Pumped Storage Plants in the Future Power Supply System

Peter Vennemann, Lothar Thiel and Hans-Christoph Funke

Kurzfassung

Pumpspeicherkraftwerke in der zukünftigen Energieversorgung

Pumpspeicherkraftwerke (PSW) können mehrere Gigawatt Leistung und mehrere zehn Gigawattstunden Kapazität bereitstellen. Innerhalb der nächsten Dekaden werden die spezifischen Speicherkosten aller alternativen Techniken deutlich über denen der PSW bleiben. Kurze Startzeiten und niedrige Startkosten prädestinieren PSW für den Regelenergiemarkt. Da PSW darüber hinaus auch auf anderen Märkten agieren (Netzdienstleistungen, Stromveredelung) und nicht von einer einzelnen Primärenergie abhängen, bieten sie Investoren eine verlässliche Rendite. Prognoseabweichungen regenerativer Einspeisung können am Besten mit PSW kompensiert werden. Große Speicherkapazitäten senken die CO_2-Emission des Gesamtsystems. Netznutzungsentgelte für PSW gefährden die Integration weiterer erneuerbarer Einspeisung und erhöhen die Gesamtkosten der Strombereitstellung. Eine Gesetzesänderung wird dringend benötigt. Potenzial für weitere PSW ist in den deutschen Mittelgebirgen vorhanden. Seit 1985 hat sich die Stromproduktion von PSW mehr als verdreifacht. In Zukunft erfordert die zeitliche Entkopplung von Verbrauch und Erzeugung zusätzlich die Nutzung aller technischen Möglichkeiten der Energiespeicherung und der Laststeuerung.

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Fundamentals

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 or horizontal 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].

