

Pumped Storage Hydroelectric Power Plants: Issues and Applications

Short Research Paper to assist the ERRA
Licensing and Competition Committee

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Description of the work-plan issue from the work plan of ERRA Licensing/ Competition Committee:

“There is a growing interest to build pumped storage hydroelectric power plants in order to use them for system regulation purposes. The high penetration of intermittent renewable generators requires more system flexibility. This technology could provide this flexibility to the electricity system. Several questions could occur before implementing this type of project, like:

- Is the pumped storage facility a generation unit, which should compete with other generators on the ancillary service market?, or this technology should be classified as system regulation facility (owned, operated by TSO - consequently the cost of investment and operation should be covered by the system operation charge)?
- Should the pumped storage facility pay network/system charge in both ways of operation (purchasing electricity for pumping/storing and generating/delivering electricity to grid), or "only" one way?”

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List of Abbreviations

PHS - Pumped Hydro Storage

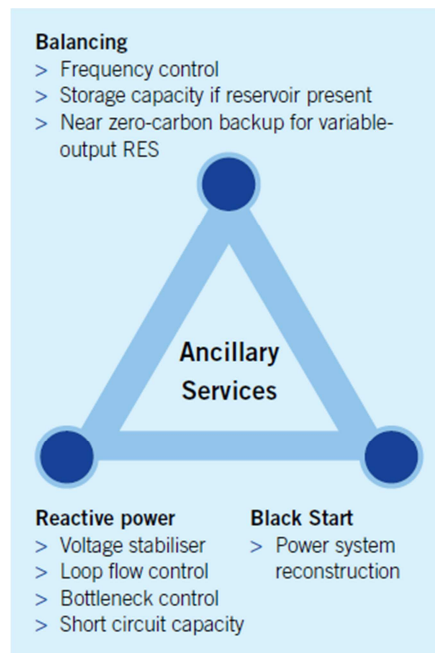
LCOE - Levelized Cost of Electricity

O&M - Operation and Maintenance

Introduction

Role of Hydropower in the electric power system

Hydropower plants providing electricity and energy storage through their large reservoirs. Serving as a dispatchable, responsive source of bulk power is hydropower's biggest upside, both in its application in pure-generation plants and in pumped storage plants. This technology can be a cost-effective renewable energy source offering high efficiency and operational flexibility (see 1. Figure). As a multifunctional technology, it is indispensable to the electricity system, and will be even more important nowadays and tomorrow.



1. Figure: Possible ancillary services of hydropower generation [20]

With the expansion of the intermittent renewable energy sources which have variable output, hydropower could serve as a flexible generator to mitigate the imbalance in the supply and demand. Pumped storage plants can additionally serve as controllable loads, drawing electricity from the grid to charge their reservoirs when excess energy is available. The technical challenges of maintaining grid stability is also a crucial issue, and hydropower could have a positive impact. The ancillary services are important for every generation unit to be competitive in the liberalized electricity market. [20][21]

23% of the reservoirs worldwide have not been equipped with hydropower generation capability. These reservoirs primarily exist to provide another service such as irrigation, water supply, flood control or ship canal locks. As civil engineering works are a major part of the investment of these plants, equipping multipurpose plants could result a lower levelized cost.

The lifetime of the electro-mechanical equipment of hydro plants is typically 40 to 50 years, but plants themselves may have lifetimes of a hundred years. From 2015, in Europe, 5-6 GW per year will reach the age of 40. Refurbishing old plants can improve their efficiency by up to 5%, so if all expiring capacity were upgraded, around 200 MW of newly available capacity could be added per year.

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Pumped hydroelectric energy storage is a large, mature, and commercial utility-scale technology currently used at many locations in the world. Pumped hydro employs off-peak electricity to pump water from a reservoir up to another reservoir at a higher elevation. When electricity is needed, water is released from the upper reservoir through a hydroelectric turbine into the lower reservoir to generate electricity. Because most low-carbon electricity resources cannot flexibly adjust their output to match fluctuating power demands, there is an increasing need for bulk electricity storage due to increasing adoption of intermittent renewable energy. This technology can be the backbone of a reliable renewable electricity system. [20][21][22]

Situation worldwide

Pumped storage is the mature and cost-effective bulk energy storage available today. With over 150 GW, pumped hydro storage power plants represent around 99% of the world's electrical energy storage capacity. Currently Japan is the worldwide leader but China expands quickly and expected to surpass Japan in 2018. The 1. Table shows the 10 countries with the most installed capacity. [22][2]

