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Review

Study of the drivers and asset management of pumped-storage power plants historical and geographical perspective

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ABSTRACT

PSP (Pumped-storage power plants) represent the only mature option for large-scale electricity storage, and offer a wide range of grid management services, ranging from peak power production to ancillary services. This technology has undergone drastic progress in reliability, efficiency and generation capacity, with modern PSP being able to switch from pumping to generating mode in a few minutes and working at different levels of part load. This article presents a historical perspective and the current trends in PSP deployment at a global level. It covers initial investment rationale, the evolution of the operational management and trends in installed capacities, and a systematic overview on the contribution of PSP to electricity system flexibility and reliability to different electricity markets and different power grid configurations. Particular attention is devoted to the electricity production mix evolution in the selected countries. The role and operation of PSP have evolved significantly over time to adapt to new electricity mix and market conditions. Insights regarding the prospects and barriers of PSP in the coming decades are discussed, and estimates of remaining potential are compared with future storage needs, highlighting that alternative energy storage technologies will need to emerge alongside PSP to meet the future needs.

Contents

1. Introduction 561
2. Overview of pumped-storage technology and economy 562
   2.1. Definitions 562
   2.2. PSP technologies 562
   2.3. Services provided by pumped-storage power systems 562
3. Historical and geographical overview of PSP implementation 563
   3.1. World situation 563
   3.2. Japan 564
   3.3. China 565
   3.4. USA 565
   3.5. Europe 566
      3.5.1. Italy 570
      3.5.2. Germany 570
      3.5.3. Spain 571

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0360-5442/

3.5.4. France 572
3.5.5. Austria 572
3.5.6. UK 573
3.5.7. Norway 574
3.5.8. Switzerland 575
4. Conclusion and prospects for further analysis 575
Acknowledgments 577
Acronyms & definitions list 577
References 577

1. Introduction

Until now, PSP (pumped-storage power) systems have been by far the most competitive solution for large-scale electricity storage (10–600 GWh) [1,2]. PSP remains the most mature technology currently available [3], offering high global roundtrip efficiencies (75–82%) [4], fast response-time (minutes to seconds), and a long lifetime (50–100 years) [5]. More than 150 GW of PSP capacity is installed worldwide in 2014. Other energy storage systems usually have less profitable business models or less mature technologies, but are expected to become more widely available in the next couple of years [6], especially CAES (compressed-air energy storage) [7] or PtG (power-to-gas) approaches [3].

PSP systems have played different roles in different countries since their early development a century ago. One of the initial rationales for building the first PSP plants was the need to transfer the excess electricity from the emergent coal power plants (during morning and daytime) to power back the hours of maximal light demand in the evening [8]. With the development of NPP (nuclear power plants) and coal-fired thermal plants in the 1970s, there has been a concomitant surge of new PSP constructions as well as a redefinition of the role of existing PSP, where they played a leverage and peaking role [9], while also providing a "black-start" ancillary service for the power system in order to help restore it after blackouts. The growing needs for peak and superpeak production have also driven the construction of major PSP around that time. Finally, the past decade has seen a flurry of renewed interest for the technology in many countries, with the advent of new renewable and intermittent energy sources and the market liberalization: PSP schemes are now used as a renewable integration tool [4,10].

However, recently a lot of concerns have arisen regarding PSP technologies as peak asset, in particular in regards to much cheaper solutions such as gas-fired power plants for example [11–13], which can be relatively easily operated in a large part-load spectrum and with high flexibility in terms of response times and part-load operation. Due to the low price of CO_2 (Carbon dioxide) and coal as well as the impact of overcapacity in the market, electricity is currently extremely cheap in Europe and the United States. In addition, the business case for arbitrage between base-load and peak-load period has vanished partly due to the injection of subsidized renewable electricity during peak demand. Between 2008 and 2015, base load electricity prices on European markets fell from over 70 €/MWh down to around 40 €/MWh on average, while the peak/off-peak difference flattened. Prices on the European electricity stock market are expected to remain low until at least 2019 [14].

Section 2 introduces some general concepts and technologies regarding pumped-storage, while Section 3 is dedicated to a more in-depth description of the pumped-storage role worldwide. A general overview of the PSP situation is first described, and then focuses on the main players in the field of pumped-storage. In Europe, due to the longer and more complex development of PSP, the significant differences in electric mix between countries as well as the complex topographies of mountain ranges across countries have shaped a very specific and intertwined electricity system. Therefore, the granularity of the continent has been found insufficient to draw meaningful conclusions and a more specific analysis has been carried out for some European countries. This complements the data to have a complete and thorough picture of pumped-storage in the world through its main actors, its evolution, and giving insights in its future role in the generating portfolio.

The present study presents an in-depth analysis of the development of pumped-hydro storage power plants in a broad selection of countries, both from a historical as well as techno-economic perspective, identifying both common aspects and specificities notably in terms of drivers, plant typologies and asset management strategies. It presents all relevant countries in the field of PSP in a systematic and coherent fashion, along with a wealth of tables and maps that cannot be found elsewhere in the literature. While the situation in countries such as the USA or Germany has been discussed in some details in other studies, other countries such as Portugal, Italy and China have received much less attention in the literature. Indeed, the present analysis dwelves for the first time in the specific situation of PSP plants in these less-studied territories which are nonetheless playing a major role in this field.

Such a country-by-country methodological framework has been brought forward only by Deane et al. [15], concentrating more specifically on economic drivers and investments characteristics and excluding important countries such as Italy or China. More recently, Rehman et al. [4] proposed a thorough review of pumped-hydro storage systems giving an overview of relevant technological aspects, including plant size considerations, usefulness of PSP in the overall electric network management and the novel seawater-based concepts; the paper however principally aims at demonstrating the added value of PSP in direct or indirect combination with PV (photovoltaics) and wind-energy plants.

Other studies concentrate more specifically on one given country or one specific configuration, Yang et al. [16] performed a detailed plant-by-plant analysis related to the United States, concluding that, while PSP construction has gone through a lull in the last decade, it will prove a key technology in certain regions for the proper integration of higher shares of renewables. The same conclusion is reached by the comprehensive studies presented by Steffen et al. [17] for Germany – correctly identifying profitability in the current European sluggish and low-price electricity environment as an increasingly braking factor for new PSP constructions or investments –, Anagnostopoulos et al. [18] for Greece and Baztan et al. [19] for Spain. Another interesting axis of study is the one revolving around the optimal integration of renewable energy sources and PSP in island territories or countries, such as the analysis proposed by Padron et al. [20] for the emblematic installation on Gran Canaria islands. A very detailed analysis for other European islands in the Mediterranean Sea has been provided by Papaefthymiou et al. [21], reinforcing the argument for an optimal