Major Characteristics

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

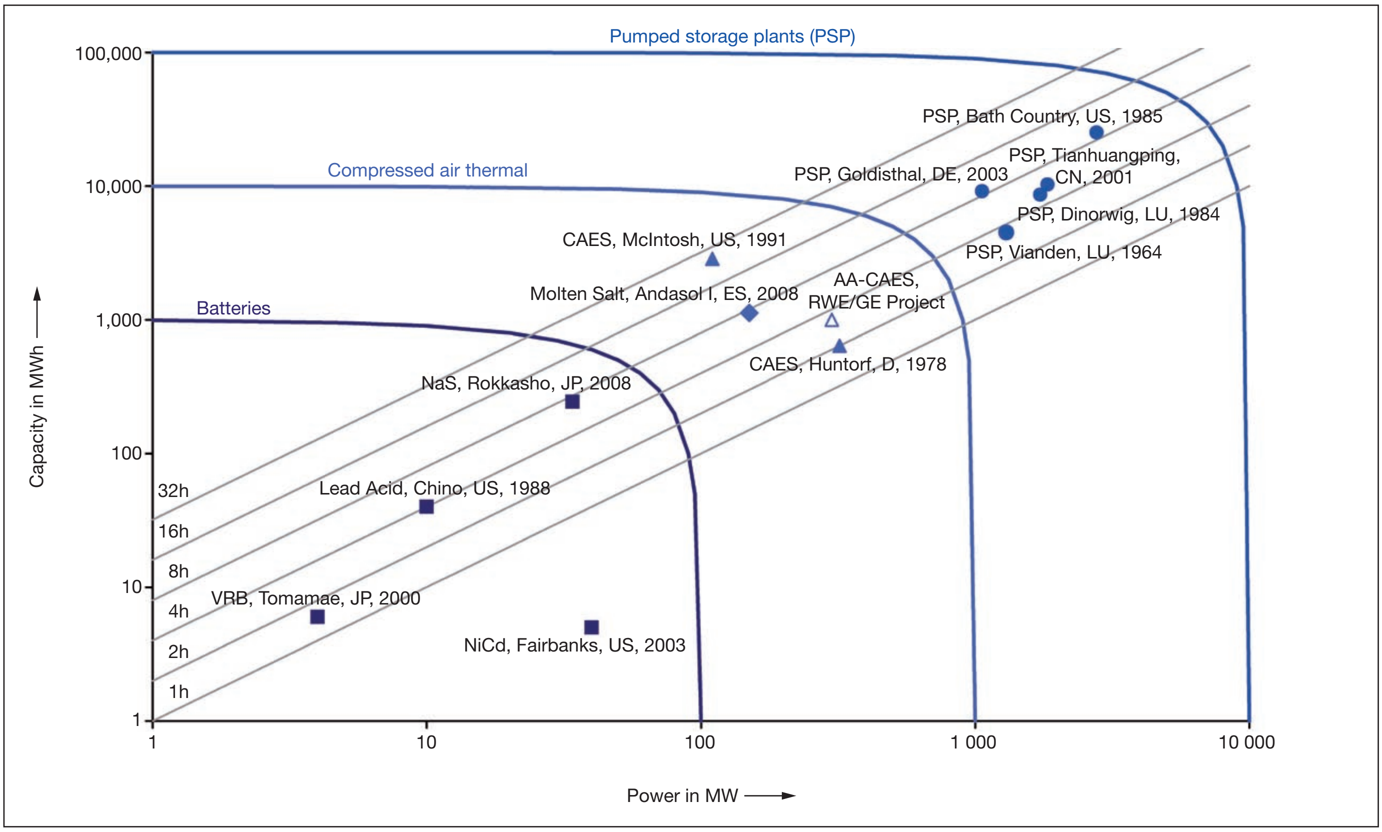

Figure 1. Order of magnitude of capacity and power of selected, large electricity storage sites (AA-CAES – Advanced Adiabatic CAES, CAES – Compressed Air Energy Storage, NaS – Sodium Sulphur Battery, NiCd – Nickel Cadmium Battery, VRB – Vanadium Redox Flow Battery). The turbine power of the CAES in Huntorf and McIntosh include additional natural gas combustion. The mere compressor power is 60 MW in Huntorf [36, 37] and 49 MW in McIntosh [38]. The projected AA-CAES of RWE and GE is planned to be operated without additional natural gas combustion. Thermal energy storage systems (Andasol I) can only be used in conjunction with a primary, thermal energy source. The conversion of electrical energy into thermal energy and back is inefficient.

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.

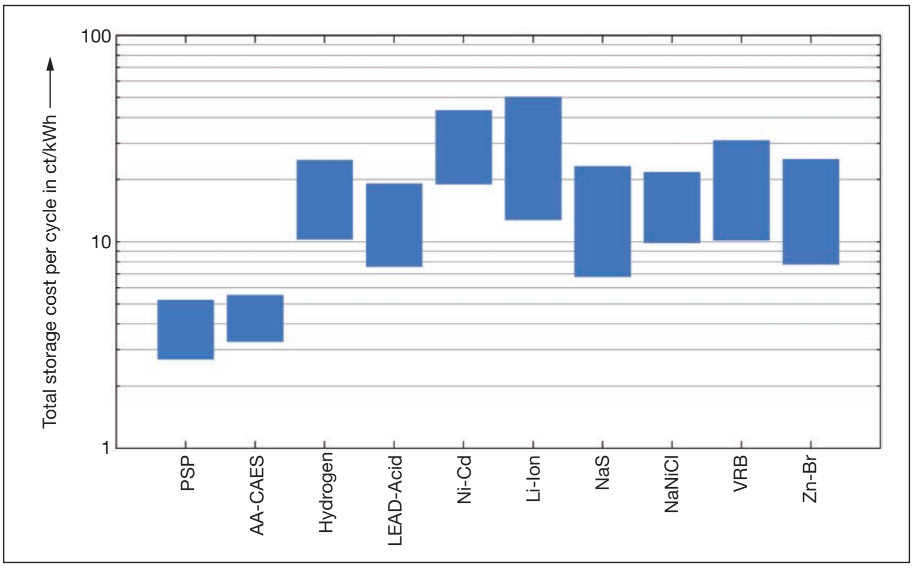

Figure 2. Total specific storage costs according to Leonhard et al. [10] considering one full storage cycle per day (Li-Ion – Lithium Ion Battery, NaNiCl – Sodium Nickel Chloride Battery, Zn-Br – Zinc Bromide Redox Flow Battery). For the hydrogen cycle, an electrolysis, storage in a salt-cavern, and usage in a gas and steam combined-cycle is considered. The upper limit of the bars represents the price level 2008, while the lower limit gives an estimate for the storage costs in at least ten years. The PSP bar gives a cost indication depending on location.

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.

