Energy Storage
Electricity storage technologies

IVA’s Electricity Crossroads project
ORDLISTA

AA-CAES – Adiabatic compressed air energy storage

AEC – Alkaline electrolysis cells

CAES – Compressed air energy storage

CH₄ – Methane gas

CT – Combustion turbine

DoE – US Department of Energy

EEA – European Economic Area

GW – Gigawatt

GWh – Gigawatt hour

H₂ – Hydrogen gas

kW – Kilowatt

kWh – Kilowatt hour

MW – Megawatt

MWh – Megawatt hour

m³ – Cubic metre

Nm³ – Normal cubic metre

NaS – Sodium sulphur

UPS – Uninterruptible power supply

PEM – Polymer electrolyte membrane/proton exchange membrane

SMES – Superconducting magnetic energy storage

VRB – Vanadium redox battery

Wh – Watt hour
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Summary

The need for energy storage is increasing as the proportion of intermittent energy production in the energy system increases. Different types of storage technology are needed depending on demand and type of electricity generation. The most common energy storage technologies today are pumped hydropower, batteries, compressed air and flywheels.

The most common drivers and application areas for energy storage are listed below:

• Price arbitrage
• Balancing energy
• Black-start services
• Stabilising conventional generation
• Island and off-grid storage
• T&D (transmission & distribution) deferral
• Industrial peak shaving
• Residential storage

Different energy storage technologies have different applications in the energy system. Capacity, cost, energy density, efficiency level, and technical and economic life are factors that determine in which context the technologies are the most suitable. Pumped hydropower and compressed air, for example, are both suitable for energy balancing, while batteries are best suited as reserve power and for over-generation and off-grid systems. But larger battery units may be used in the future for other purposes. Geographical conditions are examples of other factors that must be taken into consideration in applications for pumped hydropower and compressed air energy storage (CAES).

It is likely that all of these storage technologies will be used in some form or other in the future, but the technology advancing the fastest today is battery technology. One reason for this is that batteries can be used on a small scale in households and vehicles, but they can also be used on a large scale by combining multiple modules. Also, the most recent advances in Tesla's batteries indicate that cost levels will fall faster than expected. Since batteries can be produced on a small scale, the threshold for widespread commercialisation is very small.

Pumped hydropower is expected to grow the most in China and India which have the right geographical conditions to build efficient plants. Other countries need to consider other unconventional technical pumped hydropower solutions, such as pumping sea/ocean water and storage in underground caverns.

Compressed air technology will likely be used the most in the USA where a number of suitable locations
have already been selected for compressed air plants. Projects are also in the pipeline in the EU where the first adiabatic compressed air solutions are now being developed.

Energy storage in the EU at this time is focused on three different areas: small-scale use, arbitrage and reduction of capacity peaks\(^1\). The drivers for storage markets in Europe are:

1. Use in microgrids isolated from the grid.\(^2\)
2. Batteries in combination with solar cells in residential contexts (mainly in Germany at the moment).\(^3\)

There are still legal barriers to overcome for energy storage, and the definition of energy storage and ownership rules are still unclear. In Sweden, grid companies are permitted to own their stored energy, but they can only use it for the purpose of covering grid losses or to temporarily compensate for power cuts/failures. In other words: stored energy use is only permitted in emergencies. An amendment to Sweden’s Electricity Act (Ellagen) is needed if energy reserves are to be commercially attractive for grid companies.

Batteries are expected to have a larger share in the future energy system in Sweden, both in homes and as part of the future electric-powered transport system. Other forms of energy storage will be developed in Sweden as well, and price trends will determine what these will be.

