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2016 CIGRE International Colloquium

Hybrid Wind-Water Power Plant to facilitate Renewable Energy System Integration

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SUMMARY

The transition to a renewable energy based electricity system poses many technical, economic and social challenges. In Germany, the expansion of wind and solar generation has been well accepted. However, infrastructure projects like pumped storage plants, which facilitate the integration of volatile generation from these sources, continue to face significant opposition. The purpose of this paper is to present a new hybrid wind-water energy storage power plant that has a low environmental impact, a short planning and construction time, and a high flexibility that facilitates the integration of renewable energies. Furthermore, the combined wind and hydro power plant share the same construction site since they are integrated into one another, which reduce the infrastructure and grid connection costs. The first sections describe the fundamental concepts of the hybrid power plant using drawings and photographs to illustrate how the claimed advantages are achieved. Technical details that allow for an extremely flexible operation are presented in the following sections, and the planned operation is described. Additionally, facts are presented that demonstrate the significant importance that the flexible pumped storage plants play in balancing an electricity system that includes a large amount of generation from renewable energy sources. This is not only true for the economic perspective, but also for the stability of the electrical grid itself. This is illustrated by the load regime of a flexible hydro plant already operating in the German markets for ancillary services. The paper concludes that the presented hybrid wind-water power plant is an easily accepted and profitable solution for an environmentally friendly and technically sound integration of volatile generation from renewable energy sources.

KEYWORDS

renewable energy system integration, pumped storage, pump-turbines with variable-speed, wind farm, business model pumped storage, Effects on generators and turbines, Impacts on distribution and transmission networks, pumped storage plants, storage, hydro power, wind power, renewable energy, balancing, storage, distributed generation, batteries

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INTRODUCTION

The transition to a renewable energy economy in Germany poses many technical and economic challenges. In the past, energy was stored in fossil or nuclear forms, which made it possible to control generation in order to fit the demand. In the case of wind and solar generation, no comparable energy storage exists. Since the power generation from these sources is volatile, if a 30% share of this weather-dependent electricity is anticipated, then the electrical system has to cope with conditions where solar and wind generation vary from 100% of the load in good conditions to 0% when conditions are bad. Consequently, backup storage and increased flexibility are needed to compensate for the volatility of Renewable Energy Sources (RES). Decreasing costs for renewable energies offer new possibilities for nations with few natural resources (i.e. Germany), nations with a poor infrastructure and island nations. However, citizens' and NGOs initiatives are often opposed to infrastructure projects that are related to the expansion of renewable energies. Notable examples include transmission grid expansions and the construction of new hydro plants (i.e. USA, Germany). Pumped Storage Plants (PSPs) are presently the state-of-the-art solution to provide energy storage and flexibility for renewable grid integration. PSPs are a mature and commercially viable technology for over 100 years as a large scale solution. PSPs not only achieve a high efficiency (78% to 82%), but are also extremely durable (> 50,000 load cycles) with an expected lifetime of 60 to 80 years. However, the environmental impact of their construction is often times perceived to be high by residents living in the vicinity of designated sites. In the following, a hybrid wind-water power plant solution will be presented, which is well accepted by authorities and residents alike [1]. The plant described in the following sections features a low environmental impact and an extremely high flexibility which facilitates the integration of renewable energy into the electrical grid. It is therefore a noteworthy alternative to chemical battery based systems.

CONCEPT FUNDAMENTALS

The basic idea of the newly developed hybrid wind-water power plant combines a small wind farm consisting of four wind towers (3.6 MW class, total 14.4 MW) and a pumped storage power plant at the same location, which includes a series of different environmental-friendly measures. All four rotor hubs are positioned at the same geodetic height. At this altitude, there are moderate prevailing wind speeds (average speed estimated to be 6.2 m/s) so that each turbine generator set can be expected to produce 11 GWh of electricity per year. Such a plant is now under construction near the small town of Gaildorf, which has a population of 12,000 residents and is located in the Northeast of the German federal state of Baden-Württemberg. Future pumped storage plants will be available in three standardized output classes, i.e. 16MW or 24MW or 32 MW. They will have a certified type of approval, and are designed for a gross head range from 150m to 350m between the lower and upper reservoir.

