Pumped storage plants – Status and perspectives

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Kurzfassung

Pumpspeicherkraftwerke – Status und Ausblick

Pumpspeicherkraftwerke (PSW) ermöglichen Speicherbetrieb im Gigawatt-Leistungsbereich über mehrere Stunden oder längere Zeiträume. Kürzeste Anfahrzeiten gestatten als stehende Reserve die Teilnahme am Sekundärregelenergiemarkt. Der Wirkungsgrad eines Speicherzyklus liegt mit 75 bis 80 % auf Höhe chemischer Speicher. Keine Technologie erreicht niedrigere, spezifische Speicherkosten. In den EU-27 Ländern, Norwegen und der Schweiz sind insgesamt etwa 44 GW PSW-Leistung installiert.

Deren Nutzung korreliert in Europa stärker mit der installierten, konventionellen Erzeugungsleistung, als mit den topografischen Bedingungen. Ausnahmen sind Italien und Frankreich. Im künftigen Elektrizitäts-Erzeugungsportfolio verlieren die Begriffe Grund-, Mittel- und Spitzenlast ihre Bedeutung. Statt dessen muss sich der konventionelle Kraftwerkspark einer zwischen nahezu Null und der vollen Leistung pendelnden Residuallast stellen. PSW sind zur Erfüllung dieser Flexiblitätsanforderungen die erste Wahl.

Zudem führt der Betrieb von PSW zur Senkung der CO_2-Emissionen des Gesamtsystems. In Deutschland, Luxemburg, der Schweiz und in Österreich befinden sich zurzeit PSW mit einer Leistung von insgesamt 9 GW in Planung oder in Bau. Weitere Projektideen werden entwickelt. Norwegen besitzt ein technisches PSW-Ausbau-Potenzial von bis zu 25 GW Leistung und mehrwöchiger Speicherkapazität. Die Wettbewerbsfähigkeit norwegischer PSW für den Ausgleich regenerativer Einspeisung in Deutschland wird von den Kosten für Seekabelverbindungen und den Umweltschutz-Anforderungen abhängen. Netznutzungsentgelte für Pumpstrom bremsen ebenfalls den zügigen Zubau von PSW.

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Introduction and scope

Pumped storage plants (PSP) buffer electrical energy by commuting huge amounts of water through an elevation difference. The detailed working principle and different design types were compiled in an article published last year in this journal [1]. In that paper, we also elucidated the major characteristics of PSP in the context of other storage technologies as well as the technical potential for the integration of renewable electricity generation. In the present paper, we will quickly summarise the main messages and key figures of the previous paper, then deepen the topics of future challenges and integration of renewable energy. We will focus on the current developments of PSP in Norway, Germany, Luxembourg, Switzerland, and Austria, and close with a few remarks concerning grid usage fees for storage facilities.

Key figures

Energy storage technologies in general are mainly characterised by five features: the charging and discharging power, the storage capacity, the ramp-up time, the whole cycle storage efficiency, and the specific storage costs.

In terms of power and storage capacity, PSP is the only technology offering more than one gigawatt (GW) of power and more than ten gigawatt hours (GWh) of storage capacity at a single site (Figure 1). One large PSP equals – in the order of magnitude – ten CAES or a hundred battery storage sites. Storage technologies like fly-wheels, super capacitors, or high energy magnetic fields, that either supply power below a few kilowatts or maximum discharge times in the order of seconds, are used for power quality applications rather than for bulk energy storage.

In contrast to gas turbines, ramp-up times of PSP, from standstill to full load, are usually well below five minutes in both directions. In this way, PSP, even when not turning, fulfil the strict pre-qualification criteria for offering secondary reserve [2]. This is a crucial, economical advantage over turning reserve assets. When the PSP is at or out-of-the-money at the whole-sale market, PSP can offer negative and positive secondary reserve capacity, without causing variable costs. This is impossible with a turning device that always uses some kind of fuel to run at throttled load.

Along with initial investment and lifetime, cycle efficiency is one of the dominant features determining storage costs. Table 1 shows that PSP compete with batteries in the top of the efficiency league. They are followed by compressed air energy storage. The full hydrogen cycle, consisting of electrolysis, compression, and re-electrification in a gas turbine combined cycle, is on the bottom of Table 1.

The storage cost of different storage technologies are addressed in Figure 2. Today and even in the intermediate future, only PSP and AA-CAES can be expected to reach storage costs significantly lower than electricity generation costs of peak power plants[1]. Up to date, PSP are the most economical technology for large-scale energy storage.

The utilisation of PSP in Europe is illustrated in Figure 3. In 27 EU member states plus Norway and Switzerland, a total of about

Table 1. Cycle efficiency of various storage technologies [3]. The efficiency of PSP is only topped by Li-ion and lead-acid batteries.