1. Introduction

The electricity system needs to be constantly in balance, i.e. electricity production and electricity demand need to be matched every second of the day. In cases where electricity generation cannot be controlled and does not match electricity demand, the energy (electricity) needs to be stored. By being able to store surplus generated electricity for use later on when demand is higher than supply, the balance in the energy system can be maintained without constant matching of production and consumption. This report summarises the information in a series of reports on energy storage. The focus here is energy storage through mechanical, electrical, electrochemical and chemical storage. Reports and other sources used in this report can be found in the literature list.
2. Electrical energy storage

The need for energy storage in the energy system will increase as the share of intermittent energy generation in the energy system increases. Figure 1 is a diagram of different energy (electricity) storage technologies by primary physical energy transmission technology/storage technology. This report will not cover heat storage.

The energy storage market is still relatively limited and only a few technologies have reached the commercial stage on a larger scale. Figure 2 and 3 show capacity that exists, is being planned and being developed (2014) for mechanical and electrochemical storage units. The data for these diagrams comes from the US DoE Global Energy Storage Database. The storage technologies shown in Figure 2 are described in more detail in Chapter 3.
Figure 4 (above): Potential of various electricity storage technologies globally 2030.8

Figure 5 (left): Anticipated energy storage market development.7

Figure 6 (below): Energy storage market development in SEK billions.8
Table 1: Applicability of stored energy

<table>
<thead>
<tr>
<th>Role in the energy system</th>
<th>The transmission system and centralised storage (national and European level)</th>
<th>The distribution system and regional storage (city and district level)</th>
<th>Consumer (building and residential level)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Function</td>
<td>• Seasonal/weekly/daily/hourly variations</td>
<td>• Daily/hourly variations</td>
<td>• Daily variations</td>
</tr>
<tr>
<td>Balance between supply and demand</td>
<td>• Substantial geographical imbalances</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Large variations due to intermittent electricity generation</td>
<td></td>
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</tr>
<tr>
<td>Distribution (moving energy)</td>
<td>• Voltage and frequency control</td>
<td>• Voltage and frequency control</td>
<td>• Aggregation of small amounts of stored energy to meet distribution needs (capacity problems and loss reduction)</td>
</tr>
<tr>
<td></td>
<td>• Additional peak production</td>
<td>• Power market</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Power market</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>• International market</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Energy efficiency improvement</td>
<td>Better energy efficiency in the global energy mix</td>
<td>Load and storage control for better efficiency in the distribution grid</td>
<td>Local generation and consumption, change in behaviours, increased value of local generation</td>
</tr>
</tbody>
</table>

Table 2: Application areas of different storage technologies.

- Suitable technology for the application
- More technology development or further cost reduction needed
- Technology not suitable for the application

<table>
<thead>
<tr>
<th>Storage Technology</th>
<th>Electricity quality and stability</th>
<th>Local energy optimisation</th>
<th>Moving energy in time (days or longer)</th>
<th>Investment deferment in T&amp;D</th>
<th>Reserve power/UPS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pumped hydropower</td>
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<tr>
<td>Compressed air</td>
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<tr>
<td>Lead-acid batteries</td>
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<tr>
<td>Lithium-ion batteries</td>
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<tr>
<td>Sodium-sulphur batteries</td>
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<tr>
<td>Flow batteries</td>
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<tr>
<td>Supercapacitors</td>
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<tr>
<td>SMES</td>
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<tr>
<td>Flywheels</td>
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</table>
In Revisiting Energy Storage the Boston Consulting Group (BCG) describes the estimated market potential of various technologies. This is illustrated in Figure 4. Batteries are expected to account for about half of all electrical energy storage. In terms of electrical power, pumped hydropower and compressed-air technology respectively are expected to dominate the market in 2030. These technologies are expected to gradually be replaced by hydrogen gas storage from 2020. The battery storage technologies that are expected to dominate the market are sodium-sulphur batteries (NaS), VRB (vanadium redox batteries) and lithium-ion batteries.

The graph above shows one market scenario, but it may change due to rapid development battery prices, see Figure 11.

BCG also estimates that sales of storage technologies will reach SEK 54 billion in 2015, SEK 135 billion in 2020 and SEK 234 billion in 2030 (Figure 5). The highest growth is expected to be made in North America, China, Japan and Europe. Figure 6 describes anticipated development in different markets.

