Chapter 9

Large-Scale Hydrogen Energy Storage

Erik Wolf
Siemens AG

Chapter Outline

9.1 INTRODUCTION

For the integration of fluctuating renewable energies storage technologies are essential. Large scale storage provides grid stability, which are fundamental for a reliable energy systems and the energy balancing in hours to weeks time ranges to match demand and supply. Own system analysis showed that storage needs are in the two-digit terawatt hour and gigawatt range. Other reports confirm that assessment by stating that by 2040, 40 TWh would be required [1].

The overview of various storage types as shown in Figure 9.1 indicates, that hydrogen can cover energy capacities up to very large capacities and offers a broad power

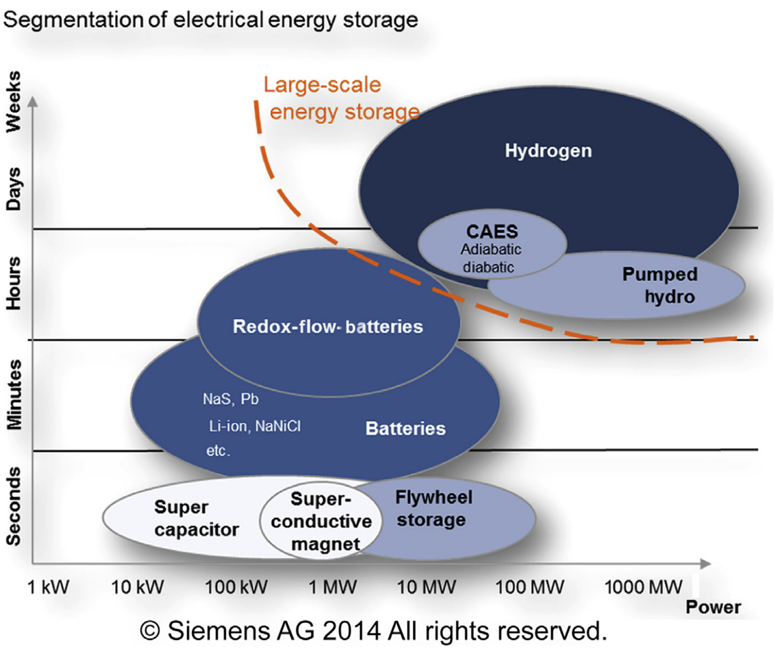
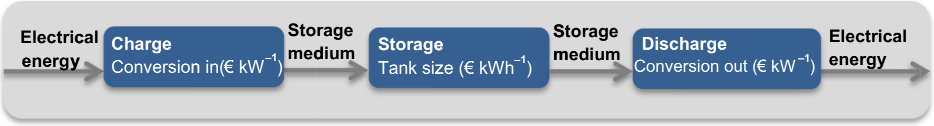


FIGURE 9.1 Overview of storage technologies and their typical power and capacity ranges.

Electrochemical Energy Storage for Renewable Sources and Grid Balancing. http://dx.doi.org/10.1016/B978-0-444-62616-5.00009-7
Copyright © 2015 Siemens AG. Published by Elsevier B.V. All rights reserved.



© Siemens AG 2014 All rights reserved.

FIGURE 9.2 Depiction of main energy storage components.

range too. That storage type is applicable at the community level, in the distribution grid and also for areas of high population density and at the transmission grid level.

As one of the most pressing questions, how to store large quantities of energy at grid level, remains unanswered. The following chapter intents to outline the general components and functions as well as the economics of a large-scale hydrogen energy storage system.

A very general way of depicting energy storage is by imagining a chain of main components connected to each other. As shown in Figure 9.2, that chain consists of a conversion-in, storage, and conversion-out box, which is common in nearly all other storage technologies, where electrons are not directly stored as supercps and superconducting magnet energy storage (SMES).

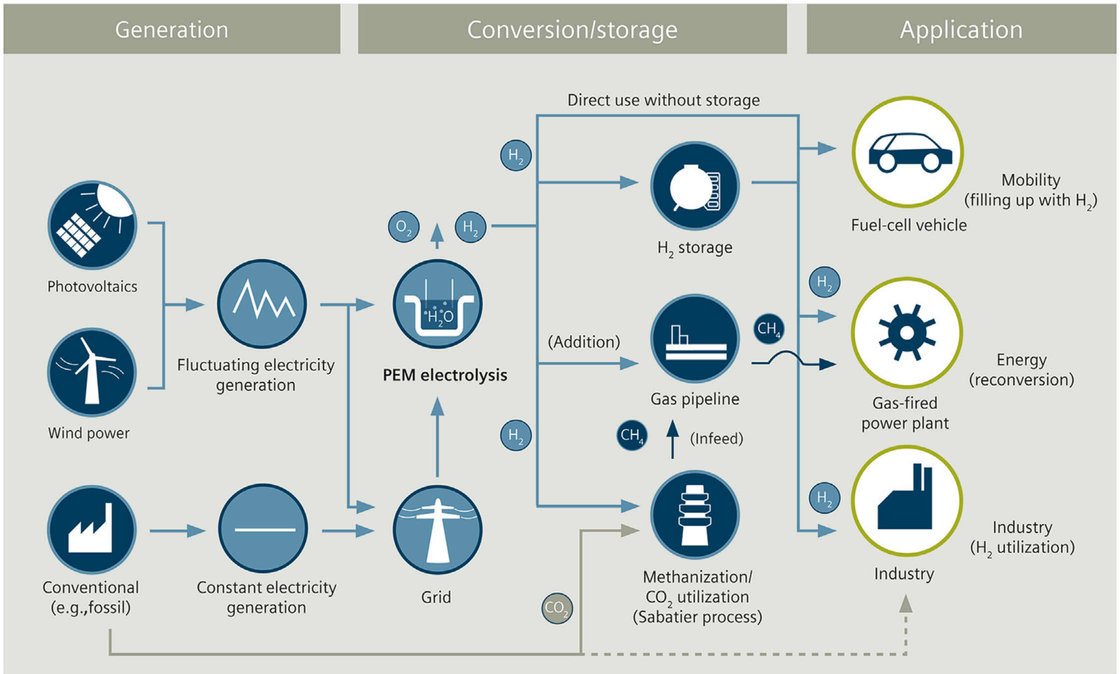
The modularity of hydrogen energy storage systems enables a spatial separation between the major components, such as the electrolyzer, gas storage, and electrical power conversion, which would be beneficial for the application.

The electrolyzer, being the conversion-in component, converts electrical energy into oxygen, low level heat, and hydrogen, which acts as the energy storage medium.

Depending on the volume of gas to be stored, and the local conditions, gas storage is either on the surface, such as tube storage, or underground, preferably in salt caverns. As already mentioned also the gas storage can be spatially separated from the other storage system components. Adding hydrogen to the natural gas (NG) grid, as raw material for chemical processes, and using it as a fuel in the H_2 mobility concept, are other options that uncover the versatility of hydrogen as shown in Figure 9.3.

Various technical options, such as internal combustion gas engines, gas turbine power plants, or fuel cells, are conceivable for the reconversion of the combustible gas into electricity. It presents the finale element of the storage system chain, the conversion-out.

Hydrogen-based energy storage systems allows for a wide bandwidth of applications ranging from domestic application till utility scale applications. The power output could start as low as in the kilowatt class like in fuel cell applications; it can also reach several hundreds of megawatt in large-scale combustion turbine-based energy storage systems. The same applies to the energy content of a storage system that starts in the kilowatt-



© Siemens AG 2014 All rights reserved.