1. Table: Installed PHS capacity worldwide, 2014 [22]

Country	Installed PHS Capacity (MW)
Japan	27 438
China	21 545
United States of America	20 858
Italy	7 071
Spain	6 889
Germany	6 388
France	5 894
India	5 072
Austria	4 808
South Korea	4 700

Possible role in the future

As the renewable revolution gains momentum worldwide, hydropower looks to become an even more strategic player. The International Renewable Energy Agency (IRENA) conducted a technology roadmap (Remap) until 2030, and hydro capacity could increase up to 60%, and the pumped hydro capacity could be doubled to 325 GW from the 150 GW installed in 2014. [11][20][21]

The pumped hydro storage (PHS) systems could serve as a bulk storage application. System-level controlling of the load flow could be feasible. PHS technology is a perfect instrument for optimising the use of variable generation over long periods. With the discharging operation of these plants in the demand's peak period, the system has much better utilization. With the uncertainty is growing in the generation, it is important to have the flexibility to ensure the security of supply. [20][21][22][2][4]

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PHS serves the grid in wide range of applications:

- Peak shaving: pumped hydro storage can be used as peak generation to meet the highest demands in short period of times
- Load balancing: Load levelling usually involves storing power during periods of light loading (off peak hours) on the system and delivering it during periods of high demand.
- Frequency regulation: hydropower contributes to maintain the frequency within the given margins by continuous modulation of active power
- Back-up reserve, spinning reserve: these plants have the ability to enter load into an electrical system from a source that is not on-line. These plants can provide additional power supply that can be made available to the transmission system within a few seconds in case of unexpected load changes in the grid
- Quick start capability: the hydropower generation could be set up in just a few minutes - it is much less than the 30 minutes of other turbines, or hours of the steam generation
- Black start capability: these plants have the ability to run at zero loads. When loads increase, additional power can be loaded rapidly.
- Voltage support: these plants have the ability to control reactive power, thereby ensuring that power will flow from generation to load.

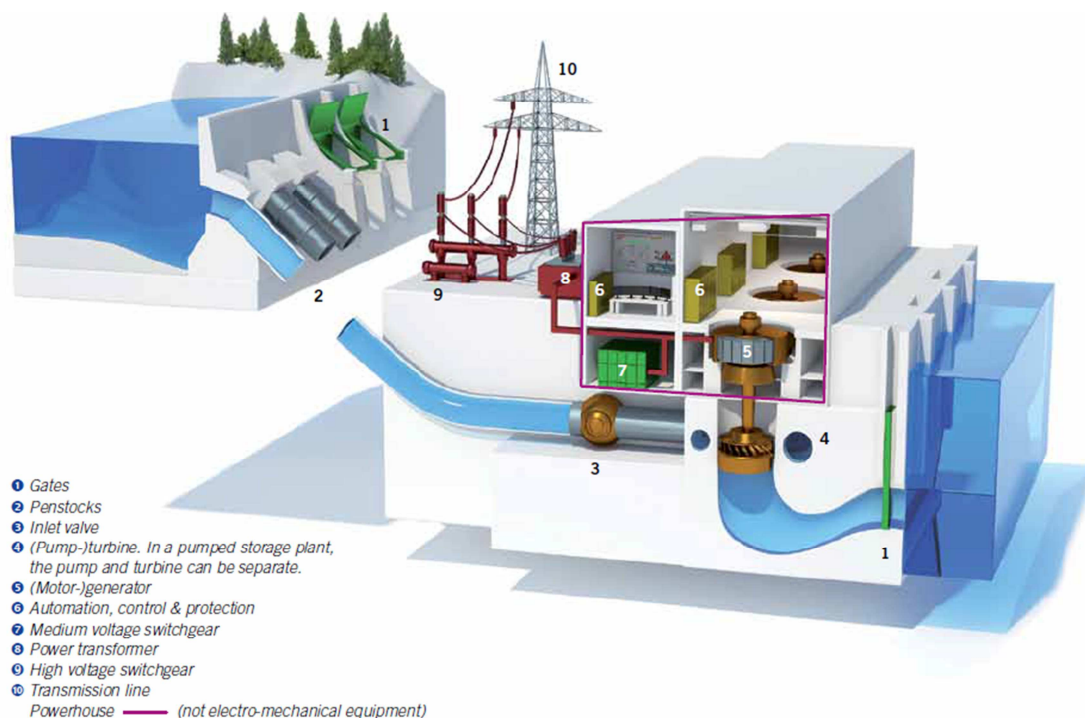
Technology Overview

A PHS facility is typically equipped with pumps (turbines) and generators (motors) connecting an upper and a lower reservoir (see 2. Figure). These plants can start up within a couple of minutes.

