Pumped Storage Plants in the Future Power Supply System

In electricity supply grids, energy feed-in and consumption must exactly correspond every time. This fragile balance is permanently regulated by keeping the frequency of the alternating current at a certain set-point, mostly 50 or 60 Hz. When consumption exceeds supply, the additional load decelerates the generators and the frequency drops. Less consumption than supply lowers the generator load and thus escalates the frequency.

Pumped storage plants (PSP) are inevitable for the permanent adoption of supply and consumption. PSP consume electrical energy by pumping water from a lower reservoir to a higher elevation. The stored potential energy is converted back into electrical energy by releasing the water down to the lower reservoir via a hydro-turbine.

Multiple electromechanical designs have been implemented. A common arrangement is a Francis-turbine, a multi-stage centrifugal pump, and a motor-generator mounted together on a vertical shaft. Merging both hydraulic machines in a single, reversible pump-turbine, coupled to a motor-generator via a vertical shaft proved to be especially economic [1] [2]. Heads of reversible pump-turbines range between about 100 and 800 metres [3]. The power output of pump-turbines ranges between 10 and more than 500 MW [4]. Larger heads are exploited with a Pelton-turbine, a multi-stage centrifugal pump, and a motor generator mounted together on a vertical shaft (for example Kops II in Vorarlberg: 800 m [5] or Malta-Hauptstufe in Carinthia: 1100 m [6]). The water quality requirements are low. PSP can even operated with sea water [7].

In turbine mode, the electrical output of the machines is usually controllable between almost zero and nominal power. In pumping mode, hydraulics only allows operation at full load. Units with separated pump and turbine can be designed for operation in hydraulic short-circuit. A part of the negative pumping power can then be compensated at the same time by positive turbine power to adjust the total power input. Hydraulic short circuit operation is also possible between two or more separate pump-turbine units that are connected by a low friction short-circuit water way. Another possibility of regulating the consumed power of pump-turbines is the utilisation of speed-variable motor-generators. A speed variation of 5 per cent is sufficient to vary the input power within a band down to two thirds of nominal input [8].

The nominal efficiency of the whole storage cycle is about 75 to 80 per cent. Besides the performance of the electromechanical equipment, the efficiency is considerably influenced by the dimension of the waterways. For the overall efficiency, it is beneficial to optimise the hydraulic design of pump turbines as a pump rather than a turbine. This comprises an efficiency penalty in turbine mode. A slight speed reduction in turbine mode compensates this penalty. The gain in overall turbine efficiency by speed reduction reaches 7.5 %, accompanied by about 2.5 % losses due to frequency conversion [9]. In pumping mode, speed variation reduces the efficiency with respect to the optimal working point, but enables part-load operation.

The totally installed pumped storage power in Germany is about 7,000 MW with a capacity of 40,000 MWh [10]. The quotient of capacity and storage reveals about 6 hours average pumping duration for filling up the reservoirs. The typical PSP is thus designed for operation based on a daily cycle. Larger capacities for weekly or even seasonal storage require an alpine topology that allows the realisation of larger reservoirs. In the EU-27 countries, a total of about 40,000 MW of pumped storage power is installed [11].

Electricity storage devices are defined by power and capacity. Figure 1 shows a selection of electricity storage sites ordered for their power (abscissa) and their capacity (ordinate). Up to 100 MW power and 1,000 MWh capacity is the domain of battery techniques. Molten salt and CAES enable power and capacity being one order of magnitude larger, respectively. The typical domain of PSP is even two orders of magnitude larger than the typical battery domain. The currently most powerful storage site, the PSP Bath County, 250 kilometres south-west of Washington, has a storage capacity of
about 25,000 MWh and a power of 2,772 MW (after refurbishment [12], originally 2,100 MW [13]).

The specific storage costs are essential for the profitable operation of a storage device. Leonhard et al. [10] recently collected the specific storage costs of various storage technologies (Figure 2). In the domain between one and ten Euro-cents per kWh, only PSP and AA-CAES can be operated. Hydrogen cycle and battery system storage costs are presently one order of magnitude higher. PSP and AA-CAES can be expected to stay the most economical mass energy storage option for the next decades.

