NEW APPROACHES OF WATER AS ENERGY STORAGE

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Abstract

Storage of electric energy has great significance for the compensation of the variability between demand and production. Increasing supplies of electricity from wind power and photovoltaic systems in central Europe lead to increasing energy fluctuations. As a consequence, the demand for storage of electric energy rises continuously.

Today pump storage is by far the most important technology for storage of electrical energy. Other methods like compressed air storage, different chemical forms of storage (batteries), flywheel energy storage and the hydrogen technology are either of minor importance or still under development. Compared to conventional pump storage plants, the remaining concepts often have considerable deficits in lifetime, costs and efficiency. However, a further expansion of today's pump storage technology is coupled with topographically suitable locations.

A number of ideas and concepts for the use of hydropower as an energy storage beyond conventional pump storage is already available. These new approaches include concepts in artificially designed landscapes, concepts using existing small reservoirs (e.g. reservoirs used for the production of artificial snow or drinking water supply), large hydraulic energy storage systems with superimposed loads to enhance overall energy density and hydraulic energy storages concepts for offshore areas.

The main aim of this work is to give an overview of existing and conceptual options of energy storage with water as a storage medium. The concepts are described in detail, advantages and disadvantages of the different approaches are pointed out.

Introduction

Man-made climate change leads to a tendency of rethinking energy production methods. It is attempted to replace fossil fuels by renewable energy sources. Especially in the field of electricity production, a big turn has already taken place. In Germany, the generation of electricity from renewable sources has increased from 3,1 % in 1990 to 17,1 % in 2010 (BMU, 2011). The main renewable energy sources in 2010 were wind (6,2 % of total electric production) and hydro power (3,4 %), followed by biogas (2,4 %) and solar power (1,9%) (BMU, 2011).

Electricity from renewable sources is subject to a volatile production, as especially wind and solar energy strongly depend on weather and climate conditions.

Today's power system is characterised by a hardly influenceable demand on one hand and an irregular feeding into the general power grid on the other, which therefore requires adjustment. This leads to a timely variant high storage demand.

Storage demands in central Europe are mostly met with pump storage hydro power facilities. Compressed air storage, different chemical forms of storage like batteries, flywheel energy storage and the hydrogen technology are used to a much smaller extent. Compared to conventional pump storage plants, those concepts normally have considerable deficits in lifetime, costs and efficiency. Pump storage plants are long-established and commercially viable. However, the design of pump storage plants is traditionally limited by natural conditions (e.g. topography, hydrology). A further expansion of today's pump storage concepts is limited by the availability of topographically suitable locations.

As storage demands will rise continuously with further renewable energy generation from wind and solar energy, other storage concepts will have to be considered. A variety of ideas already exists. Some of them use water as the energy transfer medium. Possible storage methods are described and assessed below.

Storage demand

The storage demand is characterised by various parameters, four of which are of special interest. The most important parameters are power output (unit of measurement: MW) and start time. The power output and the start time influence the flexibility of a storage method. A large output capacity and a short start time will lead to a more flexible operational mode.

A third important parameter is the capacity of the storage, which is usually given in MWh or GWh. In general, the capacity indicates the amount of energy, which is stored if the storage is full. The capacity can be specified either based on the amount of energy needed to fill the storage or based on the amount of energy that can be gained out of it. These two values can vary widely depending on the efficiency of the storage method.

In order to describe the storage characteristics adequately, the total amount of energy, which can be stored and released in a certain time period, needs to be determined. With a normal reference period of one year total amounts are referred to in TWh/a. The total amount depends on the frequency at which the storage is filled and emptied during the chosen period.

The storage demand is highly influenced by the energy demand on one side and the volatile generation from renewable sources on the other side. It can be divided in two categories: the balancing energy and the energy reserve. The balancing energy is further subdivided into the primary balancing energy, which can be activated within several seconds, and the secondary balancing energy, which can be activated within 5 minutes. The energy reserve has to cover periods between a few minutes (minute energy reserve) and a few hours to days (long term energy reserve).

Figure 1 shows a prediction of the electric energy demand in Germany for 2030. Based on the assumption that 50 % of the total energy supply is gained from renewable sources in 2030, the remaining demand (also called residual load) is shown. The residual load is between 80 GW and minus 20 GW, and has to be covered be the remaining generation system. As the fluctuation is very rapid, a big amount of balancing energy has to be provided. Some of the balancing of fluctuations could be handled by a substantial expansion of the transmission networks. However, storage systems will need to provide flexible compensation of fluctuations and could also relief grid congestions.