FIGURE 9.3 Applications and examples of use of hydrogen electrolysis.

hour category with some kilograms of hydrogen in pressurized gas steel bottles, and ends at the hundreds of gigawatt-hour size, which is equivalent to 10,000 t of hydrogen in an underground cavern.

In regard to the performance of that storage type it is difficult to quantify exactly the efficiency of such a storage system, since many conversion steps are necessary to produce, store, and reconvert hydrogen into electricity with different technologies being involved. The main contributors to the efficiency are the steps for conversion in and conversion out. Their performance depends on the operating conditions. At high loads especially, electrochemical devices suffer from increasing internal losses, but on the other hand, combustion turbine-based power generation has its highest efficiency at full load. The efficiency for the reconversion step depends on the operational mode and therefore ranges from 60% down to 55% (combined cycle power plant at full load/part load).

9.2 ELECTROLYZER

9.2.1 Introduction

The electrolyzer's main purpose is to convert electrical energy into hydrogen, which becomes the storage medium. Its high load dynamics is used for electrical network stabilization, as it acts as a fast-reacting load sink during times of strong Renewable Energy (RE) generation where it maintains the balance of energy supply and demand. It equalizes the effect of the fluctuating renewable energy fed into the grid.

In this book the chapters 'Hydrogen production from renewable energies—electrolyzer technologies' and 'Proton-exchange membrane (PEM) Electrolyzers and PEM Regenerative Fuel Cells' in detail explain electrolyzer technologies. The current chapter gives therefore only a short overview of the PEM electrolyzer technology and the PEM electrolzyer roadmap of Siemens.

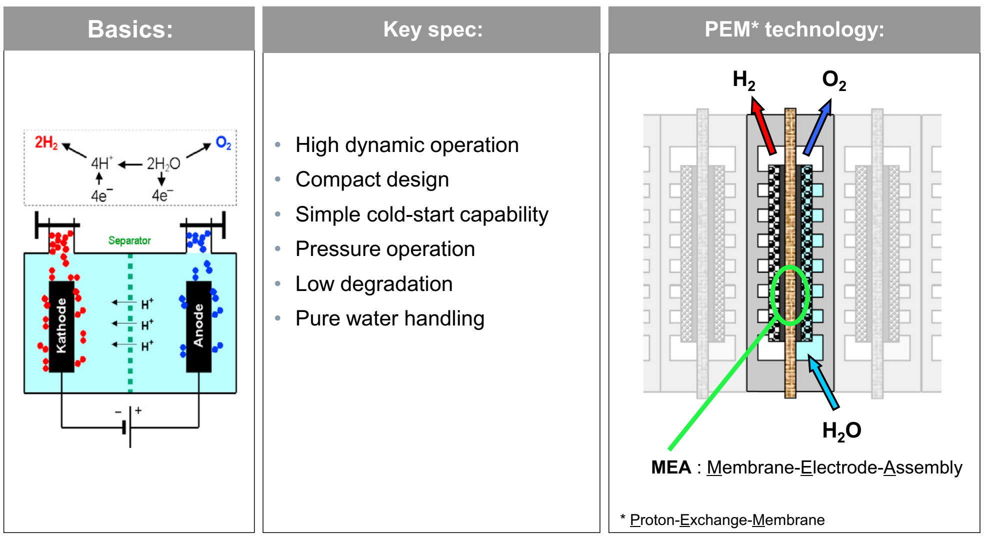
9.2.2 PEM Electrolysis Principle

An electrolysis cell uses electrical energy to split water into its basic elements hydrogen and oxygen. The core of the PEM electrolyzer technology is the proton conducting polymer membrane from which the name is derived. This membrane separates the reaction compartments for hydrogen and oxygen, and also provides the ionic contact between the electrodes, which is essential for the electrochemical process. Production of the gas itself takes place on the surface of the respective precious metal electrode as shown in Figure 9.4.

Beside the hydrogen oxygen also will be produced during the operation of an electrolyzer. There are a number of chemical and biological processes, which can make use of the oxygen. As an example it could be feed to a sewage water plant to improve the conversion rate of the microorganisms. Another application field is the use of oxygen as a bleaching agent.

9.2.3 Parameters of an Envisaged Large-Scale Electrolyzer System

On the basis of know-how gained by designing and analyzing smaller systems, an electrolyzer system with a factor of more than 10 higher power has been envisaged, which delivers peak power as well. The system is constructed by combining large-scale stacks. In the following, initial estimations on hydrogen production and system efficiency have been made and are indicated in Figure 9.5.



© Siemens AG 2014 All rights reserved.

FIGURE 9.4 PEM electrolysis principle and advantages.

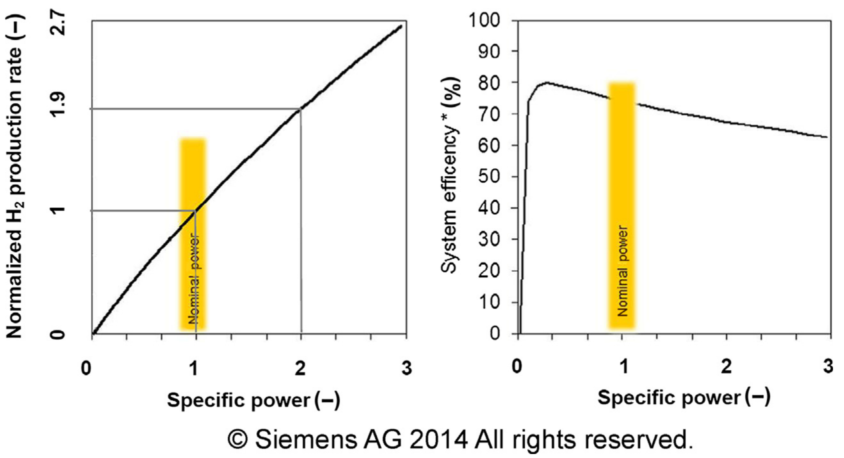


FIGURE 9.5 Parameters of an electrolyzer system.

Nominal power indicates the typical operation point of the system. Lower as well as higher values as the nominal power represent an approximation of the impact regarding H_2 production rate and system efficiency. In part load operation the efficiency will be at maximum until the tipping point where the energy consumption of the must run components like the control system or ventilation becomes dominant. At higher loads the efficiency decreases as the inner losses of the stack like the ohmic resistance becomes more dominant.

9.2.4 Development Roadmap for PEM Electrolyzer Systems at Siemens

Currently, first PEM demonstration systems with peak power of 300 kW are under evaluation. Among other effects, the impact of different load profiles on the system is being studied.

One of the goals of the current development road map is to design stacks in the megawatt class within the next 2–3 years. By modular combination of several stacks it will then be possible to configure PEM electrolyzer systems in the two-digit megawatt class.

Furthermore, stacks with a nominal power of approximately 5 MW are planned within the next 5–6 years. Subsequent to this, electrolyzer systems in the three-digit megawatt class will be possible as well.

A number of development steps are necessary in order to reach these technological goals. Up-scaling the active electrode area by a factor of 30, starting from 300 cm^2 to 10,000 cm^2 in the future is a central development goal for the success of large-scale stack designs. Main items for designing a large cell are the supply and removal of substances, heat, and current. These issues usually require a different technical solution compared to small cells. Moreover, the number of cells per stack will have to be increased too. Both measures will result in an increase in stack power. Parallel to this, the technologies for mass production of components will be defined, set up, and qualified. The development and implementation of central regulation structures for large-scale systems will be carried out simultaneously.