As mentioned earlier, the different storage technologies are at different stages of commercial maturity. Figure 7 show where the different technologies were on the maturity scale in 2013.

**Application**

Different energy storage technologies have different application potential and limitations. Table 1 shows the various functionalities in different parts of the energy system. Europe is focusing on integrating intermittent electricity generation in the energy system, while the US is placing more emphasis on ways to compensate for weaknesses in its electricity system. Table 2 shows application areas that are the most suitable for each of the technologies listed above.

**Reserve power**

Stored energy can be used as reserve power. Below is a description of different types of reserve power.

**Spinning reserve power**

Capacity which is online and can respond within 10 minutes to compensate for generation or transmission interruptions. Frequency-responsive spinning reserve power responds within 10 seconds to maintain the system’s required frequency. Spinning reserve power is the first type used when there is a deficit.

**Supplemental reserves**

Electricity generation capacity that can be offline or that consists of a block of curtailable and/or interruptible load and that can be available within 10 minutes. Unlike spinning reserves, supplemental reserves are not synchronised with the grid’s frequency. Supplemental reserves are used after all spinning reserve capacity is online.

**Back-up supply**

Reserve power that can be deployed within an hour. This is mainly a back-up for reserves. It can also be used as commercial reserves and for selling.

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**Figure 8:** Vehicle battery systems via aggregators.
Electric vehicles
Since electric vehicles could potentially function as small distributed energy storage resources, they could potentially serve as an aggregated energy solution with smart technology and control. Electric vehicle batteries could be used as distribution units in the energy system by way of an aggregator. Figure 8 illustrates how a system like this would work.

Solar cells and battery storage
Substantial efficiency gains can be made through controlled battery charging and solar energy input into the grid. Figure 9 shows regular storage compared with grid-optimised storage.

Electricity Act
There are still legal barriers for energy storage and the definition of energy storage and the rules for ownership are unclear. In Sweden grid companies are permitted to own their stored energy, but they can only use it for the purpose of covering grid losses or to temporarily compensate for power cuts/failures. In other words: stored energy may only be used in emergencies. An amendment to Sweden’s Electricity Act (Eldlagen) is needed if energy reserves are to be commercially attractive for grid companies.15

**Figure 9:** Common energy storage system compared to an optimised energy storage system.14
3. Energy storage technologies

**Pumped hydropower**

In a pumped hydropower facility, water with low potential energy is pumped from a reservoir at a low elevation to a reservoir at a higher elevation. The pump uses electricity to increase the potential energy in the water; a form of energy that can be stored. The facility is run as a pumping station when surplus electricity is available. When electricity is needed the pumping facility can serve as a normal hydropower plant. Water is released from the highest reservoir through a pipe taking it to a turbine connected to a generator. The potential energy in the water is first converted into kinetic energy in the pipe and then into electrical energy after the generator.

A diagram of a typical pumped hydropower plant is presented in Figure 10.

Pumped hydropower is a mature and established technology that is well-suited for large-scale applications but not yet implemented in small-scale solutions. Europe, including Norway, has a few remaining locations that are suitable for pumped hydropower. There are some environmental considerations that must be taken into account as these plants have a significant impact on the natural environment.

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**Figure 10:** Diagram of a pumped hydropower plant.

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**Table 3:** Pumped hydropower plants in Sweden.

<table>
<thead>
<tr>
<th></th>
<th>Drop</th>
<th>Power (MW)</th>
<th>Production (GWh/year)</th>
<th>Constructed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Letten</td>
<td>191</td>
<td>36</td>
<td>65</td>
<td>1956</td>
</tr>
<tr>
<td>Kymmen</td>
<td>88</td>
<td>55</td>
<td>34</td>
<td>1987</td>
</tr>
</tbody>
</table>
In Sweden Fortum has two pumped hydropower plants: Letten and Kymmen. These two plants are described in Table 3.

