Underground Pumped-Storage Hydro Power Plants with Mine Water in Abandoned Coal Mines

Javier Menéndez[1], Jorge Loredo[2] , J. Manuel Fernandez[3], Mónica Galdo[4]

[1] Mining Engineer. Project Manager at SADIM, S.A.
Jaime Alberti Street, Nº 2, 33900, Ciaño- Langreo, Spain (javier.menendez@sadim.es)
[2] Mining Exploitation Department. University of Oviedo. (jloredo@uniovi.es)
School Of Mines, Independencia Street Nº13, 33004, Oviedo, Spain
[3] Energy Department. University of Oviedo. (jesusfo@uniovi.es)
Departmental Building East Zone, University Campus of Viesques, 33271, Gijón, Spain
[4] Energy Department. University of Oviedo. (galdomonica@uniovi.es)
Departmental Building East Zone, University Campus of Viesques, 33271, Gijón, Spain

Abstract The Asturian Central Coal Basin in northern Spain has been an exploited coal mining area for many decades and its network of tunnels extends among more than 30 mines. Parts of this infrastructure will soon become available for alternative uses since most of the underground coal mining facilities in Spain will fade out in 2018 *(EU 2010/787/UE)*. The network of tunnels in closed-down mines has been suggested as a possible lower storage for the development of an underground pumped-storage project. This infrastructure can hold approximately 200,000 m^3 at depths that range between 300-600 m.

Keywords Hydroelectricity, mine water, pumped storage.

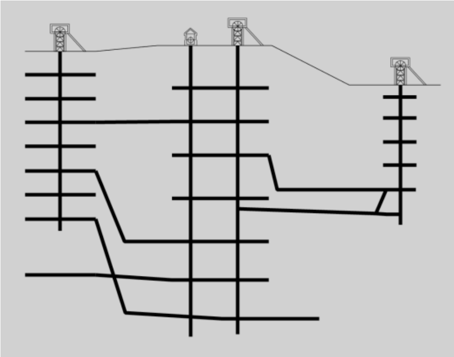
Introduction

The Asturian Central Coal Basin (ACCB) is located in northern Spain (Figure 1). It has been exploited for more than 200 years through open pit and underground mining, with indoor mining predominating in the last decades. It was one of the most important economic activities in the Principality of Asturias and an outstanding source of employment creation, which therefore contributed to the current development of the surrounding towns.

***Figure 1**. Asturian Central Coal Basin location*

Underground coal mines have a depth of up to 300-600m, with a main infrastructure composed of one or several vertical shafts, used for mineral extraction and for access of personnel and materials. It has a network of horizontal tunnels at different levels, with an average separation between levels of 80-100m (Figure 2).

Figure 2. *Typical scheme of shafts and tunnels network in coal mines*

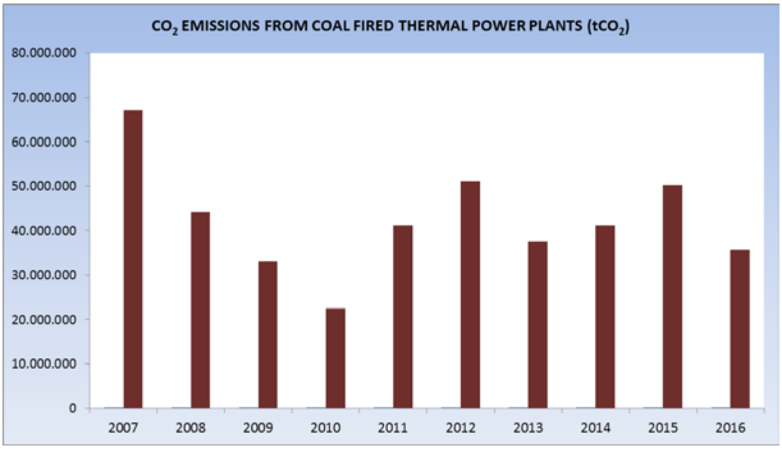


The mineral obtained is used as fuel in thermal plants for the generation of electrical energy. This being one of the most outstanding energy sources within the national energy mix in recent years, with an average participation of 15%. Although on a much smaller scale, the coal produced was also used in the manufacturing of steel.