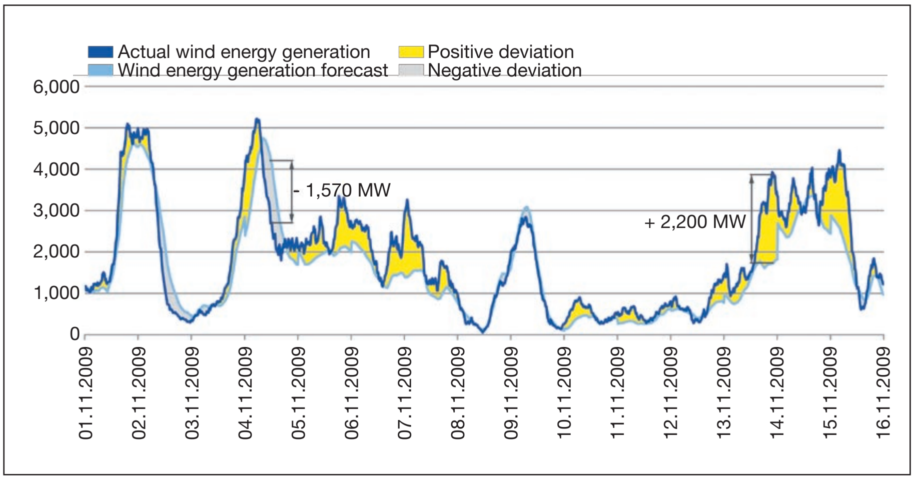

Figure 3. Daily prediction and actual wind energy feed-in for the German Vattenfall control area begin November 2009 (data from http://www.vattenfall.de).

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 CO_2 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 CO_2 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 CO_2 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 CO_2 reduction potential (Figure 5). Due to the high cycle efficiency, PSP are among the storage technologies with the highest CO_2 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

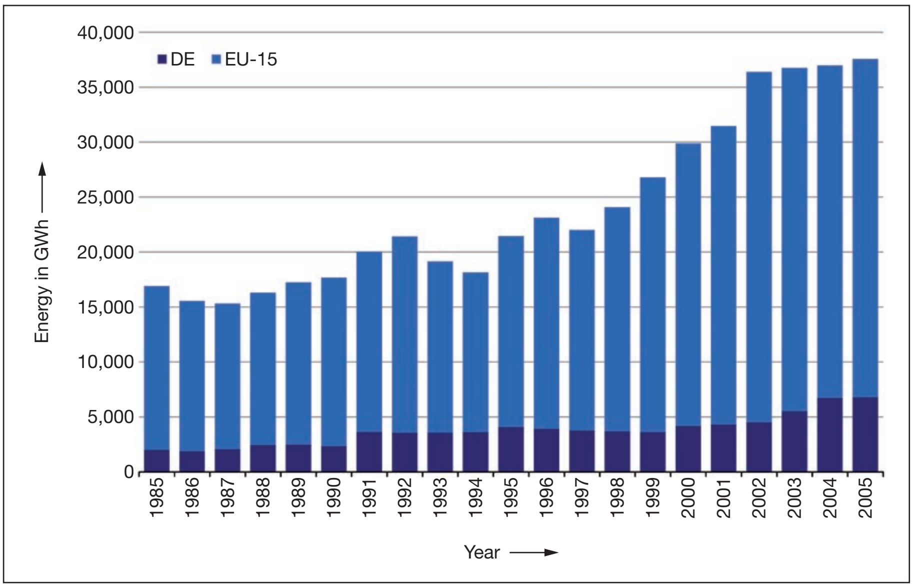

Figure 4. PSP electricity output from 1985 to 2009 according to Eurostat [11].