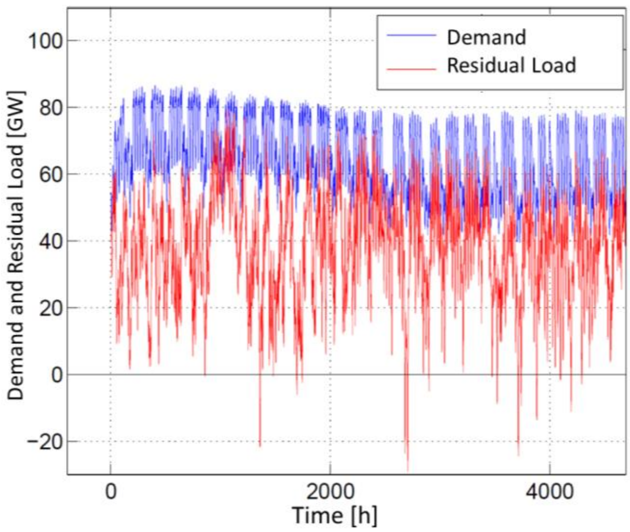

Figure 1: Example Prediction of energy demand and residual load in Germany based on a 50 % renewable energy supply in 2030 (Hundt et al., 2010).

The future storage demand will be influenced by the percentage of energy from renewable sources and the characteristics of these sources, the storage efficiency, the extent of the energy production reserve and the cooperation of countries across borders.

For Germany, today's reserve energy demand is estimated as a double digit GW number, whereas the capacity adds up to a low double digit TWh number (Vennemann, 2011). The capacity per year is substantially above that.

The balancing energy demand is estimated in the range of a single digit GW number, the capacity is a low double digit GWh number and the capacity per year is around a few TWh/a (Vennemann, 2011).

Another important parameter is the transient, which gives the required change in energy provision in a certain period. Transients can reach a magnitude of up to 4 GW per 15 minutes. In the future, transients of up to 12 GW per 15 minutes might become necessary (Hundt et al, 2010).

Storage methods

Conventional pump storage

Conventional pump storage plants are a long-proven and commercially viable technology. The efficiency of modern plants reaches up to 80%. Major advantages are a very short start-up time, high power outputs, significant capacities and a black start capability. The power output of existing plants varies between 50 MW and 2800 MW, whereas the capacity typically ranges from 500 MWh to 15000 MWh.

Pump storage plants offer a very high system quality due to their variable and secure operational mode. Energy is stored by pumping water from a low level (lower reservoir) to a higher level (upper reservoir). To use the stored potential energy, water is drained from the upper reservoir and converted back into electricity via turbines and generators.

The layout and capacity of pump storage plants is limited by natural conditions, especially by the topography of the land. The further expansion of conventional pump storage plants is therefore bound to topographically suitable locations, which can be found in the Alps and other mountain ranges. There are a few pump storage projects having either the upper or the lower reservoir as a huge tunnel system in order to minimise potential negative effects on the ecology (Bernegger, 2011).

Pump storage using existing facilities

Conventional pump storage plants are usually built at topographically suitable locations, which are mostly located in sensible mountainous regions. As a result, the construction of new reservoirs often encounters resistance from various stakeholders. Many new pump storage plants are recently installed, under construction or planned at locations, where reservoirs for hydro power purposes already exist, but no pump storage capacity is installed yet.

Reservoirs with other purposes can be found in alpine regions. Especially reservoirs used for the production of artificial snow and the accompanying infrastructure like pressure pipes could be used for small scale pump storage plants (Figure 2). Also reservoirs used for drinking water supply could provide a limited storage capacity. Beside the typically low power outputs and capacities the development of small pump turbine units poses a challenge for this type of plants.

Figure 2: Reservoirs used for the production of artificial snow in the Austrian Alps could be used as small scale pump storage plants (photo from: Hydrosnow, 2010).

Pump storage using man-made landscapes

A great portion of volatile energy from renewable sources is generated far off the alpine regions, where most of the storage capacity is located. The need for storage solutions close to the production site arises. An option for large scale hydro storage in topographically flat areas is described in Popp (2010).

The main idea is to artificially shape the landscape in order to meet the requirements for pump storage. The simplest form is a circular levee which separates a central upper reservoir from a ring-shaped lower reservoir (Popp, 2010). This arrangement is known as 'Ringwallspeicher' (circular levee storage) and shown in Figure 3.