In recent years there has been a decline in the production of national coal, motivated among other factors by the implementation of European policies focused on the reduction of greenhouse gas (GHG) emissions, as well as on a low competitiveness of national coal marked by a continued decline in the price of international coal, which is also of higher quality than the national coal.

In 2016 coal-fired power generation in Spain accounted for 56% of CO_2 emissions, with more than 35 Million tCO_2, but it only accounted for 13.7% of the electricity demand coverage. The evolution of CO_2 emissions in the generation of electricity with thermal coal since 2007 in Spain, is reflected in Figure 3.

Figure 3. *CO2 Emissions from coal fired thermal power plants (REE)*



On the other hand, one of the main conditions of the mining exploitation occurs on the water network. The long history of the Asturian mining has caused a strong alteration in the potentiometric levels and in the natural flow of the aquifers in the affected areas. The exploitations have generated to a triple porosity aquifer (Pendás et al. 2002). Where previously there were small aquifers in sandstone of a small-scale multilayer system, mining tunnels and fractured zones have now been created, that work as aquifers assimilable to the karsts (Pendás and Loredo, 2006). In fact, all the gaps caused by coal mining in the Asturian Central Basin operate as a large underground water reservoir.

Most of the mining work, whether open or underground, intercepts the piezometric level and forces the establishment of a pumping system, which, if interrupted after the closure of the activity, will bring with it a partial or total flood of the mining tunnels.

Presently, the pumping of the infiltrated waters is considered an important cost for the mines, with an average flow of 40 Mm^3 per year. Before this, to optimize the use of the economic resources, a first option of cessation of the pumping in the closed shafts was studied, proceeding to the flood of the mining hole. However, this solution is not always applicable due to the uniqueness of the mines, the interconnections created during the exploitation phase and the proximity of the mines to populated areas.

Pumped-Storage Hydroelectricity (PSH)

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.

The first idea of exploiting a disused mine as an underground reservoir dated from 1960 (Harza, 1960) and it was developed by several studies and technical reports but not accompanied by functioning pilot projects (Pickard, 2011).

Mount Hope project, located in northern New Jersey was initially proposed in 1975. It intended to use the facilities of an abandoned iron mine as a lower reservoir but it was never developed (Dames and Moore, 1981).

The feasibility of using some of the current coal mining facilities in the Ruhr region as lower reservoir for a pumped storage project has been currently analyzed by a group of five partners in Germany (University Duisburg Essen, Ruhr University Bochum, Rhine Ruhr Institute for Social Research and Political Consultancy RISP, RAG AG and DMT), supported by the European Union.

Madlener and Specht (2013) presented an extremely interesting techno-economical analysis of the possible construction of underground PHES in Abandoned Coal Mines in the Ruhr area (Germany). Also in the Ruhr area, Alvarado et al. (2016) presented a project of the possible construction of underground pumped storage power plant in Prosper Haniel mine in Bottrop (North-Rhine Wesphalia), using existing coal mine infrastructure.

This storage concept presents several advantages in comparison with conventional PHES, as for example the higher possibility of social acceptance and the larger number of potential sites. From a technical point of view, even though the construction of an underground storage reservoir is possible, the main limit is the need of competent rock, especially at reservoir depths.

An interesting unconventional pumped hydro project, proposed in Estonia (Project ENE 1001, 2010), is that of Muuga whose completion is expected in 2020. The peculiarity of this project is that it combines two different unconventional reservoirs: the sea as upper reservoir and underground chambers, resulting from granite excavations, as lower reservoir. As regards the worldwide situation, 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 is expected to surpass Japan in 2018. Table 1 shows the 10 countries with the most installed capacity.

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.

Table 1. *Installed PHS capacity worldwide (IHA 2015)*

Country	Installed PHS Capacity (MW)
Japan	27438
China	21545
United States of America	20858
Italy	7071
Spain	6889
Germany	6338
France	5894
India	5072
Austria	4808
South Korea	4700

Description

The tunnel network of a mining facility has an unusual geometry for a storage system. Nevertheless, such storage volumes, combined with the depths at which some of these facilities are located and the high flows of mine water, can be sufficiently appealing to establish a PSH project with a Francis turbine-pump. The most relevant technical aspect is related to the storage structure for the lower reservoir.