Pros and cons

The advantages are the very long lifetime, huge installed capacity and practically unlimited cycle lifetime. By storing electricity, PHS facilities can protect the power system from an outage. Coupled with advanced power electronics, PHS systems can also reduce harmonic distortions and eliminate voltage sags and surges. These systems could be an alternative for the high cost peak generation units. Low operation and maintenance (O&M) costs and high reliability are also important. Currently, pumped hydro has the lowest levelized cost of electricity (LCOE) from the electrical energy storage technologies,.

Their main drawback is the PHS system's geographical restrictions. These are dictated by the need for relatively large water reservoirs and large elevation variations between lower and upper reservoirs to provide sufficient capacity. The construction of a plant typically takes many years. Although the O&M costs are low, there is a high upfront capital investment in civil construction. This can only be returned over decades of operation. Environmental impacts are also serious concerns and have caused cancellations of proposed projects. The construction of conventional PHS systems often involves the damming of a river to create the reservoir. The blocking of the natural flow could disrupt the aquatic ecosystem, change the landscape and endanger wildlife. There are some technical solutions for those problems such as fish deterrent systems, oxygen injection systems and turbulence minimization. The potential impacts of the applications are site-specific and must be evaluated on a case by case basis. [22][12][3][4]



2. Figure: Cross section schematic of a hydropower plant [20]

Classification of PHS systems

Conventional PHS systems use two water reservoirs at different elevations to pump up water during the off-peak hours from the lower to the upper reservoir (charging). When required, the water flows back from the upper to the lower reservoir, powering a turbine with a generator to produce electricity (discharging). There are two main types of PHS facilities: off-stream (closed loop) PHS uses water that were pumped into the upper reservoir while hybrid (combined) PHS use both pumped and natural stream flow water to generate electricity (open loop). [22][2][11][12]

There are some alternative and novel designs:

Variable speed PHS: most existing systems are equipped with fixed-speed pump turbines and those may provide bulk storage but they can only provide frequency regulation during the discharging mode. New variable speed technology allows facilities to regulate frequency during the pumping process. Japan has pioneered this technology in commercial use.

Seawater PHS: Japan also pioneered this system in Okinawa. This plant uses the open sea as the lower reservoir. New projects have been proposed in connection with this technology including the Dutch consulting company (DNV KEMA) project which is planning to use the sea as an upper reservoir and construct a lower one by dredging and building a ring of dikes 50 meters below the sea level.

Underground PHS: researchers have proposed the possibility to utilize underground caverns as lower reservoirs but so far none have been built.

Compressed air PHS: an innovative design plans to replace the upper reservoir with a pressurized water container. Instead of storing potential energy in elevated water, the proposed system stores the energy in the compressed air.

Undersea PHS: another innovative concept is to utilize the water pressure at the bottom of the sea to store electricity from off-shore wind turbines. The system places submerged pressure vessels on the sea floor [22]

Technical parameters

The efficiency of PHS systems varies quite significantly (mainly because the long history and long lifetime of the facilities). The round trip efficiency - which means the electrical power generated divided by the electrical power used to pump up the water - is lower around 50--60% in older facilities but can be over 80% in some state-of-the-art PHS systems.

It is a large, mature and commercially used technology. PHS has existed for a long time: the first plants were used in Italy and Switzerland. Projects may be practically sized up to 4000 MW. While the siting, permitting and associated environmental impact processes can take many years, there is growing interest in re-examining opportunities for PHS. [2] [11] [12] [22]