9.3 HYDROGEN GAS STORAGE

Subsequent to the electrolysis process, the energy carrier hydrogen gas will be stored. A number of different solutions are available. Solid state storages like metal hydrides or chemical solvents provide a high storage density. Low investment costs are very important for large-scale storages in the three-digit megawatt-hour to gigawatt-hour range with a small number of charge and discharge cycles. Therefore, this chapter is focused on ordinary gas storages such as high-pressure gas storage vessels and underground salt caverns.

Figure 9.6 provides a general overview of different low- to high-pressure gas storages and their typical energy

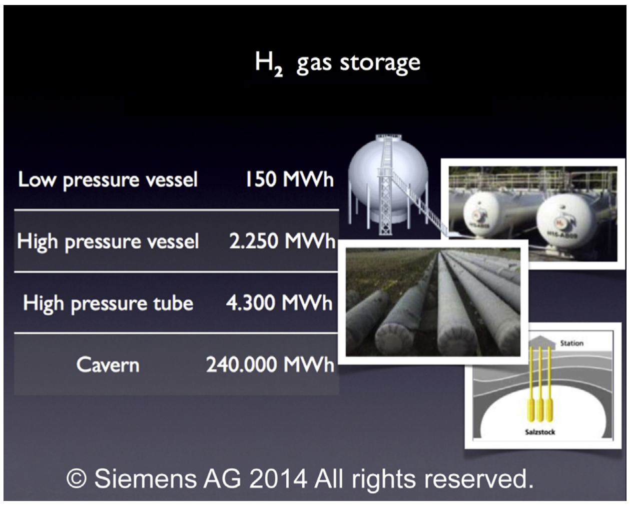


FIGURE 9.6 Overview of pressurized gas storages and their typical energy content in megawatt-hour thermal.

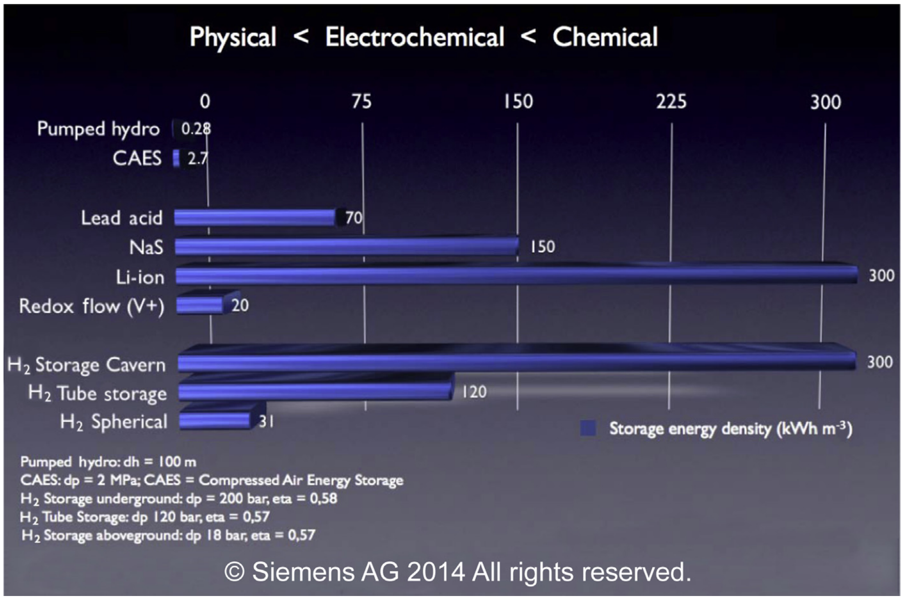


FIGURE 9.7 Typical volumetric energy density of various energy storages.

capacity. As usual for combustible gases, it is related to thermal energy. By multiplying these figures with the typical conversion efficiency of a gas engine, combustion turbine or fuel cell, the thermal energy can easily be translated into the electrical energy content.

The energy density increases with pressure. For the low-pressure vessel it is 30 $kWh_{el}\ m^{-3}$ @ delta p of 20 bar, for the pipe storage it is 120 $kWh_{el}\ m^{-3}$ @ delta p of 80 bar, and for salt caverns it can be as high as 300 $kWh_{el}\ m^{-3}$ @ delta p of 200 bar, which would be similar to a Li-ion battery cell.

A comparison of the volumetric energy density of different storage technologies is provided in Figure 9.7, which also compares three principle types of storage technologies: physical, electrochemical, and chemical energy storages, whereby the volumetric energy density increases with one order of magnitude between each class.

9.3.1 Underground Hydrogen Storage in Salt Caverns

Salt formations at depths of several 100 meters offer a series of suitable and beneficial conditions for the construction and operation of high-pressure gas storages:

- Extremely high gas tightness of rock salt even at high pressures
- High operational pressures at depths of down to almost 2000 m allowing high energy densities due to the higher operation pressure of the cavern
- Geometrical volumes of 500,000 m^3 and above allowing storage capacities of several thousand tons hydrogen
- Small land footprint on the surface
- Low specific investment costs per megawatt-hour of storage
- Very secure against manipulation and obstruction

High-pressure NG is also stored in

- depleted oil fields, and preferably gas fields
- aquifer formations, saline groundwater-bearing porous reservoirs

These two options, see Figure 9.8 & Figure 9.9, are currently under investigation to determine whether they can be used for hydrogen gas storage as well. Depleted oil and gas fields will affect the gas compositions as the hydrogen would enter spaces still containing a significant amount of residual hydrocarbons. That in return would cause an unpredictable gas composition when released during discharge, which is not beneficial for any reconversion—neither for fuel cells nor for a combustion turbine.

Depleted gas fields and aquifer formations may both suffer from the fact that hydrogen is a highly reactive gas. Such reactions can result in the buildup of biological products or chemical reactions that can both lead to a clogging of the small pores within such reservoir horizons, which hinders the flow of hydrogen during discharge. Depleted gas fields charged with hydrogen will result in fuel quality variations, which may be challenging for the grid operator and for the consumer.

Furthermore, both formations are also limited in their dynamic operation, as the gas must penetrate many pores with relatively high pressure drops.

This is the reason why the most promising option for storing hydrogen underground is considered to be artificial salt caverns, which will be further explained in the following section.