Pumped hydropower has the greatest potential in China and India which have suitable geographical locations for effective plants. Other countries in the world need to consider more unconventional designs such as pumped hydropower using saltwater and underground water reservoirs.19

Globally in 2011 there were 280 plants with a combined capacity of 132 GW. Around 40 of these plants have a capacity of between 50 and 2,100 MW.20 Figure 11 shows a geographical breakdown for the plants.

Pumped hydropower facilities have a short response time, which means they can be used for both voltage and frequency control, spinning and non-spinning reserves, as well as for arbitrage and system capacity support.21

The fact boxes above show technical data for pumped hydropower plants.

### Compressed-air energy storage

Systems based on compressed-air energy storage (CAES) use electricity (when supply is greater than demand) to compress air in a reservoir, either in underground caverns/aquifers, or vessels or pipes above ground. When demand for electricity is instead higher than the supply, the compressed air is heated, expanded and taken through an expander or a conventional turbine to produce electricity. Figure 12 is a diagram of a CAES plant with subterranean storage in a cavern in a salt mine/mine.

In the compression process a large amount of heat escapes and if this heat is not recycled, the efficiency of CAES plants is low (42–54 percent). The current generation CAES plants do not recycle the heat and the challenge for the next generation CAES plants is the very high temperatures of 650°C or more, which affect the choice of materials used for heat exchangers.

CAES is the only commercially viable, large-scale storage technology aside from pumped hydropower. There is currently one facility in Germany (290 MW) and one in Alabama, USA (110 MW). Additional projects are in the pipeline. CAES technology is expected to be used in the USA where a number of locations have already been selected. In the EU further development of CAES technology is expected, and in particular the first adiabatic CAES technology facility, ADELE, is proving to be successful.22

ADELE is a project where advanced adiabatic CAES technology (AA-CAES) is used (so-called second generation compressed air technology). Adiabatic here means that the heat generated in the compression process is used to increase energy efficiency. The goal is to increase energy efficiency to a level of 70 percent. ADELE is a demonstration plant that is expected to be operational in 2016.23

The second generation CAES technology has the potential for lower installation costs, higher efficiency and shorter construction times compared to the first genera-
Table 5: Compressed air technology

<table>
<thead>
<tr>
<th>Compressed air technology</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Used for</td>
<td>Load and energy peaks, minute reserve</td>
</tr>
<tr>
<td>Usage time</td>
<td>1 to 24 hours</td>
</tr>
<tr>
<td>Capacity</td>
<td>Depending on storage size</td>
</tr>
<tr>
<td>Energy density</td>
<td>0.5–0.8 kWh/m³ (60 bar; the energy density depends on the pressure)</td>
</tr>
<tr>
<td>Efficiency level</td>
<td>Common compressed air technology: 42–54 %, Advanced adiabatic compressed air technology: up to 70 %</td>
</tr>
<tr>
<td>Losses</td>
<td>0–10 % per day</td>
</tr>
<tr>
<td>Start-up time</td>
<td>Minutes</td>
</tr>
<tr>
<td></td>
<td>After three minutes 50 % of the capacity is available</td>
</tr>
<tr>
<td></td>
<td>After 10–14 minutes 100 % of the capacity is available</td>
</tr>
<tr>
<td>Life</td>
<td>25–40 years</td>
</tr>
<tr>
<td>Production phase</td>
<td>Common compressed air technology: commercially available</td>
</tr>
<tr>
<td></td>
<td>Advanced adiabatic compressed air technology: development phase</td>
</tr>
<tr>
<td>Investment cost</td>
<td>6,000 (common CAES)–9,600 (AA-CAES) SEK/kW</td>
</tr>
<tr>
<td>Geographical requirements</td>
<td>Close to a salt dome, empty gas field or aquifer</td>
</tr>
</tbody>
</table>

Figure 12: Diagram of a compressed air storage facility and adjacent electricity generation plant.
In one type of second generation CAES technology, a natural gas-fired combustion turbine (CT) is used to generate heat during the expansion process. In these plants, about two thirds of the electrical energy produced is generated from the expansion turbine and one third from the CT. A new compressor design and an advanced turbo unit also improves production in CAES systems based on the technology without a CT.