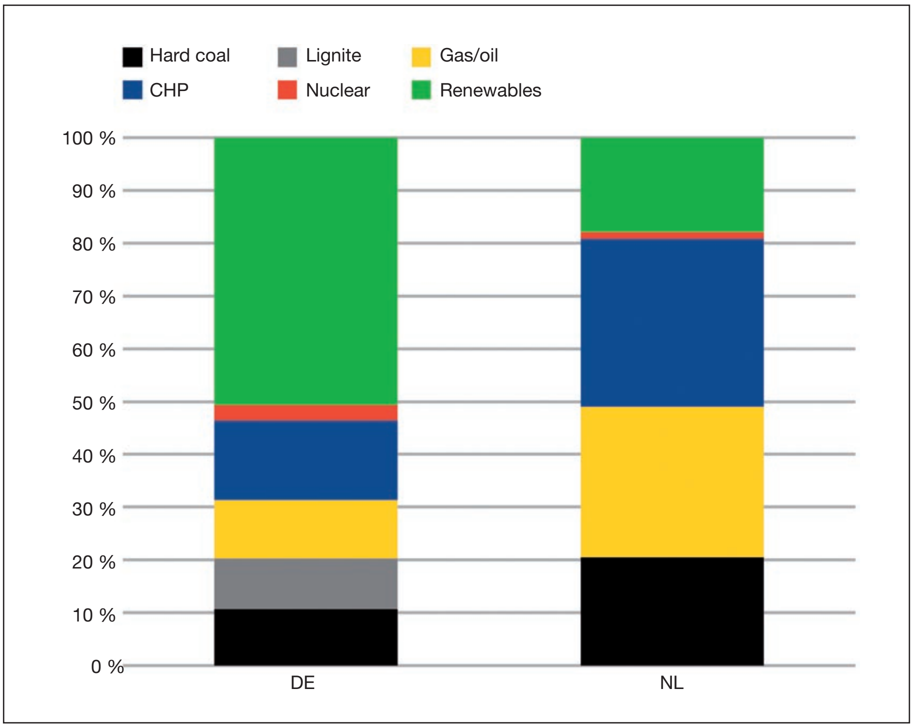

Figure 5. The carbon-rich side of the generation portfolios in Germany and the Netherlands are predicted to be almost identical by 2020. The carbon-free side is projected to be stronger developed in Germany (CHP: combined heat and power; prediction for Germany from [39], for the Netherlands from [40]).