Regarding the control energy market, PSP have two substantial strong points: short start-up time and low start-up costs. Start-up times from stand still to full load can be as short as 75 seconds [1]. Gas turbines need about seven to fifteen minutes to warm up uniformly. In the European network, a reference incident of 3,000 MW must be fully compensated within 30 seconds by primary control and immediately restored by secondary control reserve. The restoration of the secondary control range may take up to 15 minutes [14]. Hydraulic units are therefore even suitable for offering secondary control energy as a standing reserve. The total costs of an average size PSP turbine to start, are estimated to sum up to a couple of hundred Euros considering lost water, increased maintenance due to wear of windings and mechanical equipment, and unavailability costs [15]. In contrast, already the wear of the mechanical parts of a 300 MW gas turbine causes costs of order 1,000 Euros for a low-tech and of order 10,000 Euros for a high-tech machine, lost fuel during start-up being an even larger issue.
While the relative high investment for a PSP might discourage investors, the reliability of their return is attractive. Surprises are unlikely, because PSP are not dependent on a single primary energy. The consumed electricity is always composed of the cheapest electricity generation available, inclusive renewable sources. Even negative market prices are not a rarity any more and generate a bonus. The ability to act on different markets (control power, peak shaving, and auxiliary services) strengthens the stability of PSP on the market even more.

Integration of Renewable Generation

The generation of renewable energy is basically only coupled to the weather. This leads to two major problems. First, the feed-in is not coupled to the demand, and second, the feed-in is not fully predictable. Figure 3 illustrates these facts. The intermittent wind energy generation does not follow a typical daily load curve, and the predicted production shows recurrent deviations from the actual generation that can make up several thousand megawatts (positive and negative) and may last up to hours. Typical deviations regarding the output power are 30 to 45 per cent for a 14 hours forecast and 15 to 25 per cent for a five to eight hours forecast [16]. The uncoupling of demand and generation can be tackled by PSP with a capacity to power ratio of days rather than hours like offered by many alpine sites. The compensation of the second effect (forecast deviations) is a very typical domain of PSP in low mountain ranges. Figure 3 illustrates the dimension of this task, especially when the deviations of only the Vattenfall control area are compared to the total amount of PSP power in Germany of about 7,000 MW. Already based on 2007 data, about one third of the total control power demand in Germany could be assigned only to wind energy forecast deviations [17]. Thereby it is physically insignificant, whether these deviations are really compensated by secondary or tertiary control power or rather by short term energy stock market products (balancing market). Both require the ad hoc delivery of ample negative or positive power that can ideally be offered by PSP.

A third problem is related to the absolute height of connected wind power. The German Energy Agency (dena) predicts, that in case of base load (50 % of maximum annual load) and strong wind energy feed-in (90 % of maximum annual feed-in) a total of about 14,000 MW of excess power is connected to the grid. This power must be exported, consumed by the help of load management (e.g. using smart grids) and stored at additional storage sites [18]. Existing PSP and the reduction of controllable generation are already accounted for in the study. In 2007, this value was only 2,100 MW.

The increasing importance of PSP for the development of renewable energy sources is also stressed in Figure 4. From 1985 to 2005, the activity of PSP has doubled in the EU-15 countries and more than tripled in Germany. The German Renewable Energy Federation (BEE) predicts a further increase of PSP compensation energy demand in Germany from 9.2 TWh in 2007 to at least 18 TWh in 2020 and urgently recommends the exploration of new sites for PSP [19].

Depending on the primary energy mix, the operation of large storage capacities can in principal lead to both, an increase and also a decrease of total CO2 emission. An extensive study is available for the Dutch electricity supply system [20]. Beyond 7,000 MW of installed wind power, a PSP of 1,667 MW power and 20 GWh capacity would lead to a total CO2 emission reduction. By 2020, current Dutch planning envisions 12,000 MW of installed wind power [21, 22]. In this scenario, the aforementioned storage capacity would reduce CO2 emissions by 600,000 tonnes per year [20]. The numbers of the Dutch study might give a rough indication for German circumstances: Considering, that the total German electricity consumption is 5.5 times the Dutch consumption, the elaborated storage power of 1,667 MW corresponds to 9,000 MW storage power in Germany. The relative higher renewable generation capacity in Germany predicted for 2020 even suggests a larger CO2 reduction potential (Figure 5). Due to the high cycle efficiency, PSP are among the storage technologies with the highest CO2 reduction potential [23]. These are reasons, why PSP are regularly modelled as an integral part of systems with high renewable energy generation power [16, 24].