Technology	Cycle efficiency
Li-ion	90 – 95 %
Lead-acid	80 – 90 %
PSP	75 – 80 %
VRB	~75 %
NiCd, Ni-metal hydride	70 %
AA-CAES	< 70 %
CAES	42 – 54 %
Hydrogen*	<40 %

* electrolysis 65 %, compression 97 %, gas turbine combined cycle 60 %

[1] Approximately seven to ten Euro cents per kilowatt hour levelised cost of energy for gas turbines and combined cycles [21].

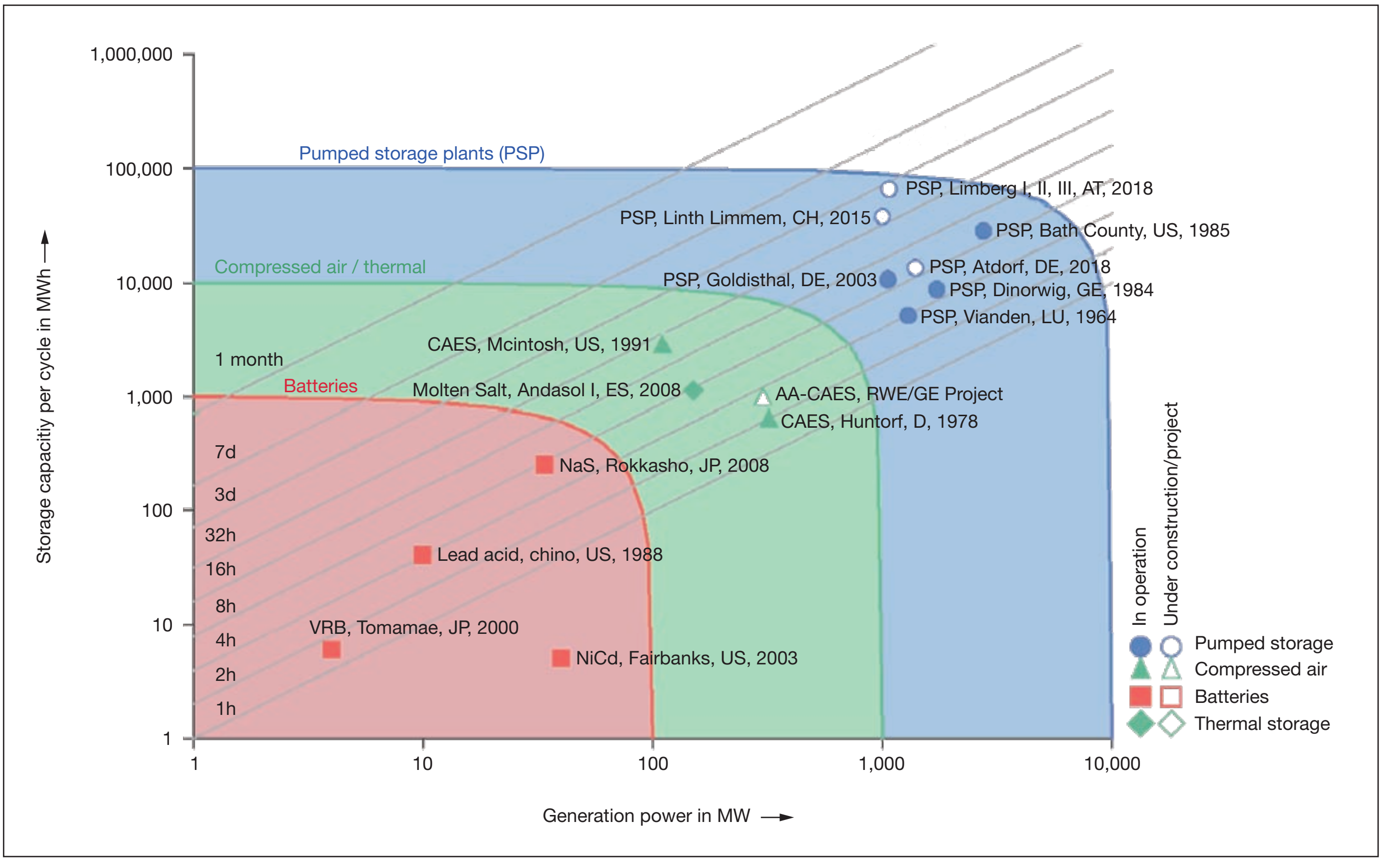

Figure 1. Selected storage sites and projects that represent the state of the art in terms of power and storage capacity (AA-CAES – Advanced Adiabatic CAES, CAES – Compressed Air Energy Storage, NaS – Sodium Sulphur Battery, NiCd – Nickel Cadmium Battery, VRB – Vanadium Redox Flow Battery). The turbine power of the CAES in Huntorf and McIntosh include gas combustion [19, 20]. Big PSP are one order of magnitude larger than CAES and thermal storages, that in turn are one order of magnitude larger than major battery sites.