In order to minimize the environmental impact, the upper reservoir of the PSP has been integrated into the bottom part of each wind tower (active reservoir), as well as the surrounding area of all four wind towers (passive reservoir), according to Fig. 1. The flat passive reservoir is decoupled by a shut-off valve from the active reservoir whenever the max. pool level is reached. The material that is excavated during the construction of the wind tower foundation will be re-used to backfill behind the concrete pool wall, in order to provide support and a smooth transition to the natural surface. The red line in Fig. 2 depicts the routing of the underground penstock, which first connects the four individual upper reservoirs. The total upper reservoir volume is 160,000 m^3, and can provide four hours of full load operation in turbine mode. Typically, a penstock routing does not have many bends, but in this case the penstock routing follows the existing forest service roads in order to prevent deforestation. The fourth active reservoir also acts as a surge tank, allowing for fast load gradients during operation of the PSP.

An innovative feature incorporated into the penstock design is the use of polyethylene (PE) for the wall material. The involved engineering team developed an innovative pipe-laying concept, which includes a special machine that enables a fast and easy penstock installation and burying method, without widening the existing forest service roads (see left side of Fig. 3). An adjacent area of the

Kocher River will be used for the lower reservoir and will have a dual use. During normal flow conditions of the river, the lower basin will accommodate 160,000 m^3 of water if the upper reservoirs are emptied, plus an additional 10,000 m^3 of evaporation reserves and 10,000 m^3 for minimum water storage, which is necessary for ecological reasons (e.g. fish population). The lower reservoir can also accommodate an additional 30,000 m^3 during a 10 year flood condition, i.e. the lower reservoir can be used as a retention pond in emergency cases. For these reasons, the total storage capacity of the lower reservoir will be 210,000 m^3. This slightly oversized lower reservoir was welcomed by the city authorities of Gaildorf, since they had to cope with new flood control requirements, i.e. obligations to invest in flood control to accommodate the mentioned 30,000 m^3 for a 10 year flood event.

Important aspects of the hybrid wind-water plant are the synergies between technologies. The planning costs for the combined plant are significantly lower than they would be for the construction of separate sites. Furthermore, the infrastructure of the service road only has to be built once. Grid connection is also significantly cheaper. When possible, the wind turbine cables share a trench with the penstock. Furthermore, the four wind generators and the three motor-generators of the PSP are connected to the same substation via 20 kV cables, which are buried. The technical and ecological meaningfulness of this particular solution was communicated at an early stage by a team of experts to local residents and authorities. This team includes not only engineers, but also geologists, biologists, geo-ecologists, noise abatement and publicity experts.