CAES plants that store compressed air above ground are typically smaller than plants with underground storage. The capacity of small plants is often between 3 and 50 MW with output of 2–6 hours.

CAES plants with above ground storage are located at suitable sites, but are more expensive to build (calculated as SEK/kW) than plants with subterranean storage. The most cost-effective plants are CAES plants with subterranean storage with a storage capacity of up to 400 MW and an output of 8–26 hours. The location of these plants involves exploiting and verifying storage options based on geological information indicating suitability for a CAES plant in the area. The adiabatic CAES technology is fairly mature technology, particularly in the case of large-scale centralised applications.

Batteries

Many different types of batteries are being developed today. The batteries that exist and their market share are shown in Figure 13. The reason for the big jump for lithium-ion batteries in 2014 is the dramatic price development.

**Figure 13:** Different types of batteries and their estimated installed capacity (MW) in the world 2014.
Costs
The big challenge for batteries is cost, despite the fact the cost is expected to fall dramatically over the next decade, partly due to economies of scale and partly due to technical innovation. Figure 14 shows the current costs and the expected cost trend for lithium-ion batteries in electric vehicles. Note also the cost level for the new Tesla batteries that have recently entered the market.

Figure 15 shows different types of large-scale lithium-ion batteries and expected cost trends.

Figure 16 shows a cost comparison between different types of batteries, current and expected.

Battery cost predictions are, however, constantly changing. Recently, for example, (1 May 2015) Tesla launched its own battery, Tesla Powerwall, and industrial battery, Tesla Powerblock. Powerwall batteries are sold for USD 3,500 (equivalent to around SEK 30,000) and have a storage capacity of 10 kWh. This is equivalent to a price of USD 350/kWh and is also for a small-scale system. The industrial battery is sold for USD 250/kWh, which is equivalent to about SEK 2,000/kWh.

Market
Boston Consulting Group estimates that the increased total market potential for storage technologies will be an additional 300 GW over and above the

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Figure 15: Current cost and future anticipated development of different types of lithium-ion batteries.  
![Chart showing cost developments for various lithium-ion batteries.]

Figure 16: Cost for large-scale battery storage, comparison of current and expected.  
![Chart showing cost comparison for different types of batteries.]
existing 100 GW. Batteries are expected to account for almost 50 percent of the total investment in the market in 2030. Batteries are, however, expected to account for only a small part of the total installed storage capacity. The following market share is expected in 2030:\footnote{34}

- Sodium-sulphur: 23 percent of the market, SEK 582 billion
- Vanadium redox (VRB): 18 percent of the market, SEK 448 billion
- Lithium-ion: 10 percent of the market, SEK 258 billion

Total investments in the battery market are expected to be equal to SEK 1,280 billion.

The market share estimated by the Boston Consulting Group above can, however, be questioned as other market predictions indicate that lithium-ion batteries are expected to dominate the market in electrochemical energy storage.\footnote{35}

Figure 17 shows the current installed battery capacity and planned capacity.

**Battery technology**

Below is a more detailed description of some of the various battery technologies.

Important parameters for a battery’s usefulness are its discharge speed (how fast the battery discharges), depth of discharge (how much of the total capacity is used in cyclic operation, i.e. if the depth is 20 percent, the battery is delivering 20 percent of its total capacity) and the number of discharge cycles during the battery’s life.

**Sodium-sulphur (molten salt) batteries**

Sodium-sulphur batteries (NaS) consist of liquid sodium and sulphur. This battery technology is mature and has a system efficiency of 80 percent.\footnote{36} The expected life is 15 years or 4,500 cycles.\footnote{37}

Energy density of this type of battery is around 60 Wh/kg and they cost around SEK 4,800/kWh in 2014.\footnote{38}

**Lead-acid**

This battery technology is also mature. The battery life varies greatly depending on the application, discharge speed and the number of discharge cycles.