44 GW of PSP power is installed. Neglecting obvious exemptions like the Netherlands, or Luxembourg, the installed power correlates with the totally installed generation capacity, rather than with topographical vantage. Noticeable is a comparably high value in Italy, especially when considering that more than half of the electricity in Italy is generated in gas-fired plants. In France, PSP power appears to be comparably low, although there are good topographical conditions and a large fraction of base load generation capacity. No PSP capacity at all is recorded by EUROSTAT for some Southeast European countries.

Challenges

Figure 4 depicts the load curve for a typical 2009 February week in Germany. In a pure conventional power plant portfolio (left graph), the load can roughly be divided into the three classical areas of base-, intermediate-, and peak load [4]. Base load plants are typically characterised by a large ratio of investment to fuel costs. Technically, they are optimised for efficiency. Intermediate load plants normally exhibit an intermediate investment to fuel cost ratio. In terms of efficiency and flexibility, they are designed for tracing the main load cycles at moderate ramp-up times and with occasional shut downs. Peaking energy is usually supplied by plants with the lowest ratio of investment to fuel cost. Technically, they are designed for multiple starts per day and shortest ramp-up times.

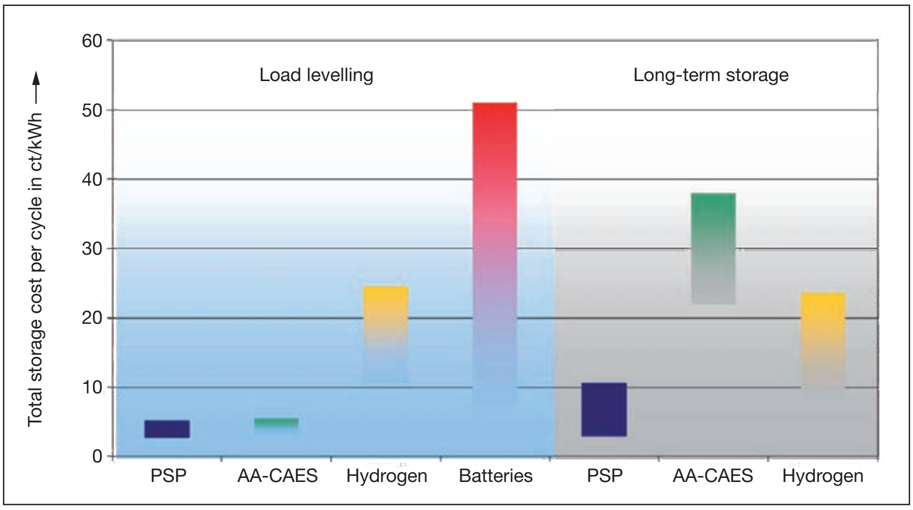

Figure 2. Energy storage costs according to VDE [3]. The upper bounds of the bars represent storage costs in 2008, the lower bounds a 2018 expectation. For PSP, the range represents different border conditions.

In an electrical power system with significant amounts of random electricity generation, this classification is not meaningful anymore (Figure 4, middle and right graphs). The classical base load domain almost completely vanishes. Gradients may be attenuated or amplified, challenging the peak load plants (compare Figure 4, Wednesday and Friday, respectively). The classical intermediate load area spreads almost the entire range from zero to full demand.

This simple example qualitatively illustrates that the optimisation criteria, which led to the development of the present power plant portfolio, are dramatically altering. The gap between random power generation and demand

Figure 3. Operational PSP power in 27 EU member states area, plus Norway and Switzerland (2008 EUROSTAT data, capacity in GW).

can only be reliably closed by adding a considerable amount of technical and economical flexibility to the system, preferably to the generation market. The development past 2020 and the influence of photovoltaic certainly intensify this trend.

The key figures of PSP that were summarised in the second section predestine PSP for covering any kind of reserve energy demand. This does not only include today's deviations, ranging from smaller load forecast deviations up to the tripping of large thermal generation units, but also the compensation of wind forecast deviations and the coverage of any kind of load gradient.

Apart from the balancing function of PSP, their storage function becomes increasingly important with rising amounts of renewable electricity generation. The German Energy Agency (dena) analysed the influence of a new 1,400 MW PSP project on the electricity generation mixture in Germany. By integrating a higher share of renewable energy, the studied project saves the atmosphere about 400 to 600 thousand tonnes of CO_2 per year [5]. In a similar study, also the Fraunhofer Institute for Wind Energy and Energy System Technology (IWES) stresses that such a PSP project supports the integration of renewable electricity generation in terms of CO_2 emission savings [6]. The European Network of Transmission System Operators (ENTSO-E), recommends a strong Central European North-South corridor to integrate intermittent wind power generation in the North Sea with the help of PSP in the Alps [7]. In the long run, ENTSO-E even envisions PSP in the Alps for fostering North African renewable electricity generation.