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

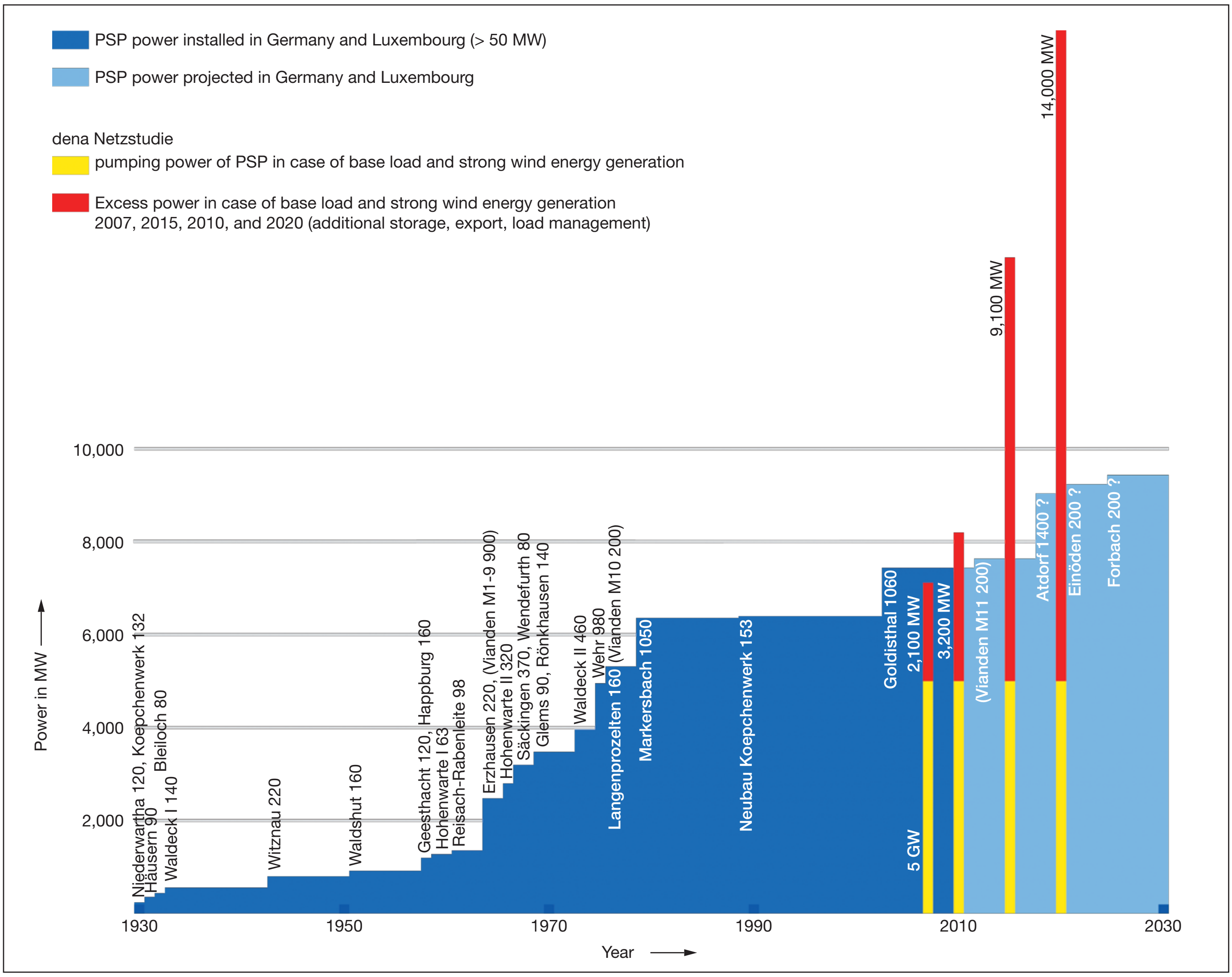

Figure 6. Development of PSP power in Germany and Luxembourg. For comparison, today‘s typical pumping power for the case of base load (50 % of yearly peak) and strong wind generation (90 % of yearly peak) is 5,000 MW. According to the dena Netzstudie 2005 [18] additional 14,000 MW must be stored, exported and consumed by means of load management in 2020.

damping effect is based on the fact, that the merit order of the electricity generation plants has an exponential character. While a pumping PSP increases the load in the flat section of the curve, a discharging PSP reduces the load in the steep section of the curve. The peak energy price is therefore stronger reduced during generation hours, than the base price is increased during pumping hours. According to dena, grid charges for PSP burden the consumers with extra costs of almost 100 million Euros per year [26]. Beyond that, grid charges for PSP are irrational, because a mayor part of the fee covers services that are not consumed by PSP but offered, like VAR compensation, and the delivery of control energy. PSP operators are thus indirectly asked to pay for their own services. It is also questionable to charge the same energy twice, once while it is stored and once when it is finally consumed. Transmission losses caused by PSP are minimal, because the energy is mainly consumed during base load hours. Last but not least, grid usage fees for PSP in France or Austria are 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.

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.

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 renaissance 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 Atdorf. 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 not be sufficient 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].

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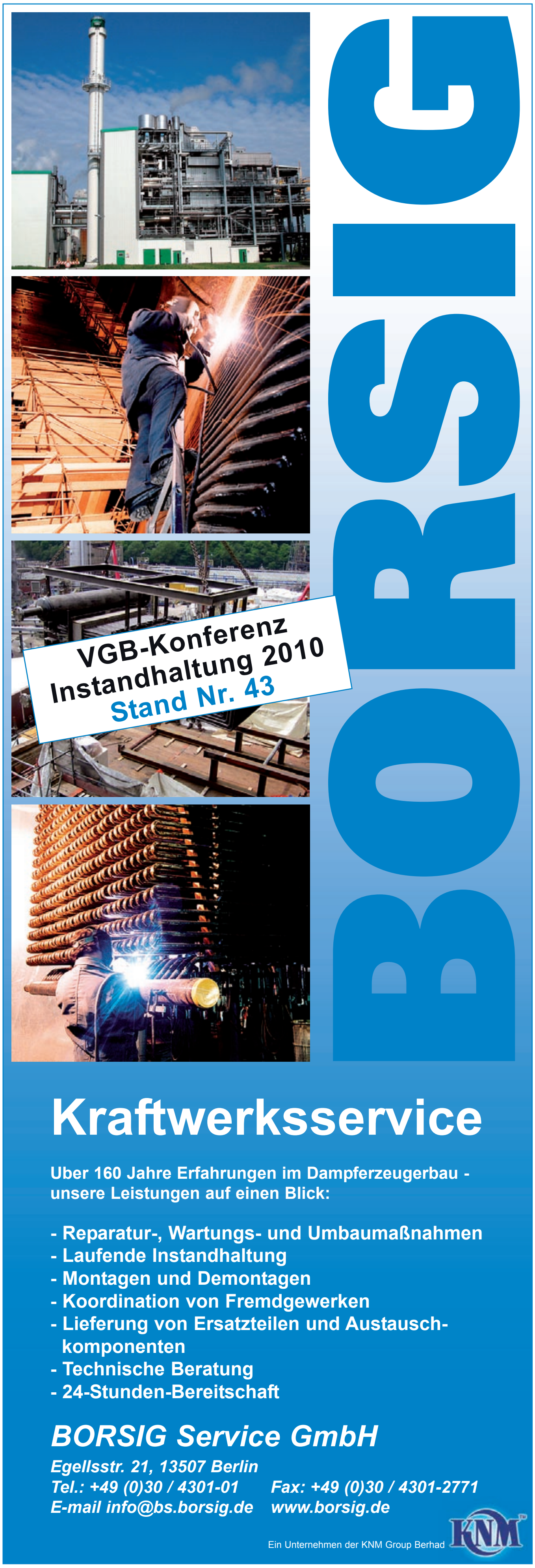