Lead-acid batteries are very widely used in combination with small-scale renewable energy production. In 1995-2009, for example, 50,000 solar battery systems were installed in homes in Morocco, and in Bangladesh 3.5 million homes have solar battery systems.\footnote{39}

The main problem for many lead-acid batteries is that they still have a low depth of discharge (less than 20 percent), low number of life cycles (fewer than 500) and a short life (3-4 years).

The energy density is around 50 Wh/kg, which is generally lower than for lithium-ion batteries. New versions of lead-acid batteries have, however, demonstrated significantly better properties, such as 2,800 cycles, 50 percent discharge depth and a life of 17 years.\footnote{40}

**Lithium-ion**

Lithium-ion batteries have high energy density and speed of discharge compared to other batteries. They are therefore efficient relative to their size and this is...
Table 6: Data for lithium-ion batteries.41

<table>
<thead>
<tr>
<th>Lithium-</th>
<th>Cathode</th>
<th>Anode</th>
<th>Electrolysis</th>
<th>Energy density (Wh/kg)</th>
<th>Number of cycles</th>
<th>2014 SEK/kWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iron phosphate (LFP)</td>
<td>LFP</td>
<td>Graphite</td>
<td>Lithium-carbonate</td>
<td>85–105</td>
<td>200–2,000</td>
<td>3,850–5,950</td>
</tr>
<tr>
<td>Manganese oxide (LMO)</td>
<td>LMO</td>
<td>Graphite</td>
<td>Lithium-carbonate</td>
<td>140–180</td>
<td>800–2,000</td>
<td>3,150–4,900</td>
</tr>
<tr>
<td>Titanium oxide (LTO)</td>
<td>LMO</td>
<td>LTO</td>
<td>Lithium-polymer</td>
<td>80–95</td>
<td>2,000–25,000</td>
<td>6,300–15,400</td>
</tr>
<tr>
<td>Cobalt oxide (LCO)</td>
<td>LCO</td>
<td>Graphite</td>
<td>Lithium-carbonate</td>
<td>140–200</td>
<td>300–800</td>
<td>1,750–3,500</td>
</tr>
<tr>
<td>Nickel cobalt aluminium (NCA)</td>
<td>NCA</td>
<td>Graphite</td>
<td>Lithium-carbonate</td>
<td>120–160</td>
<td>800–5,000</td>
<td>1,680–2,660</td>
</tr>
<tr>
<td>Nickel manganese cobalt (NMC)</td>
<td>NMC</td>
<td>Graphite, Silicone</td>
<td>Lithium-carbonate</td>
<td>120–140</td>
<td>800–2,000</td>
<td>3,850–5,250</td>
</tr>
</tbody>
</table>

constantly being improved. They have a high efficiency level of 80–90 percent.

Lithium-ion batteries consist of an array of chemical combinations, all with unique properties and costs. Table 6 shows the different types of lithium-ion batteries that exist and technical data for them.

One of the main challenges for lithium-ion batteries is safety. Due to their high energy density, the flammability of lithium and the oxygen content, they can overheat and start to burn.42

**Flow batteries**

Unlike other batteries, a flow battery has liquid electrodes. The liquid electrodes can be stored outside the battery cell, allowing larger volumes to be stored. This is one of the benefits of flow batteries and another is that they have short reaction times. Flow batteries also have a long life due to the fluid electrodes. The drawback with these types of batteries is that they have low energy density and that, due to their size, they are not suitable for mobile applications.

**Power to gas**

Power to gas (P2G) is a method used for large-scale storage of electrical energy in the form of gas. The concept can be briefly described as electricity being used to produce hydrogen gas by means of electrolysis.

The technology can, for example, be used to take surplus electricity from intermittent electricity generation, i.e. from wind and solar. The hydrogen gas produced can, for example, be used to boost biogas production, or can be used directly or stored in gas grids. The hydrogen gas produced in a Sabatier reaction can be used to produce methane gas directly.