Developments between Brattingfoss and Nant de Drance

After two decades of stagnation, the beginning of the new millennium is marked by a revival of PSP development. Figure 5 gives a quick overview of PSP larger than 100 MW in Germany, Luxembourg, Switzerland, and Austria that are either in operation (blue) or currently developed (red). Altogether, almost 9 GW of pumped storage power is currently under development or under construction. Thereof, are almost 2.4 GW located in Germany, about 3.5 GW in Austria, 200 MW in Luxembourg, and about 3.4 GW in Switzerland. If all projects can be put into practice, the currently installed capacity in this region will grow by more than half during the coming decade.

The largest projects are quickly introduced here. These are Atdorf (1,400 MW), Linth-Limmern (1,000 MW), Poschiavo (1,000 MW), Limberg II and III (960 MW), Nant de Drance (600 MW), Grimsel III (600 MW), Kopswerk II (450 MW), Reißeck II (430 MW) and Kaunertal (400 MW).

The Atdorf project is in the process of licensing. When civil works start in 2013, the plant

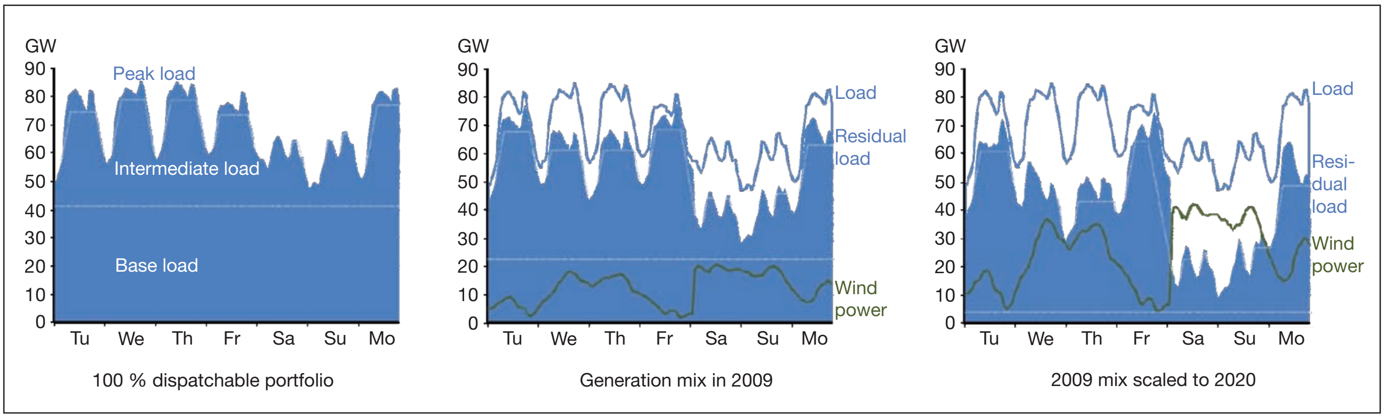

Figure 4. Load curve for a typical week in February in Germany, 2009. Top graph: Typical domains of base-, intermediate-, and peak power plants in a fully conventional portfolio [4]. Middle graph: Wind power reduces the load to a residual demand, that is served by the conventional power plant portfolio. Bottom graph: The wind power generation of 2009 is simply scaled by a factor of 45 GW of installed wind power in 2020 divided by 24 GW installed in 2009.

Figure 5. Operational PSP and development sites in Germany, Luxembourg, Switzerland and Austria.

may be operational just before 2019. The usable head of about 600 m is remarkable for German conditions. Both reservoirs must be newly created and will have a volume of nine million cubic meters each, corresponding to more than 13 GWh of storage capacity. The upper pool is planned to be constructed on a mountain top. For the lower reservoir, a small valley must be shut with three dams. The main dam will have a crest height of about 80 m above present ground. Six vertical pump turbines are mounted in a cavern accessed via a 2.8 km long tunnel. The pump turbines are connected to the upper reservoir via two vertical pressure pipes and to the lower reservoir via a single, 8.6 km long tail-water gallery connected to a surge tank. Atdorf is developed by Schluchseewerk AG, owned in equal parts by EnBW and RWE.

The first stage of the Axpo project Linth-Limmern (Tierfehd) is already operative. Construction works for the site access of the second stage and a heavy duty cableway have started. Commissioning is expected by 2016.

Poschiavo is a 1,000 MW project by Repower between Lago Bianco (Berninapass) and Lago di Poschiavo. The licensing documents have been submitted.