In a typical hydropower pumped storage project, the two reservoirs are located on the surface level. In contrast to a conventional PSHP plant, the upper reservoir of an Underground PSH power plant is the smaller problem, as it can basically be established on the surface. If an abandoned coal mine is envisaged, the (potentially large) area of the former mine may be available for use In the generally densely populated Asturian Central Coal Basin, at least small- and medium-sized storage reservoirs on the surface, may often be done without too much conflict with settlement areas. In the surroundings of the shafts there exist buildings that are protected as industrial heritage, which cannot be demolished.

The lower reservoir inevitably has to be established subsurface and in great depth. An obvious candidate solution is the use of existing cavities. The dominant mining method in the Asturian Central Coal Basin is the long-wall mining technique, which involves a controlled collapse of the sediments. The use of remaining cavities from coal mining must therefore be excluded, leaving us with the following three options: (1) to excavate and secure additional caverns; (2) to make use of existing drifts; or (3) to dig new tunnels (Alvarado et al. 2015). The Figure 4 shows a general scheme of the project with the main components, and the Figure 5 reflects the underground power house with the penstock, the inlet valve, the draft tube, the Francis turbine-pump with vertical axis and the synchronous motor-generator.

Figure 4. *Schematic configuration of main components*

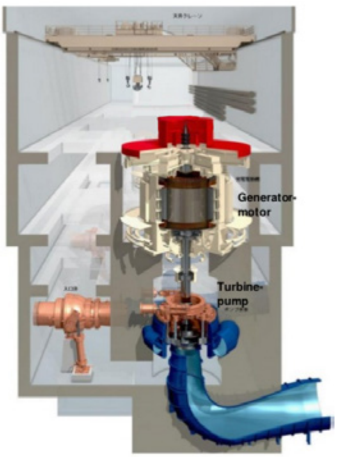
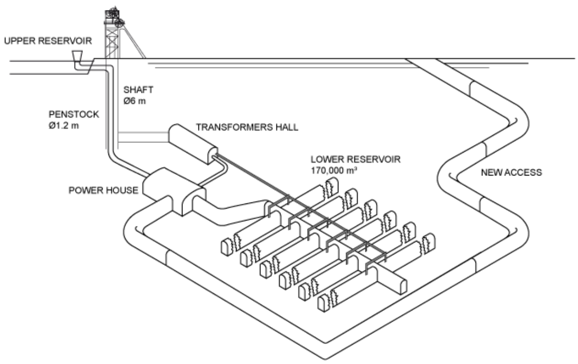


Figure 5. *Power house scheme(Alstom)*



The conclusion for lower reservoirs is that the use of natural caverns is not possible; the artificial extraction of large cavities is technically demanding and financially expensive and thus does not seem to be very reasonable (Alvarado et al. 2013). In certain cases, existing drifts may at least be partly usable, e.g. after additional extension measures. However, for a general concept, considerations have to be based on the fact that the drifts for a rib-shaped storage system in the completion stage, would have to be built totally new.

The penstock is located inside the main shaft. It is a vertical pipeline. If the diameter of the penstock is reduced, the load losses increase. If the penstock's diameter is reduced, the head and the output of the turbine are reduced also. The switchyard would be located on the surface, and the rated voltage would be 11,000-30,000 kV.

The initial approach is to use the main shaft to introduce the hydraulic and electric equipment and materials. If the dimensions of the shaft are not enough, we can make a new access drift, between the outside and the power house (Figure 4). The dimensions of this drift would be 5 meters wide and 4.5 meters high.