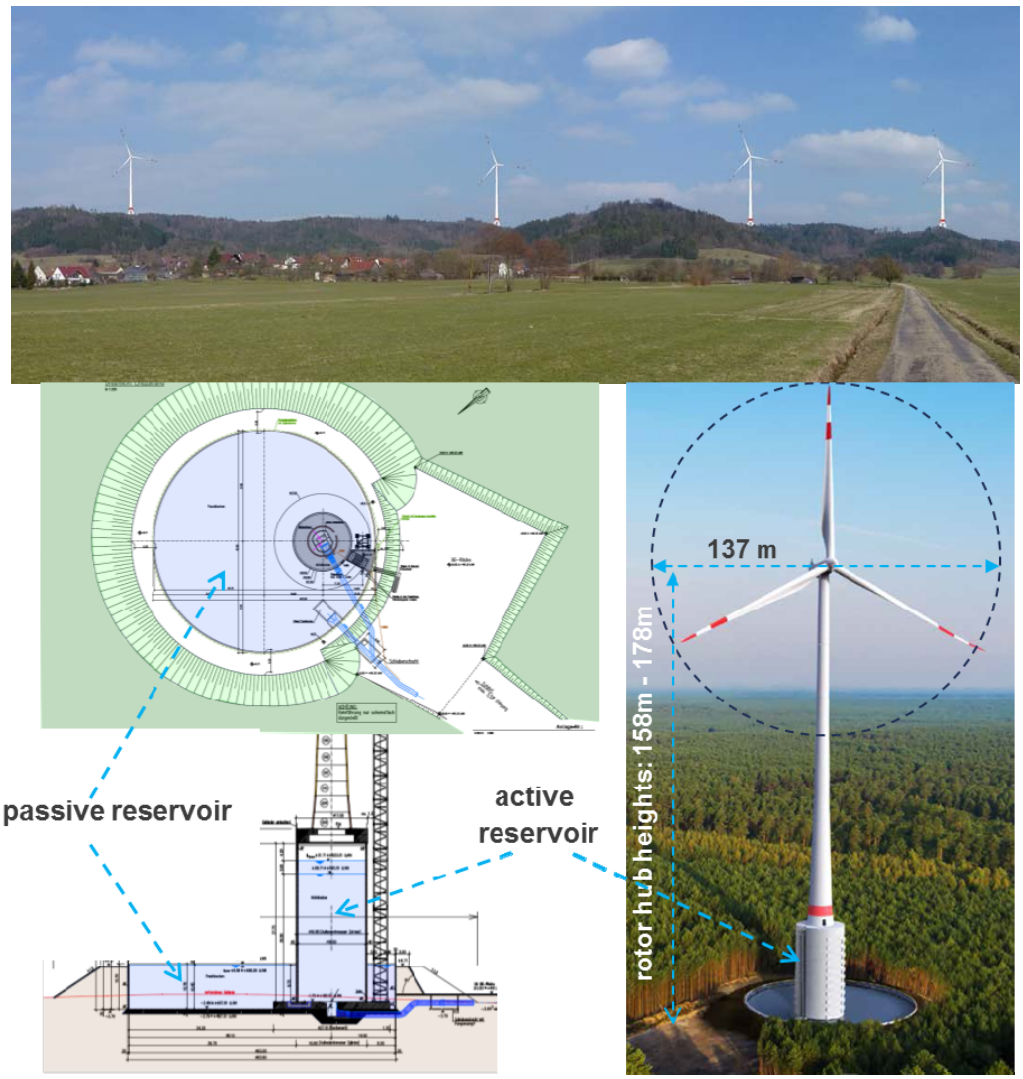

Fig. 1: Top: Photo composition showing the wind farm.
Bottom: Details for the water storage in and around the wind tower