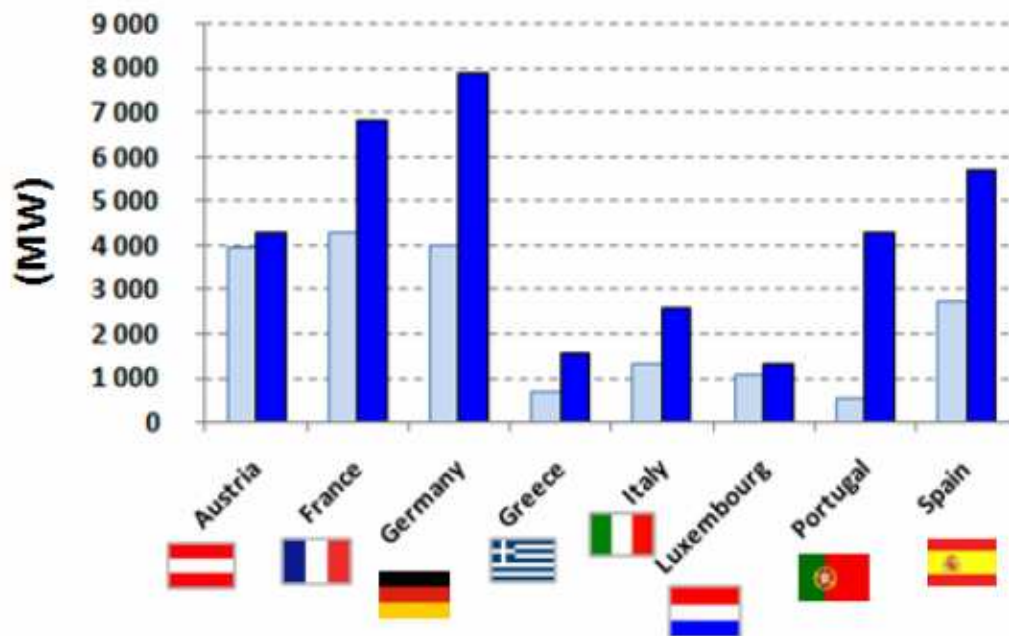
Regulation of Pumped Hydro Storage Systems

Policy challenges of hydropower plants

Hydropower facilities used to satisfy various needs. This means that there is often a strong interaction between water management and energy as one being needed for the use of the other. Most governments are administrating hydropower projects and the related public water resource management through public licensing processes. The licensing process is usually the moment in a hydropower project's lifespan where all water, land use and infrastructure needs are assessed at a regional level. The government is responsible for the arbitration among the conflicting needs; the plant owner is responsible for the water management at the operation level. The long life span of those facilities creates occasions where the balancing discussion of different needs has to be updated. Due to these most concessions are time bound in proportion to the amount of capital investment or the terms and conditions can be revised upon the demand. [20][21][22]

Pumped hydro storage policy and current framework

PHS plants are not considered as renewable energy sources in the European Energy Directive. However this technology can be an effective tool to facilitate the integration of intermittent renewable energy sources. As it can be seen on the 3. Figure, a significant growth is expected in this technology in Europe. The light blue columns represent the installed capacity in 2005 while the dark blue columns represent the expected capacity in 2020. [26]



3. Figure: Pumped hydro storage installed and forecast capacity in the EU (MW) [26]

But in contrast, storage has not been the focus of any specific regulatory action. It is important to mention this when PHS is called mature. PHS is considered by regulation like as many other generating technologies. However, there is desire for capacity to increase system flexibility in which

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PHS is exceptionally competitive from a technical viewpoint. The significant grow in the penetration of renewable energy sources will stress this need. [18]

PHS (and all storage technologies) is treated in the same way as other generating devices with the same characteristics in the European Network Code ¹on Requirements for Grid Connection (reference [23]). Some important statement from the network code:

- PHS Power generating modules shall fulfill all requirements in both generating and pumping operation
- With regard to disconnection due to under-frequency, any power generating facility being capable of acting as a load except for auxiliary supply, PHS shall be capable of disconnecting its load in case of under-frequency.

There are also some statements about storage facilities in the Network Code on Demand Connection (reference [24]), but it is only applicable for PHS systems which only provides pumping mode.

The renewable energy directive (reference [25]) clarifies that electricity produced from PHS units should not be considered as renewable energy. However it is also written that there is a need to support the integration of energy from renewable sources into the transmission and distribution grid.

Currently there is no particular investment framework for pumped hydro storage. It is worth mentioning that from the investment decision to starting operation of a pump storage investment requires years. Pumped hydro storage is seen as an electricity consumer and electricity generator, depending on its operation and equipment. Therefore, pumped hydro storage pays in most EU countries double fees (tariffs) for network access, some TSOs charge nothing for the pumped hydro storage's role as electricity consumer, other TSOs recognize it as a renewable based generator (country survey results in reference [8]). It would be important to define storage as a specific element, not an aggregation of generation and load. It will depend on the application in some cases but this technology differs from the conventional network elements and the regulation should focus on the possible advantages instead of the drawbacks. Common rules should be applied regarding transmission access fees and use of system fees for electricity storage systems in order to avoid deployment of an electricity storage facility in one country with favorable rules in order to provide services in another country with less favorable rules.