The diagram in Figure 18 illustrates the production process for hydrogen gas (H₂) and subsequent production of methane gas (CH₄).
Table 7: Power to gas, H₂ production.  
AEC: Alkaline electrolysis  
PEM: Polymer electrolyte membrane/Proton exchange membrane

<table>
<thead>
<tr>
<th>Power to gas, H₂ production</th>
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<tbody>
<tr>
<td><strong>Used for</strong></td>
</tr>
<tr>
<td><strong>Usage time</strong></td>
</tr>
<tr>
<td><strong>Capacity</strong></td>
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<tr>
<td><strong>Energy density</strong></td>
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<tr>
<td><strong>Efficiency level</strong></td>
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<td><strong>Losses</strong></td>
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<td><strong>Start-up time</strong></td>
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<td><strong>Life</strong></td>
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<td><strong>Production phase</strong></td>
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<tr>
<td><strong>Investment cost</strong></td>
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<td><strong>Geographical requirements</strong></td>
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</tbody>
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Table 8: Power to gas, CH₄ production.

<table>
<thead>
<tr>
<th>Power to gas, CH₄ production</th>
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<tbody>
<tr>
<td><strong>Used for</strong></td>
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<tr>
<td><strong>Usage time</strong></td>
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<tr>
<td><strong>Capacity</strong></td>
</tr>
<tr>
<td><strong>Energy density</strong></td>
</tr>
<tr>
<td><strong>Efficiency level</strong></td>
</tr>
<tr>
<td><strong>Losses</strong></td>
</tr>
<tr>
<td><strong>Start-up time</strong></td>
</tr>
<tr>
<td><strong>Life</strong></td>
</tr>
<tr>
<td><strong>Production phase</strong></td>
</tr>
<tr>
<td><strong>Investment cost</strong></td>
</tr>
<tr>
<td><strong>Geographical requirements</strong></td>
</tr>
</tbody>
</table>

Table 7 and 8 show information on P2G in the two cases where hydrogen gas (H₂) and methane gas (CH₄) are produced.

In general the technology is very flexible in terms of capacity and is particularly well-suited for decentralised applications. No specific geological conditions are required. In 2025 storage costs (calculated as levelised cost of energy, LCOE) for 180 cycles a year are expected to be sek 1.30/kWh, and for 360 cycles a year about sek 1.15/kWh.44

Extensive research is taking place to develop technology for hydrogen gas storage using a number of different methods.

**Flywheels**

A flywheel stores kinetic energy. A high-mass rotor spins fast and without resistance using magnetic bearings. By reducing the rotor speed energy is extracted and by adding energy to the rotor it spins faster and the energy is stored.

In most modern flywheel technologies the rotor system is enclosed for reasons of safety and efficiency. It is usually in a protective steel case encapsulating the rotor, engine/generator and other rotating parts. This also prevents it from causing harm to personnel and surrounding equipment in the case of a possible ro-
tor failure. Encapsulation also has a positive impact on the flywheel’s efficiency. The rotor often spins in a vacuum enclosure or one filled with low-friction gases such as helium.

Flywheel technology has high energy density which means that it requires little space to store a relatively large amount of energy. Response times for flywheel technology are also very short, often 4 milliseconds or shorter, and they can be deployed for short periods of up to an hour. A flywheel can be dimensioned at between 100 kW and 1,650 kW. They have an efficiency level of around 93 percent and an estimated life of around 20 years.46

Thanks to the short response time, a typical application for flywheels is an uninterrupted power supply (UPS).47

Beacon Power has developed large-scale flywheel solutions such as a unit with a capacity of 20 MW (200 units of 100 kW, around 25 kWh) which is mainly used to correct frequency imbalances in New York. The use of flywheel technology solutions for voltage quality applications is expected to increase significantly over the next decade.48 Sales are expected to increase significantly in Europe and Asia, while the US is expected to remain the largest market until 2021.49