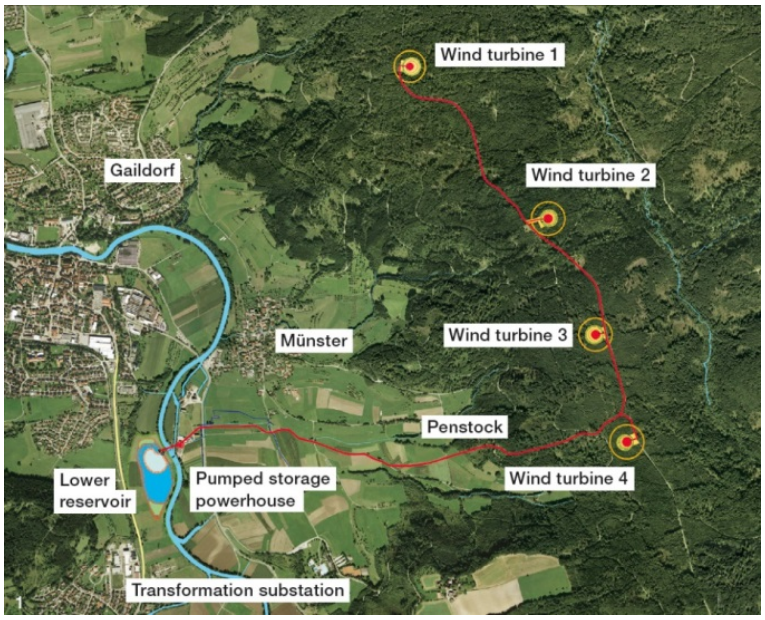

Fig. 2: Aerial view of the basic arrangement of the hybrid wind-water power plant

DESIGN CONCEPTS ALLOWING FLEXIBLE OPERATION

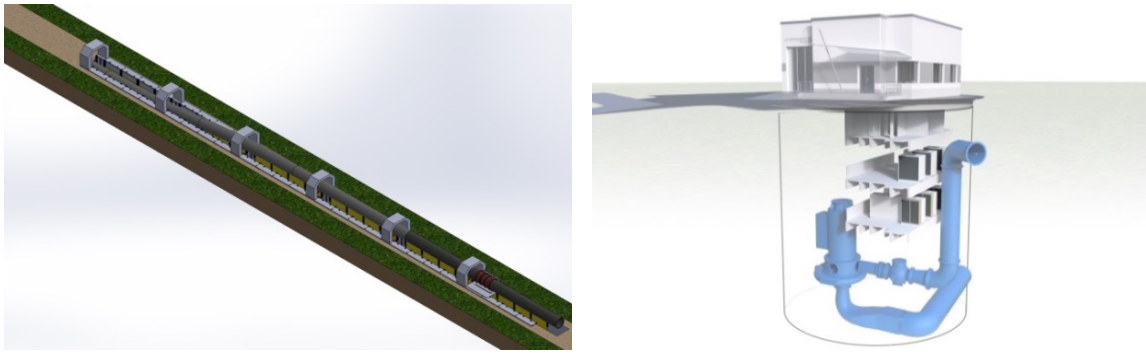

Fig. 3: Basic concept for penstock laying on the left, 3-D model of the deep excavated power house on the right, indicating only 1 of the 3 vertical power units

The power house will be of a deep excavated type, comprising of three identical reversible and variable-speed pump-turbines, and three squirrel cage type induction Motor-Generators (asynchronous MG). The total active power for the Gaildorf PSP will be approximately 16 MW. The stator terminals of each MG are connected to a four quadrant 3-level Voltage Source Inverter (VSI) using IGCT technology for the power semiconductors. The foreseen VSIs are able to directly control the mechanical shaft torque (DTC technology). This solution allows a very high flexibility, which is mandatory in order to survive in the German market environment. The advantages of the chosen variable-speed solution allow for very fast load control in both pump and turbine mode, which is important to integrate volatile renewables. Other advantages are that such units can be operated with higher water head variations, and the part load limits in turbine mode may drop to lower values. Another focus in the power plant was to improve the dynamic responses of the pumped storage when supplying ancillary services. For example, all three vertical power units have the ability to supply positive primary frequency control, i.e. the start-up time in turbine mode from stand still to full load will be 30 seconds.