There is no EU legislation to regulate this issue and TSOs treat pumped hydro storage as they see it fit to their local market circumstances. The different approaches across national markets create distortions which have an impact on access and related costs for pump storage energy in neighboring markets. [8]

Recommendations for market and policy changes

Many stakeholders say that it is uneconomic to build new PHS plant today in the present legal and regulatory framework. Even when developers are willing to invest in large electricity storage facilities, they explain that access to finance is difficult because of the various regulatory and market uncertainties that may have a negative impact on profitability.

PHS systems should be fully optimized in the day-ahead markets. Real time market level optimization also should be considered if it is feasible. This will allow scheduling the PHS more accurate. It has to be taken into account that the PHS has lost opportunity costs based on multiple hours for ancillary

¹ The European Network Codes are binding regulation throughout the EU energy markets

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service clearing prices. A sub hourly settlement compensation of PHS systems should be considered. PHS could utilize fast response to meet shorter swings. Capacity adequacy at a system level is also a boundary condition for planning.

PHS systems also should be paid for their performance: the ability of providing superior regulating reserves (fast response) and load balancing ability. A possible compensation system for voltage control also could be feasible. The most appropriate way to operate a PHS system is to tender on a non-discriminatory basis, using open instruments such as auctions.

When an additional need for flexibility is identified in a power grid, starting point should be a circumspect analysis which considers the alternative options available (for flexibility it could be conventional peaking units, demand side management, interconnections, generation unit or network upgrades). An optimizing algorithm for this service could choose from the options, based on the technical and economic (capital, O&M, fuel and CO₂ costs etc.) parameters and effects. [17][18][20][21][22]

	 DE	 FR	 GB	 IT	 ES	 GR ¹
	Can storage participate in the wholesale market?					
Time-shift	✓	✓	✓	✓	✓	✓
	Can storage participate in the frequency reserve market?					
Frequency reserve	✓		✓			
	Can TSO/DSO own and operate storage?					
T&D	✗	✗	✓ ²	✓ ³	✗	✗

4. figure: Ancillary service markets for energy storage in Europe

The clear definitions for storage technologies are important to more effective regulatory act. It should be added to different regulations as well. A cost-of-service model of regulation would not only be affected by the technical objective function but the problem of functionalization. Storage could be categorized as generation, transmission or distribution unit functionally. Generally the benefit realized from the operation decides the type. However, it will often be difficult to ascertain which of these categories is predominant, not to mention the ancillary services and aggregated operation. The unbundling principle is another issue because if storage is treated as a generation facility it could not been owned by the system operator. Currently – as it can be seen on 4. Figure – storage could be used commonly for time shift operation in Europe. Transmission and distribution grid investment deferrals are only possible in Italy and the UK currently in Europe, generally the system operators are not allowed to have control over an electricity-generating facility due to the unbundling principle. In the UK, storage – and small generating units as well – can obtain exemption from the obligation to hold a generation license on a case-by-case basis. This allows the system operators to deploy small storage systems on investment deferral purpose. In Italy, the system

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operators are allowed to operate a storage system if it is proven to be the most efficient solution for a problem.

Because of the complexity of the topic and the information asymmetries, these challenges appear currently hard to overcome. Other forms of incentive regulation could be adopted like output based models of regulation (where remuneration is linked to external parameters like renewable penetration growth and imply the avoided costs). [18]