Grid Charges Dispute

Since January 2008 grid usage fees in Germany also apply for electrical energy that is consumed only for temporal storage. Grid
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Figure 5. The carbon-rich side of the generation portfolios in Germany and the Netherlands are predicted to be almost identical by 2020. The carbon-free side is projected to be stronger developed in Germany (CHP: combined heat and power; prediction for Germany from [39], for the Netherlands from [40]).

charges escalate the storage costs and therefore constrain the urgently needed expansion of storage capacity. The German Federal Government recognised the obvious effect of obstructing the further integration of renewable energies and liberated new storage sites for ten years from grid usage fees. But also charges for existing PSP have severe negative effects on the total costs of the electricity supply. The mechanisms are in detail described in a recent publication by Krebs and Ermlich [25] as well as in a broad study conducted by the German Energy Agency (dena) [26]. One of the main effects of reduced peak shaving activity by PSP due to grid charges is a reduced price damping effect. The price

Figure 6. Development of PSP power in Germany and Luxembourg. For comparison, today’s typical pumping power for the case of base load (50 % of yearly peak) and strong wind generation (90 % of yearly peak) is 5,000 MW. According to the dena Netzstudie 2005 [18] additional 14,000 MW must be stored, exported and consumed by means of load management in 2020.
The development of pumped storage power in Germany is illustrated in Figure 6. The first plants emerged together with the early pumped-storage projects in Switzerland and Austria, which were much lower than in Germany. In Switzerland, grid usage fees do not apply for PSP at all [27]. In this way, the German grid usage fees cause heavy distortions of the competition on the European energy market.

The Higher Regional Court (OLG) in Düsseldorf judged that the term “end consumer” (German: Letztverbraucher) also applies to PSP. Therefore, an exemption of PSP from grid charges could not be allowed in the scope of present legislation, even if this would be preferable [28]. An amendment of this situation should soon be accomplished.

References

The development of pumped storage power in Germany is illustrated in Figure 6. The first plants emerged together with the early high voltage transmission system. The development boomed in the sixties and seventies, when electricity generation increased from about 100 to almost 500 TWh per year (area of present-day Federal Republic of Germany) [29]. PSP expansion stopped, as generation growth slowed down to about 640 TWh today. A second boom of storage power can be expected with the further development of renewable electricity generation.

Topographical requirements for building large PSP are easily met at numerous sites in low mountain ranges as they are found in wide areas of Germany. Alone in the area of the former German Democratic Republic, about twenty sites could be determined, that offer comparable conditions to the site of the PSP Goldisthal [30]. The sum of the installable power at these sites is about 14,000 MW assuming an average pumping duration of 5.5 hours at full load. In Austria, the renais-
sance of pumped storage projects has already started. 1,100 MW of additional PSP power are in construction and 1,200 MW are about to begin [31, 32]. In Luxembourg, an additional 200 MW unit is going to be installed in Vianden, the storage capacity will be increased. In Germany, up to 1,400 MW are projected in the southern Black Forest close to Atrdorf. Another 200 MW may be realised at Einöden [26] and Forbach [33], respectively.

Figure 6 also illustrates the order of magnitude of excess wind generation in relation to the installed PSP power according to dena [18]. The relation stresses the fact that the development of further PSP capacity alone will by far be not sufficiently to level the imbalances of the future electricity supply system, as earlier described in literature [34]. The parallel development of other storage technologies, controllable local block heating stations, as well as an advanced load management utilising smart metering and e-mobility is inevitable, if we do not want to waste renewable energy generation capacity. There is wide consensus that future energy supply scenarios do not function without massive storage capacity [35].

Future Development

The development of pumped storage power in Germany is illustrated in Figure 6. The first plants emerged together with the early high voltage transmission system. The development boomed in the sixties and seventies, when electricity generation increased from about 100 to almost 500 TWh per year (area of present-day Federal Republic of Germany) [29]. PSP expansion stopped, as generation growth slowed down to about 640 TWh today. A second boom of storage power can be expected with the further development of renewable electricity generation.

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