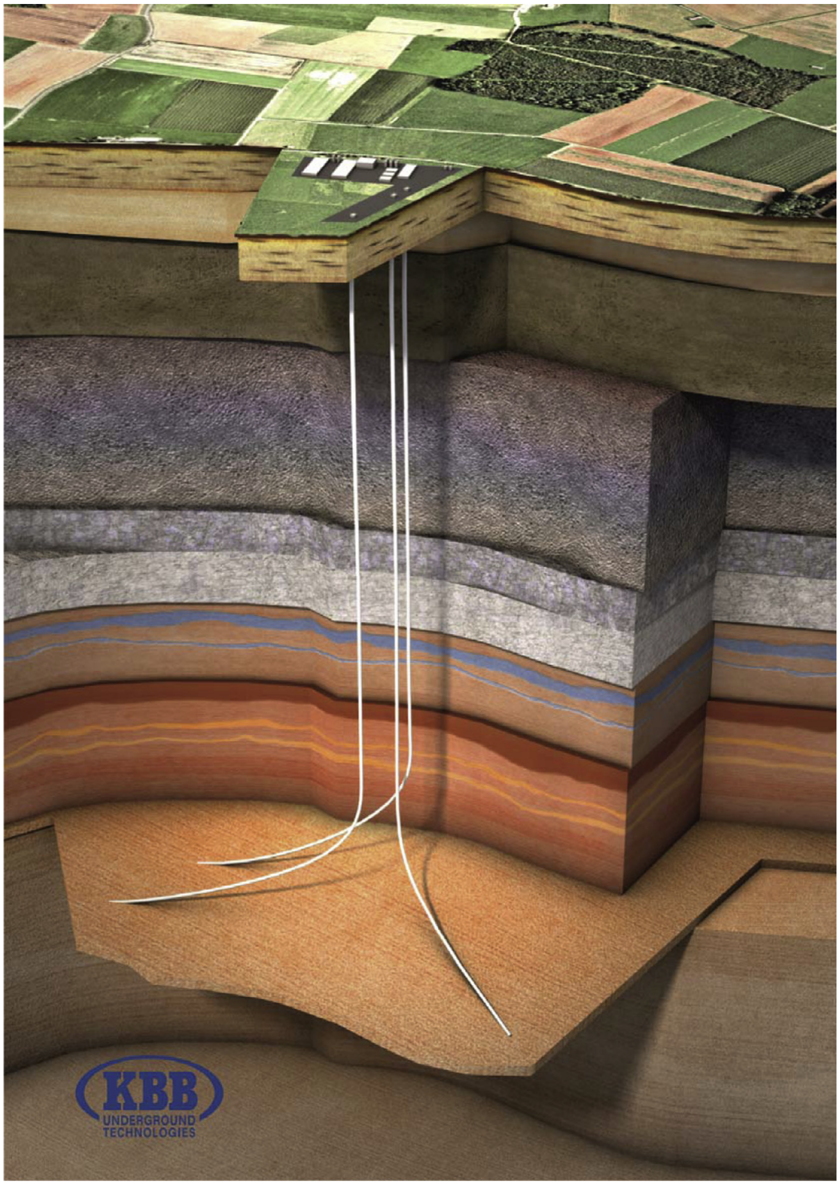


FIGURE 9.8 Gas storage in depleted oil and gas fields.

9.3.2 Utilization of Artificial, Mined Underground Salt Caverns and Their Potential

Salt caverns, as shown in Figure 9.9, are a well-established way of storing large quantities of NG in Germany. About 24% of Germany's NG reserves are stored in caverns. Nearly 200 such caverns are in operation or close to becoming operational, and there is still a large potential for further storage capacities. The reasons for the recent boom in such NG storage projects is the high flexibility of charging and discharging the gas, and the good availability of suitable formations, especially in the northern part of Germany. These circumstances also underpin the high attractiveness of hydrogen storage projects.

The amount of work required for geological exploration prior to a gas storage project is usually minor because most such formations have already been well explored in the past for oil and gas.

For many years, a small number of salt caverns have also been used to store hydrogen. Hydrogen storage facilities of this kind are in Teesside, Great Britain (3 caverns, 70,000 m^3 each, 370 m); Clemens Dome, Texas (1 cavern, 580,000 m^3, 1000–1300 m); and Moss Bluff, Texas (1 cavern, 566,000 m^3, 335–1400 m), USA, where they are integrated in petrochemical factories. The leakage rates of

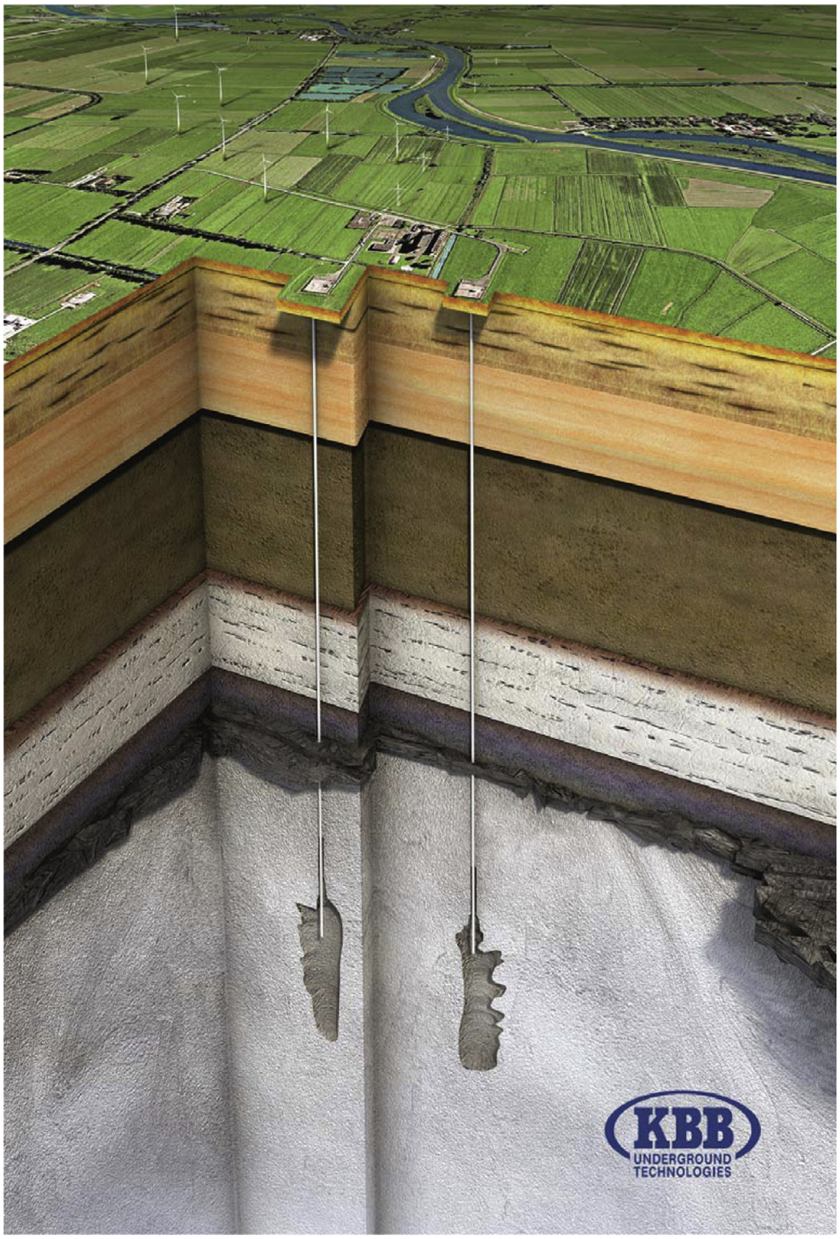


FIGURE 9.9 Artificial underground salt cavern.

hydrogen through salt are negligible and at the limit of what can be detected. Currently, for use with hydrogen, German industry adopts the safety equipment installed in the wellhead, and within the cased well connecting the cavity to the outside world, according to the latest European safety standards.

Typical technical design parameters of a hydrogen cavern at 1000 m depth are a volume of 500,000 m^3, and an operational pressure range between 60 bar and 180 bar. The storage capacity provided would amount to 140 GWh thermal or 85 GWh of electrical energy equivalent—10 times the energy capacity of Germany's biggest pumped hydrostorage in Goldisthal. Larger cavern arrays with up to 20 caverns could provide 1700 GWh of electrical energy equivalent, which is a substantial amount considering that all pumped storages have an aggregate capacity of 40 GWh.

The power output of a cavern depends on the well head and the thermodynamic limits of the cavity and is approximately 700 MW.

