Low-enthalpy Geothermal Energy Potential of Mine Water from Closured Underground Coal Mines in Northern Spain

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Abstract. The contribution of renewable energies to the world's total energy demand has increased particularly during the last decades, and they will continue gaining market share. The European energy and climate policies have as one of their targets 20% of final energy from renewable origin by 2020. Underground coal mines closured and flooded constitute large underground reservoirs that can be economically managed to supply geothermal energy (heating and cooling) by means of heat pumps. This paper analyzes the geothermal potential of the water stored inside the coal mines of the Asturian Central Coal Basin (ACCB) and the reduction of CO_2 emissions compared to the use of fossil fuels. The results of the study that has been carried out show a capacity of 50 MWt. The potential for generation thermal energy is 112,000 MWh/year with an electric consumption of 14,000 MWh/year. The Coefficient Of Performance (COP) medium is 8 kWht/kWhe. The reduction of CO_2 emissions compared to other fuel sources can reach 80%.

1 Introduction

Renewables were the third largest contributor to global electricity production in 2015. They accounted for 22.8% of world electricity generation, after coal (39.3%) and gas (22.9%) and ahead of nuclear (10.6%) and oil (4.1%). However, the relative position of renewables and gas can be influenced by various factors among which the weather conditions play prime role. Hydroelectricity supplies the vast majority of renewable electricity, generating 16.0% of world electricity, which is 70.3% of total renewable electricity, whilst biofuels and waste, including solid biofuels, play a minor role in electricity generation, supplying 1.9% of world electricity. Although growing rapidly, geothermal, solar, wind and tide energies accounted for only 4.8% of world electricity production, 21.2% of total renewable electricity in 2015 [1].

Geothermal electricity generation remained almost static in the Organisation for Economic Co-operation and Development (OECD) Americas over the period 1990 to 2016, although the region remains the largest geothermal electricity producer, with a 48.8% share of OECD production in 2016. The United States is the largest producer with 37.2% of the OECD total in 2016, with a production of 19.2 TWh, slightly above the 16.0 TWh level in 1990. The second largest producer is New Zealand, with 7.9 TWh in 2016, representing 15.2% of total OECD production. Other major producers are Italy (12.0%), Mexico (11.7%), and Iceland (9.8%).

In the framework of a circular economy it can be found new possibilities for mine water which can be considered as a potential resource generating new economic activities in the mining regions.

Another alternative for the use of the closed mines is the construction of Compressed Air Energy Storage (CAES) plants. CAES plants have received increasing research attention lately [2,3]. CAES plants uses surplus renewable energy to compress and conventionally store air in underground rock caverns, but it is still a technology under development whereas batteries and other technologies offer smaller capacities. After the closure of the mine, the mining voids resulting from the extractive operations, together with the spaces created due to the fracturing induced by mining, can be filled up with water, once the closured mines are flooded, materializing then a new aquifer or "mining reservoir". Due to the temperature of the stored water, it can be successfully used as a source for low enthalpy geothermal energy. In addition to the production of electrical energy, one of the main uses of the low enthalpy geothermal energy is in the generation of thermal energy.

This paper analyses the geothermal potential of the water stored inside the flooded underground closed mines for heating and cooling of buildings, and the reduction of CO_2 emissions compared to conventional fossil fuels, such as natural gas and diesel oil.

2 Geological and hydrogeological characteristics of the study area

The Asturian Central Coal Basin (ACCB) is located in north-western Spain, and it constitutes the main coal

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mining district of the Iberian Peninsula, with more than two centuries of extractive activity that will be closured for the end of the 2018. Underground mines geometry of this coal basin may be highly complex, with a typical depth of up to 500-600 m, and main infrastructure composed of vertical shafts with a diameter of 6 m, used for mineral extraction and for access of personnel and materials. In the whole of this historical coal mine district has an extensive network of horizontal tunnels at different levels, with an average separation between levels of 80-100 m [4].

From a geological point of view, the Asturian Central Coal Basin (ACCB) lies within the so-called "Cantabrian Zone", which constitutes the external part of the Variscan Orogen in the NW of Spain. The ACCB can be subdivided into four different geological units (from W to E): Riosa-Olloniego, The Justa- Aramil, Caudal-Nalon and Lois-Ciguera. The whole sedimentary sequence comprises about 6000 m of Upper Carboniferous siliciclastic-dominating rocks, mainly conglomerates, sandstones, greywackes and mudstones, with a few limestone horizons [5]. From a hydrogeological point of view, the ACCB is constituted by materials of very low porosity and permeability which constitute small aquifers associated to multilayer sandstones, with limestones, shales and coal seams as confining levels. After two centuries of mining activity, the created mine voids and the effect of the induced fracturing on the enclosing rocks have created a secondary permeability which induces important changes into the hydrogeological parameters of the area. A cause of this secondary porosity, the values of porosity, permeability and transmissivity increase significantly from their initial values: porosity from 1 to more than 10%, permeability from 10^{-1} to 100 m day^{-1}, and transmissivity from 10 to 1000 m^2 day^{-1} [6,7]. From an initial situation before mining, with only small aquifers, the coal mining and the associated fracturing creates a new hydrogeological system. Table 1 shows the results of the mine water analysis that has been performed on two samples in the ACCB.