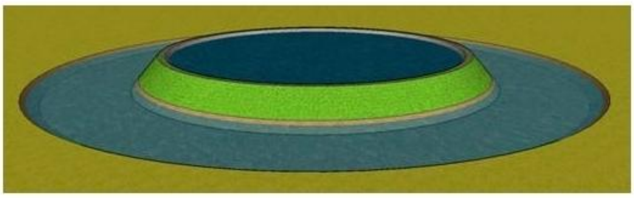

Figure 3: Scheme for a circular levee storage plant (Ringwallspeicher) for use in topographically flat areas (Popp, 2010).

An inverted arrangement with a low lying inner reservoir and a higher outer reservoir could also be implemented at sites within large lakes and/or the sea. Conventional pump and turbine technology can be applied. The essential feature is the use of the excavated material of the lower reservoir for the construction of the levee. Existing sites, where large excavations of earth movements have already taken place (e.g. abandoned mines), provide a potential opportunity to install this concept.

The engineering skills necessary to construct the levee are available in Europe. The dimensions of the circular levee could cover a wide range. Small levees of a couple of meters in diameter are imaginable. Also very big arrangements with several kilometres in diameter and a height of several tens of meters seem possible from the engineering point of view. A wide range of power output and storage capacity could be achieved depending on reservoir dimensions.

Pump storage in mining areas

Abandoned mines and their associated infrastructure offer a storage potential in regions without natural height differences. Different options are possible. Underground pump storage facilities could make use of the wide tunnel system, which is typical for collieries. A pipe system, which is installed in the tunnel system, could be combined with a superficial water reservoir, which represents the upstream storage. The underground pipe system acts as the downstream reservoir.

Another possibility is the use of abandoned mine tips, as described in RWE Innogy (2011). Especially in the mining regions in the North of Germany, many mine tips with adequate dimensions exist. The establishment of reservoirs in these abandoned tips requires only minor earth movement. Conventional pumps and turbines could be used.

Figure 4: Pump storage using abandoned mine tips (RWE Innogy, 2011).

Large hydro storage - Power Tower

The Power Tower is a new hydraulic energy storage method based on the well-established pump storage technology, which can be installed independent of topographic circumstances (Neisch et al, 2012). The Power Tower consists of a closed system, which can be positioned close to sites where volatile renewable energy is generated. Its main feature is a water-filled cylinder, which houses a vertically movable load (Figure 5). The load causes a constant pressure in the lower reservoir regardless of its position. The magnitude of the pressure can be increased by an additional spring mechanism. In order to store energy, water from the upper reservoir is pumped to the lower reservoir. As a consequence the load rises in the cylinder and the energy content increases (load at the top = system fully charged). In order to release the stored energy, the flow direction is changed. The load descends in the cylinder and powers a turbine. With this arrangement, electrical energy can be stored with high efficiency (above 85%).

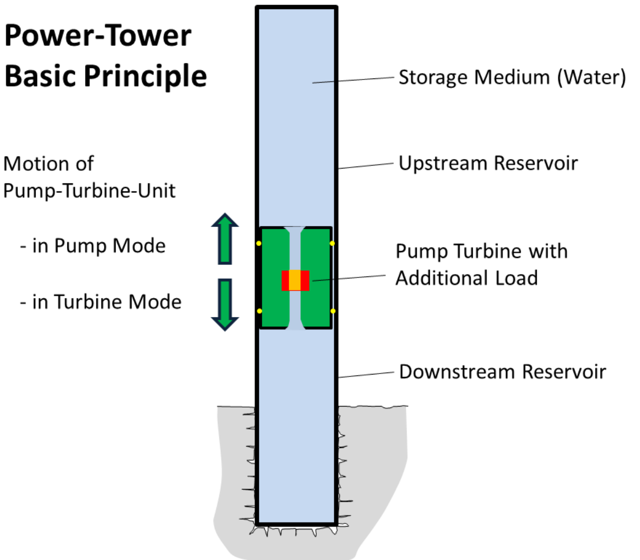

Figure 5: Basic principle of the Power-Tower storage unit (Neisch et al, 2012).

The functionality of the Power Tower at a small scale is demonstrated by a prototype installed at the hydraulic laboratory of the University of Innsbruck, Austria. A 2.20 m high acrylic glass cylinder with a diameter of 0.64 m is set up and armed with a load of 1 ton of steel. Outside the cylinder, a small pump turbine is set up, which is connected to the main grid via a frequency converter. Hydraulic losses in the system and the efficiency of the machine parts are determined. Further improvements to the prototype are planned, e.g. the use of pump turbines integrated in the load, and the use of a spring mechanism to increase the load.