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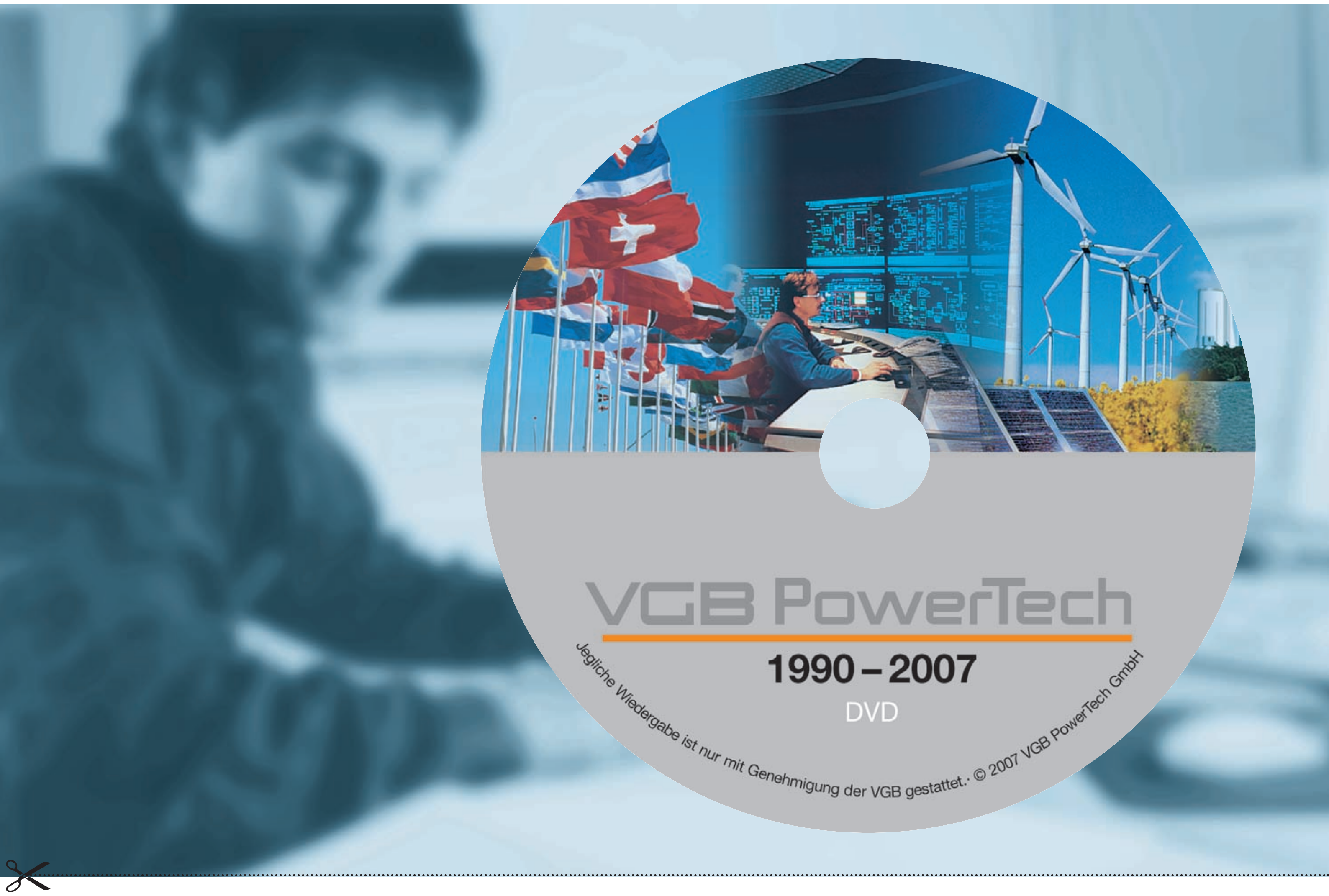

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