SMES – Superconducting magnetic energy storage

SMES is a type of magnetic energy storage that uses superconductors. SMES has a high efficiency level of over 90 percent and is based on instantaneous charging/discharging cycles, making SMES extremely well-suited for electricity quality support solutions. SMES solutions are generally small scale with a current maximum storage capacity of around 10 MW. The physical size of the spool is a limiting factor for this technology. The extremely heavy weight of magnetic systems a natural obstacle for upscaling. It is essentially impossible to build and implement larger scale SMES solutions. Increasing the thickness of the superconducting threads would raise the heat that develops and lower efficiency. Also, the effects of the magnetic field around the equipment has not yet been thoroughly analysed.

SMES is a technology that is the most established among the technical high voltage solutions in installations in Europe, Japan and the US. The US is expected to be an important market for SMES technology, along with Germany and Japan, but not on the same level as the fast markets for flywheel and supercapacitor technologies.50

Supercapacitors

The advantages of supercapacitors are their high energy density, efficiency and the number of possible discharge cycles during their life; they have the ability to charge and discharge in more than one million cycles.

Supercapacitor technology is on the cusp of a breakthrough in the market for storage solutions for power grids. The US, Korea and Japan are expected to be the main markets for supercapacitors.51

Table 9 shows a comparison of SMES, flywheels and supercapacitors.
4. Comparison of different storage technologies

As indicated earlier, the various storage technologies have different advantages and drawbacks. The table below shows a comparison of the different types of storage technology presented in this report.

<table>
<thead>
<tr>
<th>Energy storage method</th>
<th>Capacity (MW)</th>
<th>Usage time</th>
<th>Efficiency level (%)</th>
<th>Start-up time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pumped hydropower plant</td>
<td>&lt; 5000</td>
<td>1–24 h</td>
<td>65–85</td>
<td>s-min</td>
</tr>
<tr>
<td>Compressed air technology</td>
<td>Depends on storage capacity</td>
<td>1–24 h</td>
<td>42–54 (normal) 70 (advanced adiabatic)</td>
<td>min</td>
</tr>
<tr>
<td>Lead-based batteries</td>
<td>0.001–50</td>
<td>s–3 h</td>
<td>60–95</td>
<td>-</td>
</tr>
<tr>
<td>Lithium-based batteries</td>
<td>0.001–0.1</td>
<td>min–h</td>
<td>85–99</td>
<td>-</td>
</tr>
<tr>
<td>Flow batteries</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vanadium redox batteries</td>
<td>0.03–7</td>
<td>s–10 h</td>
<td>85</td>
<td>ms</td>
</tr>
<tr>
<td>Flow batteries</td>
<td>0.05–2</td>
<td>s–10 h</td>
<td>70–75</td>
<td>ms</td>
</tr>
<tr>
<td>Zinc bromide batteries</td>
<td>0.5–50</td>
<td>s–h</td>
<td>85–90</td>
<td>-</td>
</tr>
<tr>
<td>Sodium-sulphur batteries</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Power to gas, H₂ production</td>
<td>kW–GW</td>
<td>s–months</td>
<td>62–82</td>
<td>s-min</td>
</tr>
<tr>
<td>Power to gas, CH₄ production</td>
<td>kW–GW</td>
<td>s–months</td>
<td>49–56</td>
<td>min–h</td>
</tr>
<tr>
<td>Flywheels</td>
<td>0.002–20</td>
<td>s–min</td>
<td>95</td>
<td>s-min</td>
</tr>
<tr>
<td>SMES</td>
<td>0.001–10</td>
<td>s</td>
<td>90</td>
<td>ms</td>
</tr>
<tr>
<td>Supercapacitors</td>
<td>0.01–1</td>
<td>ms–s</td>
<td>95</td>
<td>ms</td>
</tr>
</tbody>
</table>
5. Appendix

FOOTNOTES


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