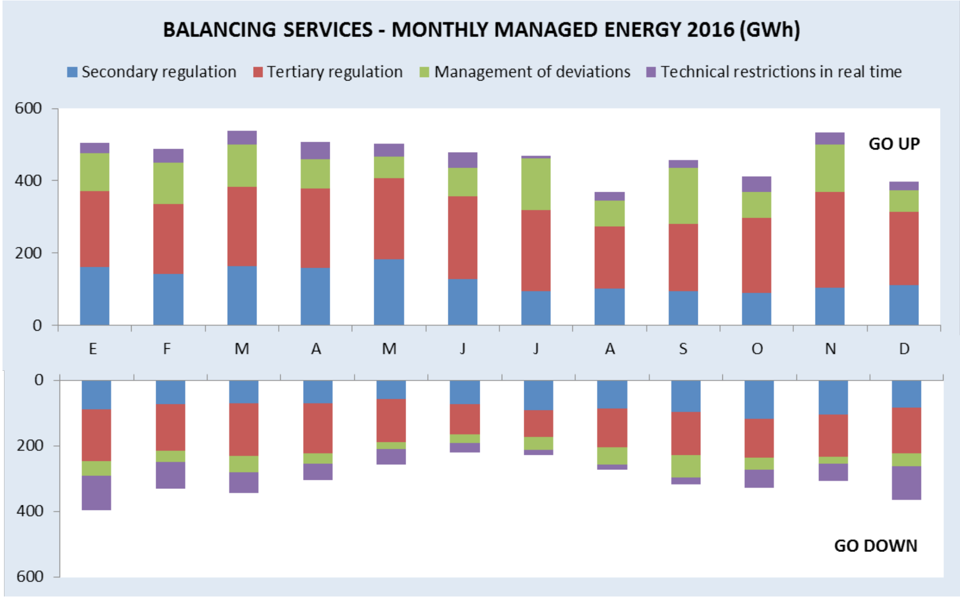
The pumping period takes 9 hours and the turbine period takes 6 hours. Also we can run the turbines at a 50% capacity and produce the same energy in double the amount of time, than if it were to run at 100% capacity. As we want to increase the profitability of the project, we can participate in a secondary electricity market, offering our availability. If we run the turbine during 12 hours at 50% capacity, we can run up and down the turbines output, between the rated output (100%) and the minimum technical output (40% rated output). Nine projects have been studied in mines that are not currently flooded. The main characteristics of a project type, are reflected in the Table 2.

Table 2. *Main characteristics and cost assessment*

Characteristic	PSH
Total Cost (M€)	40
Cost/kW (€)	1701
Lower Reservoir Length (m)	5700
Cross Section Lower Reservoir (m^2)	30
Net Water Head (m)	300
Reservoir Volume (m^3)	170000
Flow (m^3/s)	8
Turbine Power (MW)	23,52
Production time 100% Capacity (h)	6
Energy/cycle/MWh	141

The economic feasibility of the project was analyzed taking into account two energy markets in Spain. These markets are the Spot Market (for energy trading) and the secondary control power market (providing electricity balancing services) (Budeux, S. et al. 2016). In Spain the energy managed in the balancing services in 2016 was 21,351 GWh (Figure 6), with a very outstanding participation by the pumped storage plants, due to its dual role of generation and consumption of energy.

Figure 6. *Balancing services in electricity markets in Spain 2016 (REE)*



Conclusions

The implementation of an underground PSH project using coal mine facilities, is an appealing option for energy storage, particularly in Spain where the underground mining is currently phased out, with an expected closure date at the end of 2018. Also, the significant reduction of the adverse impacts on the landscape and local residents, could be an advantage.

The water necessary for the initial filling of the reservoirs as well as for the replacement of the losses by evaporation, will be taken from the runoff of the mine, so a public water course is not necessary

The most relevant technical aspect is related to the storage structure for the lower reservoir. Based on the techno-economic evaluation, it has been concluded that it is necessary to build a new network of tunnels for the lower reservoir.

PSH can provide many services to the power system, as flexibility of operation and speed to vary the power delivered to the grid. This aspect is fundamental to deal with the variations in production due to fortuitous failures in the thermal power plants and of any significant variations in the production of intermittent renewable power generation.

PSH facilities are the most technologically advanced, widely available resources to provide balancing and integration of variable renewable technologies, such as wind and solar. In addition to the benefits provided by peak power production, pumped storage can generate when the wind is not blowing or the sun is not shining.

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