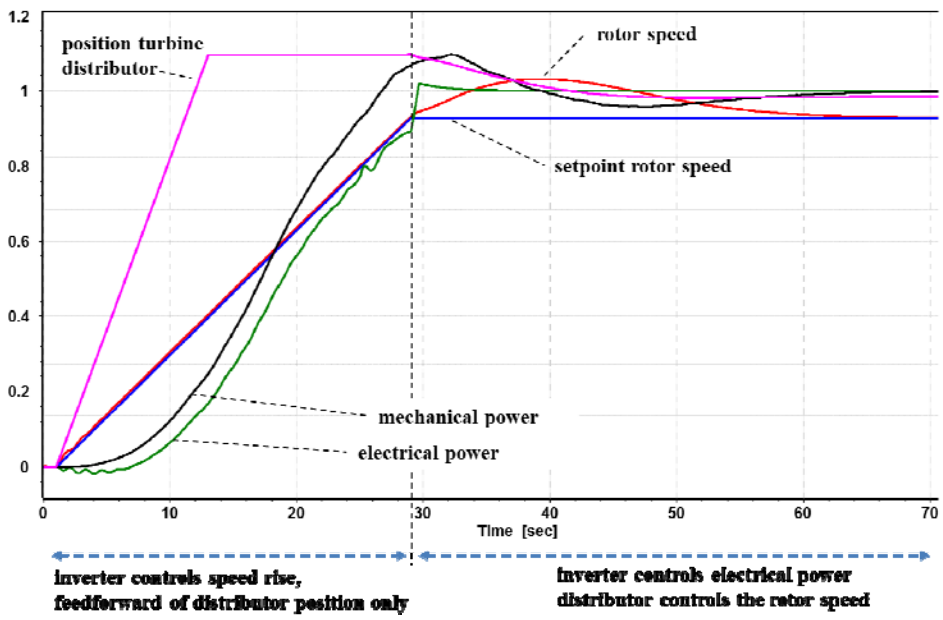

Fig. 4: Start-up of one unit in turbine mode

Fig. 4 illustrates the anticipated start strategy of one unit. At the beginning the distributor is ramped up by the digital governor of the turbine and the inverter is controlling the rotor speed. After reaching 90% of the synchronous speed the digital governor is controlling the rotor speed and the inverter controls the electrical power. This simulation demonstrates the capability of these units to provide primary frequency control from stand still condition to full load within 30 sec.

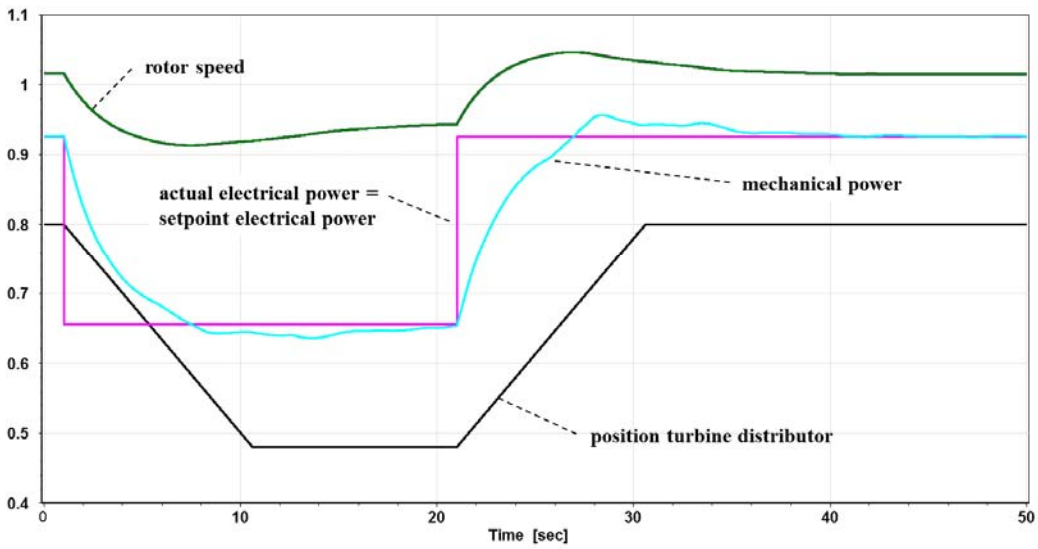

Fig. 5: Load control in pump mode

Fig. 5 shows the load control in pump mode, where the inverter is controlling the consumed power. The digital governor of the turbine is only controlling the distributor position, where the setpoint is derived from a hill chart, which calculates the optimal distributor opening for a given pump power and actual net head. The rotor speed is not controlled explicitly in the pump mode, i.e. the rotor speed adjusts itself as a function of power and head. The inverter control dynamics are so fast, that there is no difference between setpoint and current value of the consumed power. Fig. 5 illustrates that small speed changes result in large load changes since the load consumption of a pump is proportional to the speed cubed ! A similar control strategy was utilized for the two variable-speed power units of Goldisthal [3].