The construction work for the pumped storage power plant Limberg II has reached the commissioning phase. At the end of 2010 one out of two units first generated power in turbine operation. The final commissioning and the official inauguration are expected by mid-2011. The plant exploits the difference of altitude between both annual storage reservoirs Mooserboden und Wasserfallboden allowing furthermore an optimised operation of the existing Kaprun storage power plants. The turbine output of Kaprun storage power plants will increase from 353 MW to 833 MW. In pump operation the output will increase from 130 MW to 610 MW. The machine units with a turbine output of 240 MW each are installed in an underground cavern, the transformers are installed in a separate transformer cavern. A water works channel extending over 5.4 km in the right flank of the valley connects the two annual storage reservoirs. It consists of pressure tunnel, surge tank, pressure shaft and tailrace channel with a design flow of 144 m^3/s. Power transmission is provided by a 380 kV power transmission line. In addition, public approval procedures for the new pumped storage power plant Limberg III are ongoing. Detail planning has been submitted during the year 2010 to the competent authority. First hearing is planned in spring 2011. A construction period of four years is expected. The project Limberg III will exploit the same two reservoirs as Limberg II, allowing furthermore an optimised operation of the existing Kaprun storage power plant. The turbine rated power of Kaprun storage power plants will increase from 833 MW to 1,313 MW. In pump operation the output will increase from 610 MW to 1,090 MW. The machine units with a total output of 480 MW are designed for variable speed control allowing a flexible output in the pump operation.

The project Nant de Drance, by Alpiq and SBB, is currently licensed with 600 MW. Additional 300 MW are under evaluation. The six kilometre long access gallery is presently under construction. Commissioning is planned for 2016.

Grimsel III is currently being licensed. Approvals for the 600 MW plant are expected in 2014 at the latest. Considering four years for construction, commissioning would be 2018. The project Grimsel III is developed by the Kraftwerke Oberhasli AG KWO, which is owned by BKW (50 %) and the three municipal service companies of Bern, Basel and Zürich.

Kopswerk II was planned as a pump storage power plant nearby the existing facility Kopswerk I. It was commissioned at the end of 2008, only four years after the construction decision. The power station is installed in an underground cavern deep inside the mountain and equipped with three machine units allowing turbine and pump operation. The maximum power provided in turbine operation is 525 MW and about 450 MW in pump operation. The three machine units are built as ternary systems being operable for power control mode (hydraulic short circuit). The existing Kopsee is used as upper reservoir and the available equalising basin Rifa as lower reservoir. Power transmission is provided by a 220 kV power transmission line.

The construction work for the expansion and modernisation of the existing power plant facilities of Malta and Reißeck/Kreuzeck commenced in autumn 2010. Commissioning is expected in autumn 2014. The connection of the hydraulic systems of these two power plant groups shall allow a better use of the existing facilities. A new tunnel will connect the storage reservoir Großer Mühldorfer See to the existing head race channel at the power station Rottau. This head race channel is further con-

Figure 6. Result of a systematic study of PSP potential between 48° and 52° latitude and 6° to 11° longitude, respectively (RWE internal).

nected to both lower reservoirs Gößkar and Galgenbichl of the power plants group Malta. The mechanical equipment consists of two pump turbines each with an output of 215 MW. With an annual output of 430 MW Reißeck II will increase the turbine output of the power plants group Malta/Reißeck from 1,029 MW to 1,459 MW. Output of pump operation will increase from 425 MW to 855 MW. Mean gross head is 595 m. The length of the tunnel is 5.2 km. Power transmission is provided by a 220 kV high voltage cable.

The existing facility Kaunertal is one auf Austria's largest storage power plants. The project is currently in the planning phase and comprises the extension of the existing storage power plant Kaunertal to a new power plants group. This group will include the existing storage power plant Prutz I (former Kaunertal power plant, 370 MW), and a new power plant Prutz II (nearby Prutz I, 500 MW), including a new diversion system (additional power production of 600 GWh/a). A further PSP Gepatsch (400 MW, located on the toe of the Gepatsch dam) is also planned. The new PSP Gepatsch will require the construction of a new storage reservoir including a new dam. There are two variants for a dam location, either Taschach or Fernergrieß. The existing Gepatsch reservoir will operate as lower reservoir. The existing tunnel connecting the storage reservoir Gepatsch to the power plant Kaunertal (new Prutz I) will be abandoned and used for energy transmission of the PSP Gepatsch. A new head race channel is planned parallel to the former tunnel.