The comparison between the different underground storage options concludes that at the current state of technology, predominantly salt caverns will be of importance for future hydrogen storages. Consequently, the

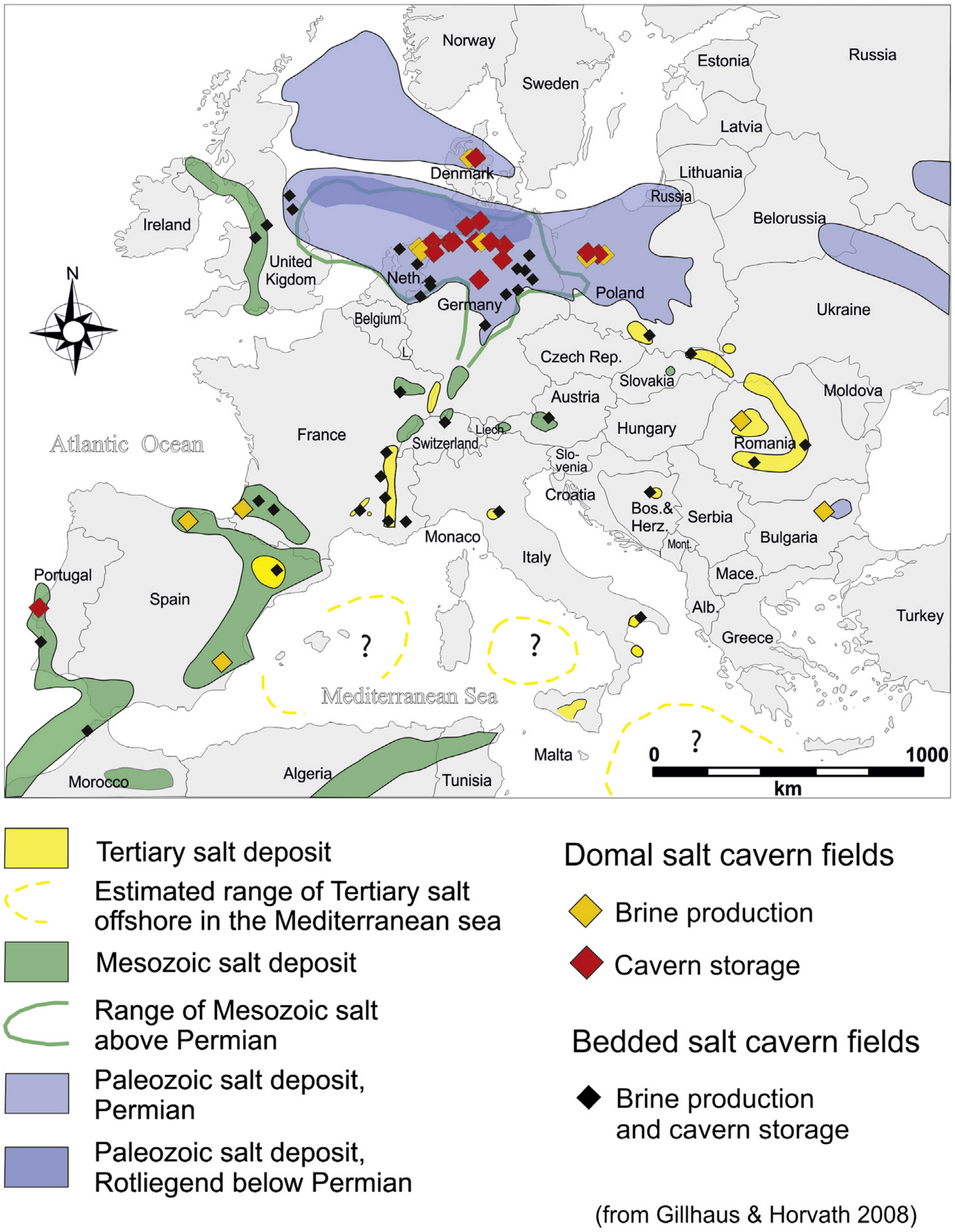


FIGURE 9.10 Salt deposits and cavern projects in europe [2].

focus for underground storage exploration is in regions with salt deposits. Unfortunately, the distribution of salt deposits overall is not equal. The light blue and blue areas in Figure 9.10 and Figure 9.11 show the situation in Europe and in Germany. Black and red diamonds represent actual caverns and cavern fields. An EU funded research project has been started with the aim of investigating the potential for storing hydrogen in Europe. As a result of the work, information will be provided on the location and the storage capacity for a number of selected countries.

9.4 RECONVERSION OF THE HYDROGEN INTO ELECTRICITY

Various technical options are available to reconvert the energy carrier hydrogen into electricity. In large-scale applications starting at 30 MW power output, the use of highly efficient combined cycle power plants will be a preferable solution. Such power plants consist of a combustion turbine, which burns the hydrogen, and a steam turbine that utilizes the gas turbine's released exhaust gas heat. Such power plants are highly flexible, and can contribute to the daily peak power demand.

