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Concept and potential of pumped hydro storage in federal waterways

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HIGHLIGHTS

- A new concept for pumped hydro storage at federal waterways is introduced.
- A general methodology for storage potential assessment is presented.
- In a case study for Germany the potential has been calculated to approx. 400 MWh.
- Characteristics and boundary conditions of the concept and its versions are discussed.
- Low capital cost can be expected due to synergies with existing infrastructures.

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ABSTRACT

In future energy systems with high shares of non-dispatchable renewable generation, the storage of electricity will play a key role. Today, a number of different storage options are discussed to cover the fast growing demand for storage. One of these options involves federal waterways for pumped hydro storage plants. The paper analyses the concept and the results of achievable storage potentials for Germany. The total storage potential for Germany sums up to approx. 400 MWh of which the majority can be attributed to four flight of locks which have been identified as the most suitable sites.

1. Introduction

In future energy systems with high shares of non-dispatchable renewable electricity generation, storage will play a key role [1–5]. For the case of Germany, an increasing demand for storage capacity is projected for load balancing on different time scales (short and long term) [6]. Furthermore, the increasing importance of systemand ancillary services (regulation reserve/power frequency control, etc.) with increasing renewable electricity generation is demonstrated in [7,8]. A comprehensive overview on the requirements to energy storage technologies for the provision of system (grid) services and a comparison to the characteristics of storage technologies is provided by [9].

The installed storage capacity in Europe and Germany today is almost completely accounted for pumped hydro storage power plants [10]. The discussion around the transformation process of the energy system (in Germany referred to as "Energiewende") covers new and the expansion of existing pumped hydro storage power plants to meet the growing storage demand. In Germany and Europe at present, a large number of projects are built, planned or sites are discussed [11–13]. In addition to conventional pumped hydro storage power plants (use of differences in height due to natural topography) several other approaches are in discussion for so-called unconventional pumped hydro storage plants [14].

One interesting unconventional option is the use of height differences at existing weirs, ship-lifts or locks on waterways. The concept has been introduced first by [15]. However, the concept had not been demonstrated so far and it remained relatively unknown by November 2010. At that time the concept of storing energy using German federal waterways was further detailed [16,17]. At present, the EnERgioN project at Leuphana University Lüneburg is investigating the possibility of storing energy in the Elbe Lateral Canal between Uelzen and Lüneburg as part of a detailed case study [18,19].

As the technical concept [20] and methodologies for potential assessments of conventional pumped hydro storage plants are well developed [21–23], there is a significant knowledge gap regarding fundamental conceptual descriptions and methodologies to assess storage capacity potentials of unconventional approaches. In this

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context, the paper introduces the concept and analyses the potential using federal waterways for energy storage in a systematic way on a country level for Germany as an example and identifies the most attractive sites for pumped hydro storage plants at waterways. The developed general methodology of energy storage potential assessment at waterways can be applied to other countries, too. As waterways are used with a clear priority for shipping purposes different boundary conditions including minimum water levels and maximum water level changes have to be considered regarding the additional use for energy storage purposes. Furthermore different storage concepts using single locks and flights of locks are introduced and their characteristics are discussed.

Notwithstanding some first demonstration projects of unconventional storage options already exist, a consistent and comprehensible general approach to determine the total storage potential for pumped hydro storage in waterways is lacking. For the current discussion of the German "Energiewende" and the discussion about future need for storage options [6] the determination of realistic storage capacity potentials for all possible options is fundamental and mandatory. The paper gives an approach to this outstanding analysis.

2. Basic principles

In pumped hydro storage power plants, electricity is converted to hydraulic potential energy that can be stored until it is needed and then reconverted into electricity. Pumped hydro storage power plants are characterized by reversible pumping/generation modes, made possible by a hydroelectric generating set comprising a turbine, a generator and an electric pump (Fig. 1).

In pumping mode, electricity is used to pump the water into the upper reservoir. In generation mode, the water is released and flows through turbines back into the lower reservoir. The turbines are connected to electric generators.

In Germany, 30 pumped hydro storage power plants with a capacity of approx. 6400 MW are currently in operation [13]. Table 1 summarizes the most important characteristics of existing German pumped hydro storage power plants.