Potential

Beyond actual planning's, there is further potential for the development of PSP projects in Europe. Figure 6 summarises the result of a current study, conducted for RWE in the Western and Southwestern part of Germany. Along with topographical criteria, the strongest constrictions resulted from the exclusion of protected areas. These are especially areas under the designation of the European Union, like Special Areas of Conservation (SAC), and Special Protection Areas (SPA), along with national protection areas like national parks. Areas inhabited by private persons were also excluded. Nature reserves, biosphere reserves, natural parks, and landscape preservation areas lead to the deprecation of sites, relative to others. Altogether, twenty project ideas were developed, that could be build ecologically justifiable, and with specific investment costs[2] below 1,300 €/kW. The size of the project ideas ranges from 50 to 440 MW. The maximum head found in the analysed area is 365 m. Accounting for the above mentioned criteria, a potential of 3.5 GW of power and about 14 GWh of storage capacity were identified. These numbers illustrate the potential, but also stress the outstanding character of the project Atdorf for German conditions.

The Austrian project development also concentrates on optimal economical and ecological areas. These are mainly enlargements of existing power plant locations (optimisation of available capacities and infrastructure, e.g. Limberg II and III, Reißeck II) as well as the utilisation of natural, or with minimal impact adjustable, water reservoirs (e.g. lakes and run of river power plants). The capacity of the project ideas under consideration ranges from 70 to 500 MW and leads to a total amount of about 2.5 GW capacity for the pipelined projects. There are further 2 to 3 GW capacity project ideas under investigation. Existing PSP power currently sums up to about 2,600 MW [8].

Also Switzerland possesses many natural and artificial lakes, that could be connected to provide additional storage capacity. The construction of additional reservoirs can practically be neglected, because of landscape and nature preservation issues. As in Austria, some cases allow for the extension of existing lakes (e.g. Linth-Limmern). In contrast to Germany, the size of the reservoirs usually allows pumping durations of days, rather than hours.

Also Scandinavian power producers entered the discussion of buffering intermittent electricity generation. Quickly, the term "rechargeable battery for Europe" emerged to describe the Scandinavian, especially the Norwegian, energy storage potential. Indeed, large amounts of balancing power could be provided by increased capacity and new pumped storage plants, which utilise existing reservoirs in the Norwegian mountains. Existing reservoirs were built for domestic purposes, storing inflow during summer and autumn to cover the high electricity demand during the long and cold winter. In addition to this seasonal variation, the reservoirs may contribute short and medium term storage for balancing purposes.

[2] The profitability threshold is more stringent under present market conditions and also depends on further, individual criteria.

Table 2. The ten largest reservoirs in Norway cover almost one third oft the total storage capacity of 84 TWh [10]. Their minimum storage level is normally reached at the end of April. About one third of the total, usable volume is usually left as a reserve. From mid-August to mid-November, the reservoirs are mostly filled completely.

Name	Capacity	
	Million m^3 [10^6]	GWh
Storglomvatn	3,506	4,589
Blåsjø	3,105	7,759
Tustervatn-Røsvatn	2,363	2,063
Svartevatn	1,398	2,923
Mjøsa	1,312	337
Akersvatn	1,276	1,531
Vatnedalsvatn	1,150	1,967
Møsvatn	1,064	2,270
Altevatn	1,027	1,145
Kalvatn	706	847

Nearly 100 % of Norwegian electricity generation is based on hydropower. The yearly generation is about 123 TWh [9], which is, for comparison, more than one-fifth of the total power generation in Germany. The existing, installed capacity is about 30,000 MW, provided by more than 1,200 plants [10]. Existing PSP power currently sums up to about 1,300 MW. Plant size ranges from 11 MW (Brattingfoss) to 640 MW (Saurdal). The Norwegian electricity system offers large amounts of regulating capacity. Existing pumped storage plants are mostly used for seasonal storage.

The reservoir capacity in Norway amounts to about 84 TWh and represents nearly half of the European storage capacity for hydropower (Table 2). Several large reservoirs are located in the mountainous area in the southwestern part of Norway, close to possible sites for new submarine cables.

Already today, the Norwegian electricity system is already partly used as a "rechargeable battery" for Denmark with its high penetration of wind power. In periods of excess wind in Denmark, power flows from Denmark to Norway and water will be stored in existing Norwegian reservoirs. In periods of little wind and high demand in Denmark, the flow of water and power is reversed.

This regulating capacity could be expanded by increasing existing capacity and building new pump storage plants in connection with existing reservoirs. A technical PSP potential of 10 to 25 GW with pump/generation cycles of days or weeks is identified in southern part of Norway. The duration of the pump/generation cycle is governed by environmental constraints, on how fast water levels in different reservoirs may be allowed to change. Environmental and recreational concerns are related to rapid changes in reservoir level and flow, unsecure icecap, local fisheries and transportation. Present operating procedures and concessions are based on seasonal variation of reservoirs. The development of new pumped storage plants, utilising the reservoirs differently, will most likely require new and revised concessions. Details are currently elaborated in the scope of a research project, named HydroPEAK [11]. The project is divided into the eight sub-projects, Scenarios and Dissemination, Hydrology, Impact of Short-term Effects on Long-term Hydro Scheduling, Pumped Storage Plants, Frequency and Load Governing, Effects of Load Fluctuations on Tunnels and Associated Hydraulic Structures, Physical Effects of Load Fluctuations in Rivers and Reservoirs, and Ice Problems in Rivers. In total, fifteen PhD and four post-doc positions are financed in the scope of these projects. The work packages are planned to be finalised between 2012 and 2015.