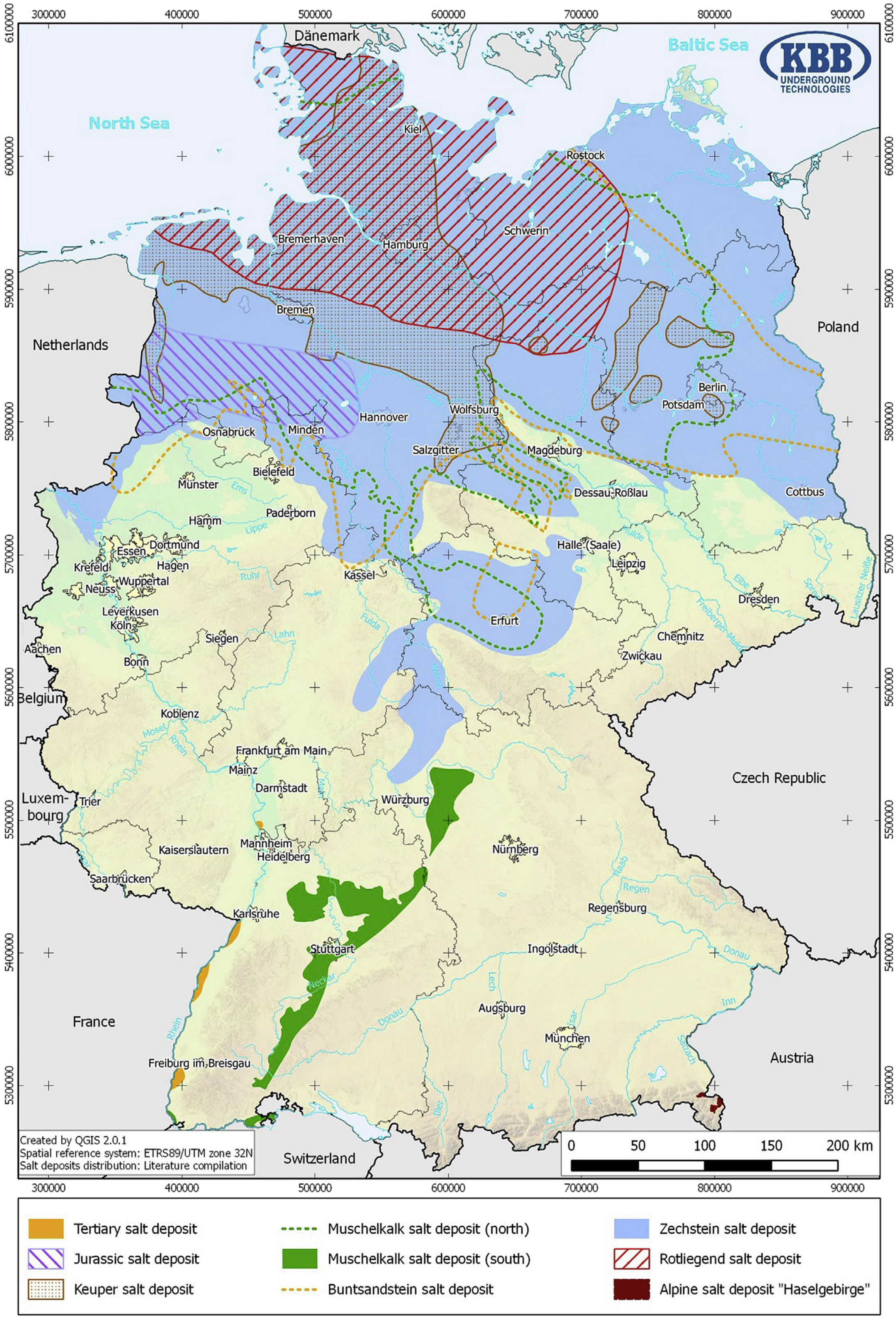


FIGURE 9.11 Overview of salt deposits and caverns in germany.

Furthermore, they can also operate similar to base load units for a couple of days or weeks during low renewable energy production. Additionally, it stabilizes the grid by providing short circuit current. The characteristic short circuit capability due to the synchronous generator gains more and more in importance due to the increase of the inverter-based energy feed-in of wind turbines and photovoltaic (PV)-based solar power. The ability of wind and PV power generators to compensate for highly dynamic grid operation events like load rejection, inrush current, and the need for short circuit current to trigger the current grid protection devices, is very limited compared to synchronous generators.

In the early stages, smaller power plant solutions such as those used at municipal level will emerge as pictured in Figure 9.12. The northern part of Germany in particular, with its high share of wind power, could become a self-sustaining region. Such projects, currently in discussion, will enable the sector to gain more experience on how to optimize and use hydrogen storages. As the conversion of the energy system continues, the power of electrolyzer will further increase into the double digit megawatt class.

In order to fulfill very high load flexibilities in combination with good part load efficiencies multiple gas turbines can be installed in parallel and operated in single-, double-, or as shown in Figure 9.13 triple-unit operation mode.

9.4.1 Aspects Related to the Electricity Grid

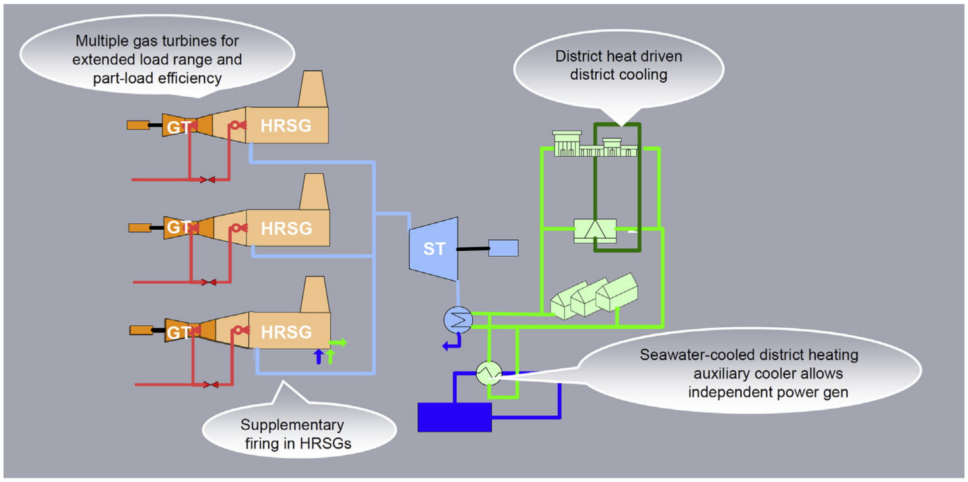
The energy storage system must satisfy two main requirements. On the one hand, it maintains the equilibrium of energy demand and supply by charging or discharging energy, as well as providing an energy reserve (megawatt-hour/gigawatt-hour) for the grid. On the other hand, it has to take over the current responsibility of the conventional power plants to stabilize the grid, mainly represented by power (megawatt/gigawatt), and also by other more complex parameters. This chapter briefly describes the context in which a storage system will operate.

In the conventional energy system, the consumers cause the main proportion of the power demand variation represented by peak and off-peak time during the day and the seasonal influence during the course of a year. With an increasing share of renewable generation, the volatility of the energy feed-in caused by the natural fluctuation of wind and solar is superimposed on the load dynamics of the consumers. The need for flexibility of the grid increases, and subsequently, this must be provided by the connected generators and consumers. Energy that cannot be integrated at a certain point in time will have to be taken up by storage systems with high load dynamics, and it must be released during supply shortages later, also with high load dynamics. In conjunction with parameters affecting grid stability such as short circuit current, reactive and active power adjustment, frequency stabilization, and others, the combination of highly flexible electrolyzer for energy take-in, and generation by flexible and grid-stabilizing combined cycle power plants offers a technical answer to the challenges faced.

The magnitude of stabilization and the energy reserve requirements directly depend on the local grid capacity, the type of generators (e.g., PV, biomass), and consumers—like industrial region vs rural villages—and must be investigated in grid studies of the respective region. It will define the type of storage to be employed.

FIGURE 9.12 Municipal gas power plant.

© Siemens AG 2014 All rights reserved.



© Siemens AG 2014 All rights reserved.

FIGURE 9.13 Multiple gas turbines for extended load range and high part load efficiency.

9.4.2 Power to Gas Solution

Large-scale hydrogen storage is one feasible way to cope with temporally surplus of renewable energy to build up provisions for compensation at a later time when energy demand exceeds the supply. Utilizing the gas grid would pose a further option for storing energy at large scale. The beauty of that concept is that it is based on an already existing infrastructure. Germany's gas grid has an inventory of 200 TWh [3]. It comprises the pipeline system, underground storage facilities like caverns and aquifers, or depleted gas fields. The majority of the gas consumed 800 TWh per year [4] is used in chemical processes, heating, and a smaller fraction for power generation and mobility.

One way to benefit from the storage capabilities of these parts of the energy infrastructure is possible by direct injection of hydrogen into the NG. Up to a concentration of 5% volume of the NG volume can be replaced by hydrogen with no problem. Also in discussions are concentrations of up to 10% volume but there are limiting factors that need further evaluation [5]. Special attention, however, has to be taken on the H_2 concentration on the point of H_2 feed-in the NG pipeline. The amount of H_2 admixed to the natural gas (NG) must be matched to the NG-flow in the pipeline in order not to exceed the H_2 concentration limits. Thereby is can become necessary to employ a H_2-storage near the feed-in point. That would ensures the required admixing quotes independent of the NG-flow and the H_2-production rate.

Furthermore, it has to take into account that for different applications the H_2 concentration in NG is limited: gas turbine $\leq$4% H_2, NG-ICE $\leq$2% H_2, gas heating $\leq$20% H_2. Further development is to be carried out in order to allow higher H_2 content in the NG.

One major hurdle may be linked to the storage of the gas mixture. In contrast to salt caverns, which do not interact with hydrogen at all, the status regarding the compatibility of an aquifer or porous stone storage to store mixtures of NG and hydrogen is still in question [6]. Chemical and biological reactions my cause damage to those types of storages.