PLANNED TRADING AND POSSIBLE PROFIT CONTRIBUTIONS

The old market for energy storage (mainly pumped storage) in Germany was arbitrage business, i.e. pumping during low energy prices (e.g. during night) and turbine generation during peak demand at high prices. The profitability of arbitrage disappeared several years ago because the energy price variation has been decreased to values which cannot cover the storage costs anymore. The remaining trading alternatives in the energy market for a hybrid wind-water power plant today, as well as the near future, are the balancing energy and control power market, the spot market, and the avoidance of penalties for balancing energy (e.g. a pumped storage plant compensates the wind generation error caused by a wrong weather forecast). The rough "equivalents" in the US to the European energy balancing and control power products are as follows:

Europe	United States
Primary frequency control (PFC)	Governor response,
Secondary frequency control (SFC)	Regulating reserve + Spinning reserve ,
Tertiary frequency control (TFC)	Non-Spinning reserve + Supplemental reserve

Energy trading markets have different flexibility requirements and different trading volumes (see Fig. 6). What can also be stated from Fig. 6 is the following: the higher the flexibility request, the lower the market volume that is required, and vice versa. Any PSP technical constraint regarding flexibility indicates lost trading opportunities.

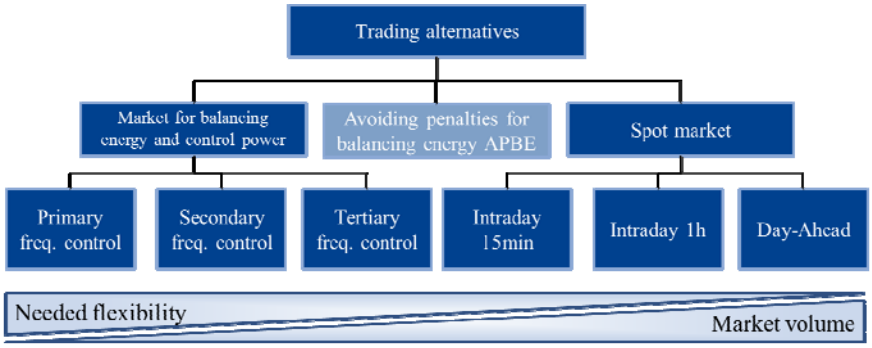

Fig. 6: Trading opportunities for the pumped storage power plant in Germany

Fig. 7 illustrates the different possible profit contributions, which vary quite significantly between the different trading alternatives: from 7.11 to 1.05 Mn €/a. The abbreviation EOM 2.0 is a new release of the German Energy Only Market act, which is now in the negotiations phase. The best estimate characterizes the most probable scenario for earnings. The highest profits can be achieved with PFC, SFC and short-term energy delivery (called here Intraday with 15 minutes and 1 hour notice prior delivery!). It should be noted that these different profit margins cannot be added together since they are alternatives; however, there is the possibility to jump from one alternative to another in order to maximize the profit according to the current energy market opportunities, since the energy market is also volatile like RES. Fig. 8 illustrates the actual load regime of a present day PSP [2]. The load regime will likely look similar for the PSP planned in Gaildorf. Fig. 8 also identifies the importance for new PSPs to be highly flexible in a market with a large portion of volatile RES.