The utilisation of existing reservoirs enables competitive construction cost in the range of 500 to 800 €/kW for pumped storage plants. The main cost drivers for balancing power from the Norwegian system will be transmission costs related to submarine cables. The present exchange capacity from Norway and Sweden southwards is modest. Large amounts of new cables must be established for planned offshore wind farms, and a prolongation to Norway could prove beneficial.

A first, direct power link between Norway and Germany, called NorGer, is currently under licensing [12]. The investment decision is planned to be made this year. The 570 km long, high voltage, direct current cable (HVDC) with a capacity of 1,400 MW, would connect the Flekkefjord area in Norway with the German North Sea coast. Costs are estimated to be about 1,200 to 1,400 million Euros.

The main challenge in utilising Norwegian reservoirs and flexibility to balance intermittent power generation in Germany will be cost of transmission and environmental issues in Norway. There are, however, limited possibilities to provide other emission free balancing services with similar capacity and duration of storage.

Grid usage fees

Concerning grid usage fees, German law does not make a difference between a regular electricity consumer and an electricity storage site[3]. Therefore, PSP in pumping mode are obliged to pay grid charges. From a systematic point of view and from the perspective of social welfare, both for physical and economic reasons, it can be concluded that this is not sensible and even counterproductive.

First of all, grid usage fees serve to cover grid services, like control energy and VAr (volt-amperes reactive) compensation. Storage facilities rather deliver these services than demanding them. Thus, grid charges for storage facilities lead to the absurd situation that PSP partially pay for their own products. Secondly, grid charges cover the capital cost of the infrastructure. According to law, this infrastructure is free of grid charges for generation sites, and thus, also for a PSP in turbine mode. No additional costs are generated when the same infrastructure is used in pumping mode. Grid charges for storage facilities limit the economical operation hours of PSP [13]. Hence, grid charges for storage sites hinder the extension of energy storage and, in direct consequence, hamper the integration of renewable electricity generation. Additionally, this leads to a reduced peak shaving effect, consequently causes network congestions and hence, implicates higher peak electricity prices. As a result, the electricity consumers in Germany are additionally burdened with about 95 million € per year.

Also the German Association of the Energy- and Water-Sector (bdew) recommends an amendment of German law to exclude storage technologies in charging mode from grid charges [14]. First steps towards this direction have been announced in the recently formulated Energy-Concept of the Federal Government [15]. Accordingly, newly erected storage sites should be exempted from grid charges for an elongated period.

The situation in Austria is similar to Germany. Austrian companies have to pay different kinds of grid charges to receive the necessary electrical power to run PSP in pump mode [16].

In contrast, the Swiss parliament has defeated grid charges for PSP. Hydropower plants, however, pay a water tax that depends on rated power and inflow. Since these are not applicable to PSP, Swiss cantons currently consider creation of a special pump tax. Switzerland,

[3] Higher Regional Court Oberlandesgericht Düsseldorf, enactment from Sep. 24, 2008, file reference VI-3 Kart 5/08.

via the Eurelectric working group hydro power, stipulates the abolition of grid charges in the European Union.

Outlook

The introduction of more intermittent power generation will require both, a highly flexible power system, and long-term reserve capacities.

Flexibility may be added to the system on both, the generation side, and also on the demand side. To some extent, load may be adjustable by demand side management in conjunction with smart grid technologies, for example. On the generation side, thermal plants still offer some potential for optimising ramp up transients and minimal load points. PSP, with their extremely short ramp up times, and the possibility to store energy, certainly offer the potential to contribute a substantial share to more flexibility on both, the demand side and the generation side.

For building up long-term reserve capacity, there are also parallel approaches. Part of the solution may be the utilisation of domestic thermal power generation as back up and selectively ramping up capacity in periods of low renewable power generation. Additionally, PSP in domestic and surrounding markets may contribute to satisfy high residual load situations. Depending on the generation mixture during charging, the latter approach opens the possibility of lower CO_2 emissions.

The long-term reserve capacity requires PSP with large reservoirs, while short-term flexibility is preferably delivered by powerful and fast PSP close to the load centres that additionally offer the option of solving critical grid situations by means of re-dispatching generation.