Another way to utilize the gas grid as storage for integration of renewable energy is to further process the electrolytic generated hydrogen by a methanation. The Sabatier process uses, carbon dioxide, which needs to be supplied, and hydrogen to form methane.

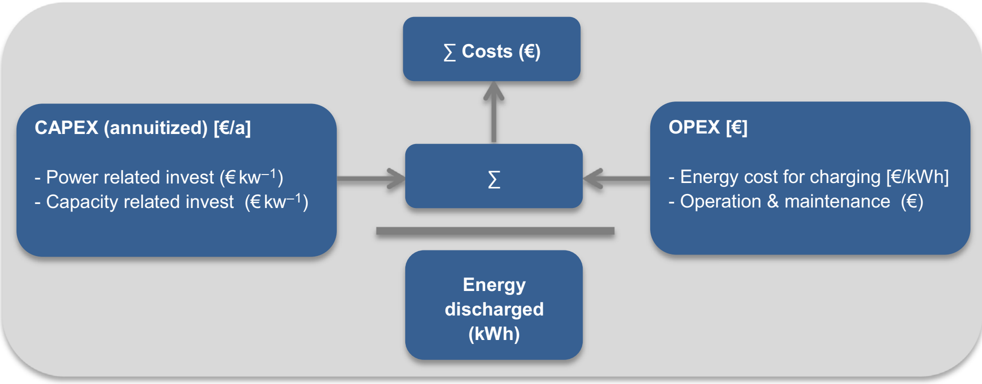
$$CO_2 + 4H_2 \Rightarrow CH_4 + 2H_2O\left(\Delta_R H^0 = -165\ \text{KJ/mol}\right)$$

This synthetic natural gas (SNG) can be fed into the NG grid without limitations. However, it should be taken into account that the additional hardware required to perform the product syntheses will roughly double the capital expenditure (CAPEX) required. The CO_2 extraction and supply will add another cost portion. In order to produce CO_2 neutral methane, the CO_2 used must be of biological origin. For example, the CO_2 released during biogas process can be considered as CO_2 neutral [7]. However, those resources are limited and may allow satisfying a fraction of the required energy only.

The SNG can be used also as fuel for NG-ICE cars. Audi opened in June 2013 in Werlte (Germany) a pilot plant for the production of SNG (1000 t SNG/a), which is called 'e-gas.'

9.5 COST ISSUES: LEVELIZED COST OF ENERGY

Levelized cost of energy (LCOE) is a method to calculate energy costs based on operational expenditure (OPEX) and CAPEX. This allows the economics of various storage technologies to be compared. The method sums up all costs



© Siemens AG 2014 All rights reserved.

FIGURE 9.14 Simplified calculation of the levelized cost of energy.

and relates them, as pictured in Figure 9.14, to the energy discharged on an annual basis.

The CAPEX term of the equation accounts for the cost of capital related to power and capacity investments to be made. The OPEX term accumulates operational and maintenance costs and the cost of energy used during charging. All costs are summed up in the cost term and are related to the energy discharged. The result is the LCOE. In Figure 9.2 the three main components of storages together with its specific costs are shown in the direction of energy flow. The CAPEX accumulates the costs of the main investments of the storage.

The so-called conversion chain describes the storage in a simplified way. The energy, which is used to charge the storage unit, is converted into hydrogen. The electrolyzer represents this part of the chain. Its specific investment costs are related to power (euros per kilowatt. Afterward, the produced hydrogen will be stored in pressurized gas tanks or caverns. The size of the tank defines the storage capacity (x-Wh), the duration of the charge and discharge, and the costs, which are related to energy (euros per kilowatt-hour). This term of the equation determines the type of technology that will be used, as it becomes the dominant investment part if the wrong option is chosen. Subsequent to the gas storage, the last conversion step takes place: the reconversion of the hydrogen to electrical energy. The specific investment costs are related to power (euros per kilowatt).

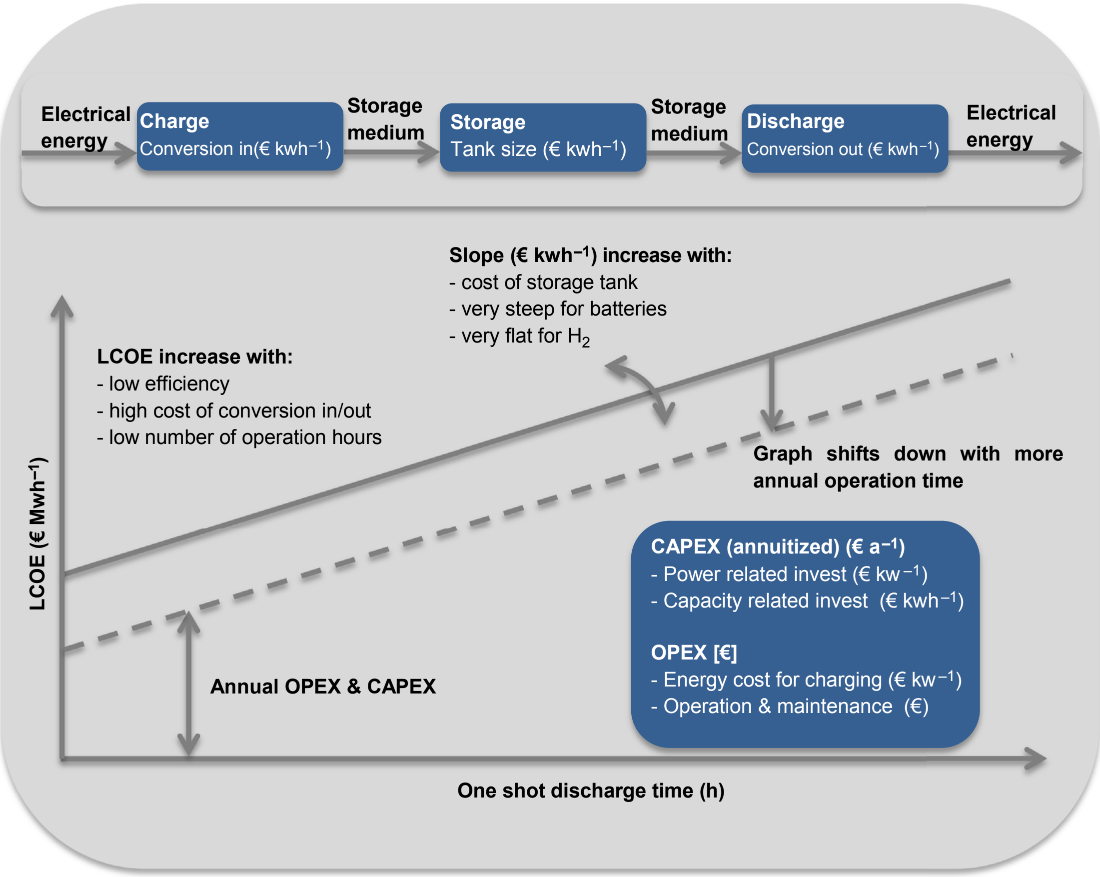
OPEX accounts for the energy costs to charge the storage, the storage efficiency, self-discharge and stand-by losses, as well as the operating and maintenance costs.

OPEX and CAPEX can be estimated fairly accurately. However, the annual amount of energy discharged must be seen as an assumption. Further system simulation must be undertaken to confirm them on regional and country-specific basis.