References

- [1.] National Renewable Energy Laboratory: The Role of Energy Storage with Renewable Energy Generation, January 2010. <http://www.nrel.gov/docs/fy10osti/47187.pdf>
- [2.] DOE/EPRI: Electricity Storage Handbook in Collaboration with NRECA, July 2013. <http://www.sandia.gov/ess/publications/SAND2013-5131.pdf>
- [3.] Electric Power Research Institute: Electrical Energy Storage Technology Options, 2010. <http://www.epri.com/abstracts/pages/productabstract.aspx?ProductID=000000000001020676&Mode=download>
- [4.] International Energy Agency: Technology Roadmap on Energy Storage, 2014. <https://www.iea.org/publications/freepublications/publication/TechnologyRoadmapEnergyStorage.pdf>
- [5.] stoRE: Empfehlungen zur Anpassung der politischen und marktregulatorischen Rahmenbedingungen für Energiespeicher in Deutschland, February 2014 (German language) http://www.store-project.eu/documents/target-country-results/en_GB/energy-storage-action-list-in-germany-with-summary-in-english
- [6.] stoRE: Facilitating energy storage to allow high penetration of intermittent renewable energy, May 2014. http://www.store-project.eu/documents/results/en_GB/final-publishable-report
- [7.] Eurelectric: Decentralized Storage: Impact on Future Distribution Grids, June 2012 <http://proclimweb.scnat.ch/portal/ressources/2887.pdf>
- [8.] European Commission DG Energy: The Future Role and Challenges of Energy Storage https://ec.europa.eu/energy/sites/ener/files/energy_storage.pdf
- [9.] International Renewable Energy Agency: Electricity Storage and Renewables for Island Power, May 2012. <http://www.irena.org/DocumentDownloads/Publications/Electricity%20Storage%20and%20RE%20for%20Island%20Power.pdf>
- [10.] International Renewable Energy Agency: Battery Storage for Renewables: Market Status and Technology Outlook, January 2015., http://www.irena.org/documentdownloads/publications/irena_battery_storage_report_2015.pdf
- [11.] International Renewable Energy Agency: Renewables and Electricity Storage: a technology roadmap for Remap 2030, June 2015., https://www.irena.org/DocumentDownloads/Publications/IRENA_REmap_Electricity_Storage_2015.pdf
- [12.] International Electrotechnical Commission: White Paper on Energy Storage, December 2011. <http://www.iec.ch/whitepaper/pdf/iecWP-energystorage-LR-en.pdf>
- [13.] Martin Crouch: Ofgem's Innovation Plan, February 2016.
- [14.] Lazards: Levelized cost of storage analysis, 2015. <https://www.lazard.com/media/2391/lazards-levelized-cost-of-storage-analysis-10.pdf>
- [15.] United States of America Department of Energy: Grid Energy Storage, 2013. http://www.sandia.gov/ess/docs/other/Grid_Energy_Storage_Dec_2013.pdf
- [16.] The Fuel Cells and Hydrogen Joint Undertaking: Commercialization of Energy Storage in Europe, March 2015., http://www.fch.europa.eu/sites/default/files/CommercializationofEnergyStorageFinal_3.pdf

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References

- [17.] stoRE: European Regulatory and Market Framework for Electricity Storage Infrastructure, 2013., http://www.store-project.eu/documents/results/en_GB/european-regulatory-and-market-framework-for-electricity-storage-infrastructure
- [18.] Bernardo Rangoni: A Contribution on the Regulation of Electricity Storage: the case of Hydro-Pumped Storage in Italy and Spain, http://www.city.ac.uk/_data/assets/pdf_file/0009/120015/Bernardo_RANGONI_electricity-storage.pdf
- [19.] Hydro Equipment Association: European Hydropower Initiative of Hydropower Companies and Associations: The hydropower's sector's contribution to a sustainable and prosperous Europe, June 2015. <http://www.thehea.org/wp-content/uploads/2015/07/policy-report-macro-economic-study-on-hydropower-in-europe.pdf>
- [20.] Hydro Equipment Association: Global Technology Roadmap, October 2015. http://thehea.org/gtr_.pdf
- [21.] Hydro Equipment Association: Hydro Equipment Technology Roadmap, August 2013., <http://www.thehea.org/wp-content/uploads/2015/12/eu-hydro-equipment-technology-roadmap.pdf>
- [22.] Chi-Jen Yang, Duke University: Pumped Hydroelectric Storage, <http://people.duke.edu/~cy42/PHS.pdf>
- [23.] ENTSO-E: Network Code on Requirements for Grid Connection Applicable to All Generators, December 2015., <https://www.entsoe.eu/major-projects/network-code-development/requirements-for-generators/Pages/default.aspx>
- [24.] ENTSO-E: Network Code on Demand Connection Applicable to All Generators, December 2015., <https://www.entsoe.eu/major-projects/network-code-development/demand-connection/Pages/default.aspx>
- [25.] DIRECTIVE 2009/28/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 23 April 2009, <http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:140:0016:0062:en:PDF>
- [26.] Eurelectric: Hyrdo in Europe: Powering the Renewables Full Report, 2011., https://www.google.hu/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&cad=rja&uact=8&ved=0ahUKEwjf0uri8vrNAHXGsxQKHRD1BmQQFggyMAA&url=http%3A%2F%2Fwww.eurelectric.org%2Fmedia%2F26690%2Fhydro_report_final-2011-160-0011-01-e.pdf&usg=AFQjCNGHrWTGOxckqb3kT7zII1XYEo3TA&sig2=pj2jUhgtOGqebZM64awzDA&bvm=bv.127521224,bs.2,d.bGg