The investment costs for the construction of a Power Tower are relatively high, but there is still potential to develop more cost-effective methods for the construction of a Power Tower to reduce investment costs. The operating costs, however, are low and the lifetime is very high. The technology used and the design of the system are simple and sturdy and the materials are environmentally friendly. A Power Tower can be installed inside water bodies or below ground, which would keep environmental impacts low. This could increase chances for building permissions.

The mode of operation offers a fast response time and also many load cycles. This allows a use for both, short term and long term storage. During non-operation periods, the state of charge remains constant. The greatest energy capacity is obtained with a load, which is half of the entire cylinder height. Since the load makes the largest share of the costs, its dimensions must be determined by a cost-benefit assessment. Generally, the dimensions of the Power Tower can be adapted to specific requirements (output, capacity, costs). While smaller systems could be installed in households (e.g. in isolated operation in conjunction with photovoltaics), very large singular Power Towers (e.g. a few hundred meters high) or the installation of Power Tower clusters would be possible as well. A major advantage of this decentralised storage option is the elimination of transmission losses in the power grid and the significant attenuation of local network loads.

Large hydro storage - Buoyant Energy

The principle of Buoyant Energy, a floating hydraulic energy storage concept, is also based on the well-established technology of pumped storage plants. The major difference lies in the arrangement and location of reservoirs at such plants. While conventional pump storage plants consist of an upper and a lower reservoir, Buoyant Energy uses a small reservoir (floating structure), which is located within a larger reservoir (Figure 6). Water can be moved from one reservoir to the other by means of turbines and pumps or pump-turbines.

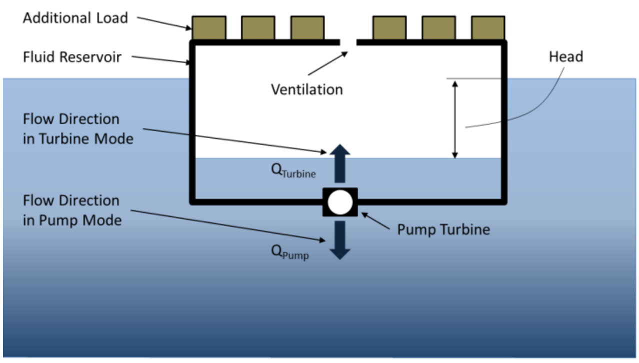

Figure 6: Scheme of the Buoyant Energy storage concept for off-shore applications (Klar et al., 2012).

The energy is stored entirely as potential energy in the floating structure. Additionally superimposed loads or spring mechanisms can increase the energy density.

In order to store energy, water from the smaller reservoir is pumped to the larger reservoir. As a consequence the floating structure of the smaller reservoir rises. In order to release the energy, the structure is lowered and the inflow into the smaller reservoir powers a turbine.

The large reservoir could be a large natural body of water, such as a lake or the sea. Arrangements of floating structures could possibly be located close to offshore wind farms in the North Sea, where a large amount of storage capacity is needed.

Due to the simple arrangement energy losses are expected to be small. Apart from hydraulic losses in the pumps and turbines, only very small losses are expected to occur at the inlet and the outlet structure. A major advantage is the constant pressure head, which allows a highly efficient operation of the pumps, turbines or pump-turbines at any time.

The number of load cycles is unlimited. An increasing number of load cycles would neither lead to a loss of storage capacity nor a loss of efficiency. The response time is in the range of a few seconds.

Giant hydraulic hydro storage

The new concept, described by Heindl (2011), considers the storage of potential energy by using water as a hydraulic fluid to transfer power underground. The concept involves a gigantic granite cylinder, which has to be carved out of the ground. Water from a nearby river is taken and pumped underneath the cylinder. The granite mass is lifted and potential energy is stored. A mass with a height of 1 km and a diameter of 1 km would be able to store the entire storage demand of Germany for one day (around 1700 GWh). At this stage, the concept does not consider hydraulic losses of the system and the effectiveness of the pump turbines. The realisation of the construction, especially of the seal between the rock cylinder and the hydraulic fluid, still has to be examined carefully.

Conclusions and Perspectives

Europe's storage demand of electric energy rises continuously due to increasing supplies from renewable sources like wind and solar power, which naturally show a high volatility. This paper gives a short overview of possible storage methods using water as the storage medium. Conventional pump storage plants are long-established and commercially viable, but the remaining suitable sites for further expansion are limited. New concepts, which are independent of topographic features, have been developed and will be further investigated in the near future. The economic viability of any energy storage method strongly depends on the political development in the near future. If incentives are made, which reward a steady feed-in of energy into the grid, storage methods will become remarkably profitable.

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