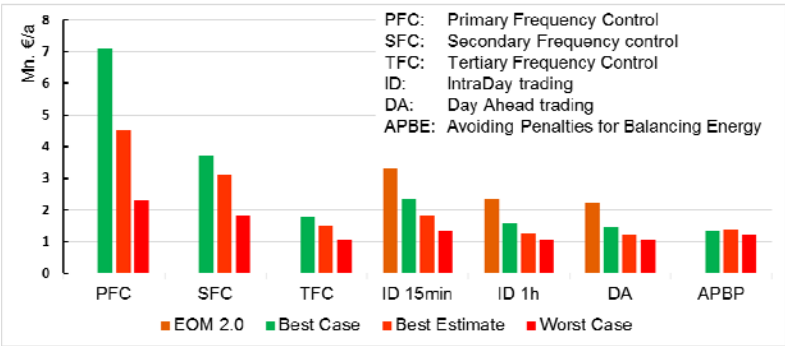

Fig. 7: Possible profit contributions for the pumped storage power plant

In order to improve visibility, the load peaks have been averaged. This highly flexible pumped storage group at the upper Lünersee in Austria is in SFC mode of operation. All new pumped storage power plants at this location are extremely flexible regarding pos./neg. load gradients, and fast change-over times between operations modes (e.g. Kops II). Pumped storage is the only mature technology for such a highly cyclical and dynamic balancing operation for grid stabilization, especially when compensating for the volatility and forecast errors of RES.

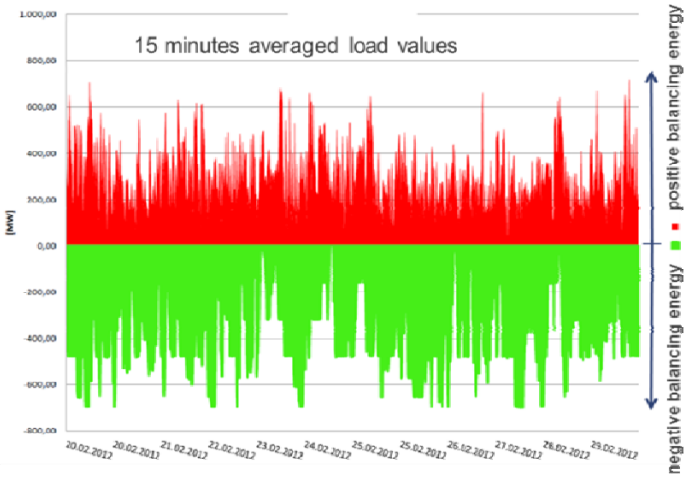

Fig. 8: Load regime for 9 days of a pumped storage group providing positive & negative balance energy (mainly SFC)

CONCLUSIONS

The described hybrid wind-water power plant offers a new and environmentally friendly alternative to integrate renewable energies and to provide electricity storage. The integration of the upper reservoir in the towers of the wind turbines reduces the impact to natural areas and significantly reduces massive public opposition, like in the case of one large artificial upper reservoir. Additionally, measures like penstock routing below the existing forest service roads and the dual use of the lower reservoir are examples of harmonious integration of a pumped storage power plant into the existing landscape. In Germany, a fast and easy approval process for windfarms is in place, which is necessary for a short project preparation, approval and implementation phase. The total project duration phase for such a decentralized hybrid wind-water power plant is 3 to 5 years versus 10 to 15 years for large pumped storage power plants. Other advantages of the wind and PSP combination are project and installation synergies, such as a common usage of the same substation, access roads, planning, land use, project and operation management, etc. The common substation with 40 MW grid connecting capacity is significantly cheaper than two separate substations with half the capacity, and also reduces the total landscape consumption. The chosen electromechanical equipment is proven and standardized technology, with the ability to achieve competitive investment costs. Additionally, they provide highly versatile power units that are a well-suited solution to the needs of the current and future energy market, which is characterized by flexibility. This solution is also suited to be implemented on islands, which intend to increase their share of RES generation without any own CO_2 emissions. The presented hybrid wind-water power plant is therefore an easily accepted and profitable solution for an environmentally friendly and technically sound integration of volatile generation from RES.

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