The order of magnitude of necessary storage capacity in Germany was deducted by dena in their second grid study [17]. The authors considered the present grid, including the extensions that were already suggested in the first grid study [18] in 2005. Actually, the latter ones are only implemented to about ten per cent. For buffering the electricity, that could not be used just because of grid bottlenecks, a storage device with a storage capacity of 1.5 TWh and a power of more than 13 GW would be required already by 2020. The actual development of PSP lags far behind these values. Especially, when we consider that some of the above-mentioned projects are not even licensed yet and even when we consider projects in neighbouring countries such as Austria and Switzerland.

The further development of PSP will largely depend on future market conditions. To sustain appropriate amounts of long-term reserve energy in a renewable energy dominated power system, a capacity market may emerge and offer new economic revenues for submarine cables and PSP. Other variables are CO_2 emission prices, electricity price spreads, investment costs and politics, expressed by incentives for certain technologies, for example. A European-wide exemption of energy storage sites from grid usage fees would be an important step for further developing the PSP potential. In this context, positive signals given in the energy concept of the German, Federal Government [15] are much appreciated.

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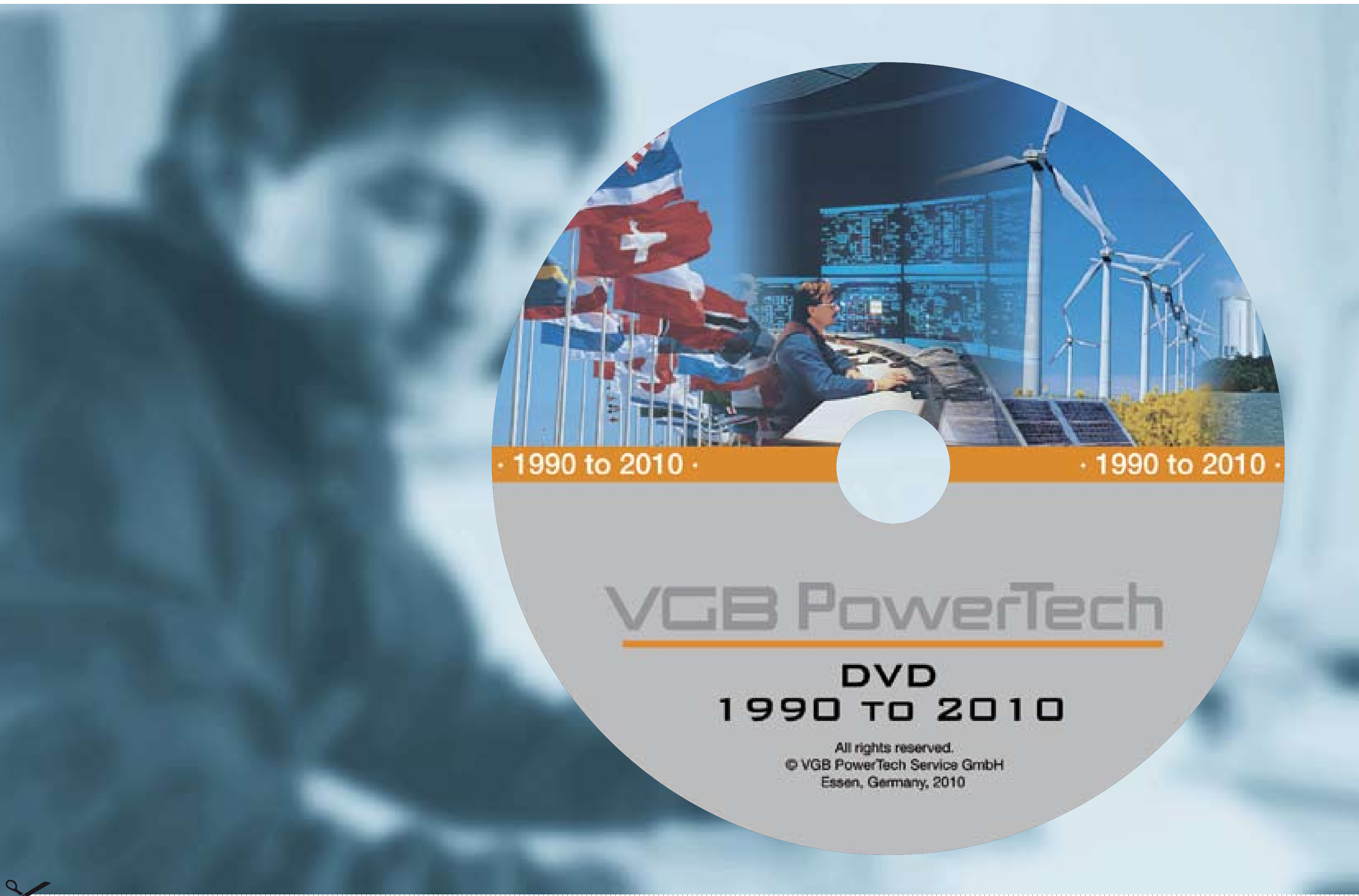

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