour \( i \).

In the winter season theoretically about 43% of an average consumption can be covered by a PV-system. In workdays and holidays these numbers are 56% and 33%, respectively. With a 2-axis solar tracking system theoretically up to 95% of electricity consumption in the winter season can be covered.

Without losses the average annual surplus of electricity generation of a PV-system in holidays and workdays is 11% and 92%, accordingly. In the summer season an average surplus is 150%, at WD and HD accordingly 227% and 89%. In the winter season the average shortage is 57%, at WD and HD accordingly 44% and 67%.
Dimensioning of electricity reserve

Approximately 17% of PV-generated energy can be directly used in workdays and 50% in holidays. This is about 32% of a workday and 56% of a holiday total electricity consumption (11-13).

\[
E_{dir} = \sum E_{c,i} - \sum \left( \frac{E_{c,i} - E_{pv,i}}{E_{pv,i}} \right)
\]

where \(E_{dir}\) – directly from PV-system consumed electricity.

\[
E_{dir} = \sum E_{pv,i} + \sum E_{c,i}
\]

About 30% of an annual average PV generated energy is used directly, which makes approximately 44% of the annual average consumption.

The easiest way to calculate needed energy reserve (storage capacitance) for indirect load coverage is based on the difference of average hourly electricity generation and consumption (14).

\[
E_{res,i} = \sum_{i=1}^{n} (E_{c,i} - E_{pv,i}) = \sum_{i=1}^{n} E_{c,i} - E_{pv,i}
\]

where \(E_{res,i}\) – needed energy reserve at the hour \(i\); \(E_{res}\) – needed average daily energy reserve.

Depending on the consumption pattern, about 35 to 40% of the generated energy should be stored for the darkness period, making up 44 to 68% of the consumption. In WD, if horizontally installed PV-panels are used, the highest energy reserve is needed in December (8.23 kWh) and the lowest in June (4.67 kWh) (Fig. 7). In holidays in turn, the highest energy reserve needed is 15.17 kWh and the lowest is 5.44 kWh (Fig. 8). Use of panels with an optimal inclination or 2ASTS, the calculated energy reserve can be reduced up to 10%. The reduction of an energy reserve depends directly on the daylight time and consumption pattern.

For WD and HD consumption coverage in December using of PV-panels with area of 700 m\(^2\) (Fig. 3) the needed energy reserve should be 8.27 kWh and 10.68 kWh respectively. For June the calculated energy reserve at WD and HD should be accordingly 2.74 kWh and 3.1 kWh. For comparison the calculated energy reserves for September with PV-panels surface of 34 m\(^2\) were for WD - 8.03 kWh and for HD - 8.16 kWh.

Another calculation method of the energy reserve but rarely used is based on the analysis of the frequency of the duration of darkness hours and average electricity consumption. The following histogram (Fig. 9) shows that 99% of darkness periods are shorter than 20 hours. In the winter season the longest period without generation is about 18 to 22 hours (in December). If a PV-system area is dimensioned to cover total electricity consumption in the winter season, the rough storage reserve calculation for December can be calculated as in (15).

Based on an average daily (0.5kWh/h), workday and holiday consumption (without electrical water heater) [4], the calculated energy reserves for the darkness period in December on an average day should be accordingly 10, 8 and 13 kWh.
\[ E_{\text{res,ad}} = I_{\text{pv,off}} \cdot E_{\text{c,ad}} = 20 \cdot 0.5041 \approx 10 \text{ kWh}, \quad (15) \]

where \( E_{\text{res,ad}} \) – needed energy reserve on an average day; \( I_{\text{pv,off}} \) – darkness period in hours; \( E_{\text{c,ad}} \) – average hourly electricity consumption.

An error between the calculation methods of the energy reserves based on formulas (10) and (14) depends on the difference of the consumption and the generation pattern. For example, as compared to workdays the calculation error of energy reserves in holidays is greater. The error of the calculated energy reserves for December is \( \leq 15 \% \). Rough calculations show that energy reserve for 20 darkness hours can cover about 90% of the total energy consumption. The longest average darkness period is 17 hours in December and the shortest one is 5 hours in June.

\[ E_{\text{res,ad}} = \frac{F_{\text{PV,off}} \cdot E_{\text{c,ad}}}{k_1 \cdot n_{\text{cycle}} \cdot k_2} \quad (16) \]

\textbf{CONCLUSION}

An increase in the efficiency of a PV system will reduce the area of PV-panels, but it has a relatively small impact on the storage system capacity. Double efficiency of a PV-system will decrease the storage system capacity only up to 10% (Fig. 10).

The higher consumption on workdays and holiday evenings has the highest impact on the dimensioning of storage capacitance. Thus it can be concluded that the profitability of a PV-system depends mostly on the price of electricity and the consumption pattern.

To assure the shortest profitability time, electricity consumption and real-time dynamic price should be increased and decreased synchronously with the PV system generation. In northern regions PV-systems are most feasible in OFF-grid systems, where the grid connection is not economically feasible. In an OFF-grid system for load coverage in the winter season, it is reasonable to use a PV system with a micro-CHP or a wind turbine. Average wind speed in the winter season is higher than in the summer season, and this can compensate the shortage of energy caused by lower solar radiation. Micro-CHP produces additional thermal energy, which can be fully used in the winter season.

In ON-grid PV-systems, according to seasonal differences of solar radiation, it is not feasible to plan a PV area by solar radiation of the winter season. It is more feasible to cover shortage with cheaper energy stored from the grid in the OFF-peak time or with other energy source. In an ON-grid system, in the winter season covering the shortage of electricity with low-tariff energy stored in the PV-system energy storage is a most suitable solution, which should be analyzed in future.
REFERENCES


14. REFERENCES