In addition, 14 new-build projects and three expansions with a total capacity of approx. 7000 MW are in the planning stage [13]. The construction of new reservoirs for pumped hydro storage power plants or for other purposes (e.g. for water management/tap water supply) is associated with considerable impacts on nature and conflicts with existing land use. The impacts and conflicts can lead to acceptance problems in society. The German potential for expansion can therefore only be partially exploited and the realization of plants that are currently in the planning stage is doubtful in some cases.

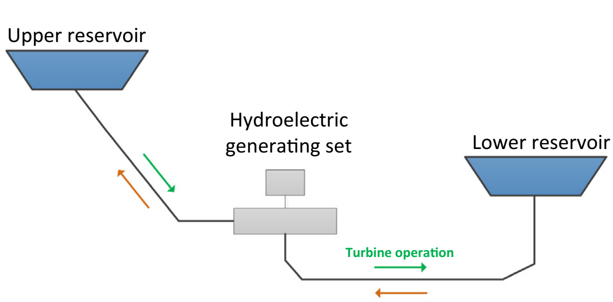

Fig. 1. Schematic of a pumped hydro storage power plant. *Source:* IEK–STE 2015.

Table 1
Characteristics of existing German pumped hydro storage power plants. *Source:* IEK–STE database 2015.

Category	Unit	Natural inflow		Total
		With	Without[b]	
Number	(–)	11[a]	19	30[a]
Installed capacity	(MW)	Approx. 1130	Approx. 5270	Approx. 6400
Power range	(MW/plant)	3–360	0.5–1060	0.5–1060
Average power	(MW)	102	277	213
Volume of water[c]	(million m^3)	0.1–5.6	0.04–12	0.04–12
Head of water	(m)	50–410	50–630	50–630
Average head of water	(m)	185	245	220
Average age[d]	(years)	65	50	55
Average efficiency[e]	(%)	68	72	70
Capacity[c]	(GW h)	7–17	33	40–50

[a] There are additional eight power plants (approx. 29 MW) which – mainly for economic reasons – are no longer operated in pumping mode at present.
[b] Inclusive the Happurg pumped hydro storage power plant (160 MW), which is presently out of service due to extensive refurbishment.
[c] Other requirements (e.g. management of water resources, flood control, low-flow augmentation) mean that only a certain proportion of the volume of water can be used for pumped hydro storage operation. For some plants, no data are available on the usable volume of water.
[d] Modernizations are not taken into account.
[e] Refurbished plants and new-build projects achieve efficiency levels of approx. 80%.

2.1. Waterways as options for pumped hydro storage solutions

The use of federal waterways for energy storage is based on the same principles like conventional pumped hydro storage power plants. The storage use necessitates the existence of weirs that create artificial height differences between large volumes of water along the waterway, which can be exploited for energy storage. The storage capacity depends on the height difference of a weir and the usable volume of water in the dammed-up section of the waterway. The sections created by the weir represent the upper and lower reservoirs for pumped hydro storage on a waterway.

As the reservoirs therefore already exist, the expense of creating them is avoided and the large area of land usually required is not needed. In addition existing structures, such as power houses at locks or ship lifts, which are already equipped with pumps, can be retrofitted or upgraded with turbine/generator assemblies depending on available space at the site [16]. The upper and lower reservoirs can be connected to the turbine via a new pressure pipeline or via the existing discharge channels. Therefore, a large proportion of the construction costs for conventional pumped hydro storage plants can therefore be avoided.

2.2. Structuring of waterways in Germany

For the assessment of the storage potential the knowledge of waterways structuring is of importance. For the example of German federal waterways are assigned to seven administrative areas (see Fig. 2: north, northwest, west, central, east, southwest, and south). The waters in the administrative areas are operated by the respective waterways and shipping directorates (WSDs) within the federal waterways and shipping administration, which are subdivided into as many as eight waterways and shipping offices (WSAs) [24]. A general distinction is made between lakes, free-flowing rivers, impounded rivers, smaller canals that are not operated as waterways and canals that are part of a waterway. Federal waterways are divided into inland waterways and coastal waterways.

German federal inland waterways have a total length of 7235 km, of which 2453 km are natural (free flowing) rivers,