Figure 9.15 shows the characteristic of the LCOE as a function of discharge time. It illustrates the dependency of the LCOE with respect to the different cost drivers. The free parameter on the X-axis is the discharge time, which can also be seen as tank size. It defines the energy amount that can be immediately drawn from the storage. During one year of operation, the storage is charged and discharged multiple times.

The origin of the function is determined by the annual capital and operation costs without the investment costs of the storage tank. The inclination of the linear function depends on the specific investment costs of the storage tank. For battery-based storages it would represent the cost of the battery stack; in the case of the hydrogen storage, the costs for the gas tanks or the cavern. Lower specific tank costs result in a flatter gradient of the LCOE function. Higher annual utilization of the storage would result in a parallel downshift to lower LCOE's.

Figure 9.16 compares the LCOE function of different storage technologies as a function of discharge time. In order to compare different technologies as shown in Figure 9.16, 3000 h of discharge per annum has been assumed. This is in the same range as the annual operation time of today's flexible power plants. System simulations confirm this assumption; however, regional measurements of the supply and demand should be used in conjunction with system simulations. The cost position of the different technologies is estimated at present (dotted line) and in future (solid line). The comparison illustrates well that Li-ion battery-based storage systems are very competitive for short-term storage applications. They offer the lowest price compared to all other technologies, including compressed air storage and hydrogen storage. Up to an operational time of 6 h, compressed air offers the lowest LCOE. For discharge times longer than 6 h, conventional gas power plants are the economic solution. But a gas power plant is not a storage system because it is not able to be charged with renewable energy. Nevertheless, the technology is available and serves as reference base.



© Siemens AG 2014 All rights reserved.

FIGURE 9.15 Trend of the LCOE as a function of discharge time.

Although the hydrogen storage appears not to have a gradient on the LCOE function shown in Figure 9.16, it is actually extremely flat at the scale of a few hours shown here due to the low specific storage tank costs of the hydrogen storage—the inclination becomes visible in timescales of days and weeks. In future, hydrogen storage that provides capacities up to weeks represents a very competitive solution. The gas power plant LCOE function does not have an inclination because it has no dedicated storage tank. The gas network provides NG.

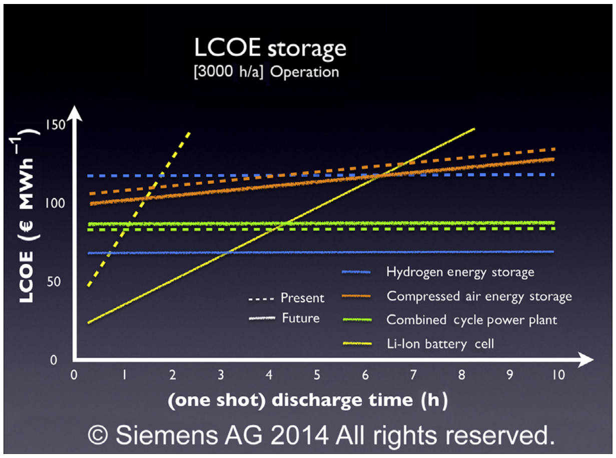


FIGURE 9.16 Comparison of the LCOE of different storage technologies related to an annual energy supply of 3000 h.

This simplified cost model does not take into account the different grid-forming features they provide inherently.

Besides the LCOE, other parameters such as the specific electrical engineering properties of storage technologies, and geographical and regional aspects may be of importance. In practical projects, it leads to rather complex decision processes not limited to costs.

9.6 ACTUAL STATUS AND OUTLOOK

Most of the components that would be required to build hydrogen-based energy storage are based on state-of-the-art technology. However, in specific aspects significant research and development (R&D) work has to be carried out now to have the solution ready in 5–10 years' time.

Large-scale energy storage system based on hydrogen is a solution to answer the question how an energy system based on fluctuating renewable resource could supply secure electrical energy to the grid. The economic evaluation based on the LCOE method shows that the importance of a low-cost storage, as it is the case for hydrogen gas storage, dominates the economics in that particular application field. First applications for that type of storage are the provision control power to the grid, which ensure the supply security of the system without the need of underutilized backup power plants. In the further course of the energy system transformation the necessity to compensate seasonal differences in RE generation and energy demand will gain importance, that is, additive to the first case, the provision of control power.

It is likely to see the first installation in regions with high RE generation rates. In particular the northern part of Germany like Schleswig-Holstein, Lower Saxony, and Brandenburg are suitable regions to install and test that type of storage. First demonstration projects are under evaluation already.

More specific, research work will be spent to investigate how the storage of hydrogen in salt caverns needs to be handled in terms of technical requirements and from the licensing point of view.

At present, PEM electrolyzers have an active cell area per cell of some hundreds of square centimeters, which allows a power consumption of a couple of hundred kilowatts per system or approximately $100\,m^3H_2\,h^{-1}$. The costs electrolyzers are still high and vary between thousands to ten thousands euros per kilowatt and systems. The costs will be reduced by the higher material usage due to increasing active cell areas. In addition, other costs such as for the control system and balance of plant will be reduced as they do not scale up 1:1 when the system size increases. By 2015, the active cell area could reach $1000\,cm^2$ and more. At a system power consumption of 5 MW, more than $1000\,m^3H_2\,h^{-1}$ of hydrogen would be produced. Between 2016 and 2020, the next scale-up step will bring on to the market systems with active cell areas up to $10{,}000\,cm^2$, with power consumption in the higher double digit to triple digit megawatt class. Hydrogen production could reach $100{,}000\,m^3H_2\,h^{-1}$ or higher at installation costs of significantly lower than 1000 € MW^{-1} [8].

The reconversion of hydrogen into electrical energy by means of a gas turbine is another field for intensive R&D work. Burning hydrogen with very little emission in a gas turbine requires a newly designed burner and fuel supply systems. Time-consuming test campaigns to assess the burners' capabilities in regard to the expected operation envelop are another essential development effort that needs to be started up.

Understanding the storage's influence on grid stability when providing positive and negative control power is what matters a electrical grid or system owner. They need to ensure the supply security at a very high level. Adequate control schemes need to be developed, analyzed, and validated in real grids.

ACKNOWLEDGMENT

I like to thank Fritz Crotogino at KBB Underground Technologies GmbH for providing the sections 1.2.1 and 1.2.2.

REFERENCES

[1] J. Auer, DB Research, Moderne Stromspeicher Unverzichtbare Bausteine der Energiewende, 2012-01-31.
[2] A. Gillhaus, P.-L. Horvath, KBB UT, Compilation of Geological and Geotechnical Data of Worldwide Domal Salt Deposits and Domal Salt Cavern Fields, SMRI Research Report, 2007.
[3] M. Specht, et al., Storing bioenergy and renewable electricity in the natural gas grid, FVEE AEE Topics (2009) 69−78.
[4] Bundesanstalt für Geowissenschaften und Rohstoffe, Deutschland−Rohstoffsituation, 2012.
[5] M. Henel, DBI, Ergebnisse des DVGW-Projektes Energiespeicherkonzepte (G1-07-10), December 9, 2012.
[6] F. Crotogino, et al., KBB Underground Technologies, meetings & conferences, 2010−2014.
[7] Erdöl Erdgas Kohle 126.Jg., Heft 10, 2010.
[8] F. Farchmin, in: J. Töpler, J. Lehmann (Eds.), Wasserstoff und Brennstoffzelle, Springer-Verlag, Berlin Heidelberg, 2013. Chapter 12.