Table 1. Mine water analysis

Parameter	Sample 1	Sample 2
Tª Water (ºC)	21,2	23
pH	7,71	7,76
Suspended Solids SS (mg/l)	< 5,0	< 5,0
Conductivity (µS/cm) a 20 ºC	1.265	1.211
Dissolved Iron (mg/l)	< 0,050	< 0,050
Iron (mg/l)	0,202	0,136
Total Iron (mg/l)	0,27	0,174
Sulphates (mg/l)	140	70
Carbonates (mg/l)	< 2,0	< 2,0
Bicarbonates (mg/l)	725,3	558,9
Dissolved Calcium (mg/l)	116	54,2
Total Hardness (mg CaCO$_3$/l)	5	3
Dissolved Potassium (mg/l)	11,2	8,92
Dissolved Sodium (mg/l)	173	160
Chlorides (mg/l)	< 3	11,8

This new "aquifer" behaves similarly to a karst aquifer, with a triple porosity (intergranular pores, fracture spaces, and mining voids for drifts and exploited layers), similar to that of the karst carbonate aquifers [6]. Under these conditions, if the pumping is interrupted, recharge by infiltration causes the flooding of mine voids and creates an underground reservoir, constituted by the mining voids associated to one or more shafts, as they are frequently connected underground [7]. 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 year^{-1}. Fig. 1 shows the schematic of an underground coal mine of the ACCB.
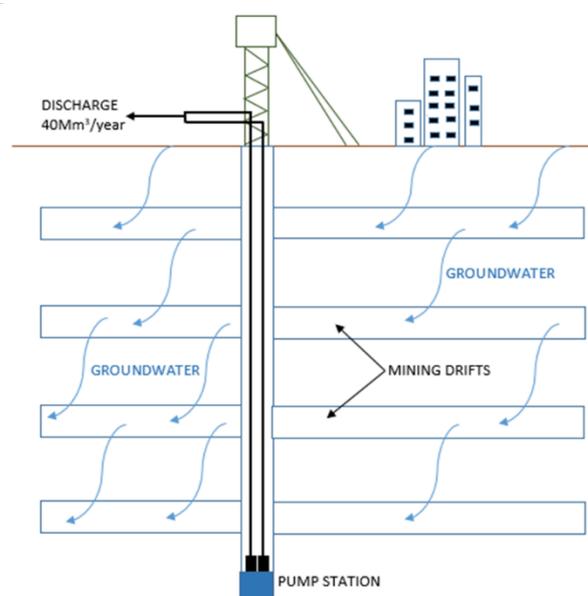
Fig. 1. Groundwater and pump system in production phase.

3. Analysis of the geothermal potential

The meteorological data allows calculating the water balance for each one of the mining reservoirs and its associated drainage basin [8,9]. Water comes into the system by means of effective rainfall (precipitation minus evapotranspiration) and then divides between runoff and infiltration. The latter can be assimilated to the flow that was as an average pumped from the mining works in the reservoir. The excess of effective rainfall which is not infiltrated into the ground (in the case of the ACCB this part is generally low, due to the reduced permeability) generates runoff that ends into the streams/rivers of the basin [9].

Once pumping is interrupted, leading to the 'groundwater rebound', water level does not rise linearly, as its rise depends on the recharge rate and the volume of voids to fill, being slower when water has to fill mine levels with high volume of voids and quicker between those levels [10]. Considering an average total

flow of 40 Hm³·year⁻¹ pumped in the entire coal mining reservoirs in the ACCB, 1.700 hours·year⁻¹ for heating [11], the thermal potential of the cool source (Pc) and the warm source (Pw) are, in W [12]:

$$P_c = \Delta T \cdot F \cdot SH \cdot \rho$$

$$P_W = P_C \cdot COP \cdot (COP - 1)^{-1}$$

where:

ΔT = Difference of temperature of mine water going in and out of the evaporator, which is generally $5°$C for common heat pumps.

F= Pumped flow ($m^3 s^{-1}$)

SH = Water specific heat = 4,186.8 J·kg⁻¹ (ºC)⁻¹

ρ = Water density = 1,000 kg m⁻³

COP = Heat pump coefficient of performance (amount of heat in relation to the drive power required).

Fig. 2 shows the general scheme of a geothermal project using mine water. As indicated in the Figure, the water temperature increases in the deepest areas of the underground reservoir.
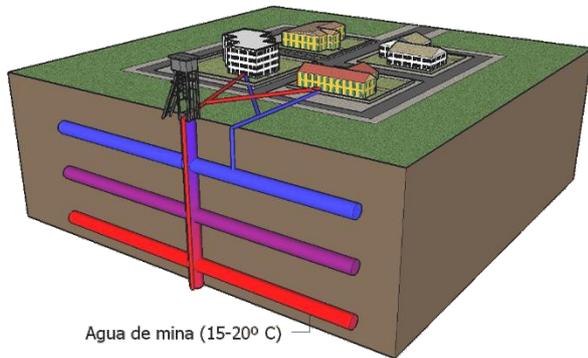

Fig. 2. Geothermal project scheme with mine water

4 Low-enthalpy geothermal energy production

4.1. Energy production

When the activity in the mines ceases, the pumping works are interrupted and the mining drifts are flooded [13-15]. The average time of inundation of an underground mine in the ACCB is about 4 years. Due to security issues, it is necessary to maintain the water level between 50-100m from the surface level, to avoid problems and flooding in nearby populations. The water stored in the coal mines has a geothermal potential equivalent to 50 MWt. The production of thermal energy in the existing populations around the closed mines in the form of district heating has been analyzed. Fig. 3 and Fig. 4 show the scheme for the use of mine water as a source of geothermal energy in district heating and cooling projects. The main elements of the facilities are: a tube heat exchanger and the heat pump. To supply thermal energy throughout the year, two modes of operation have been designed. Fig. 3 indicates the heating (winter) mode. In the primary circuit there are temperatures of 22ºC and 14 ºC, and in the secondary

circuit of 11ºC and 14 ºC. Fig. 4 indicates the cooling mode (summer). In the primary circuit there are temperatures of 24 ºC and 32 ºC, and in the secondary circuit of 28 ºC and 34 ºC.
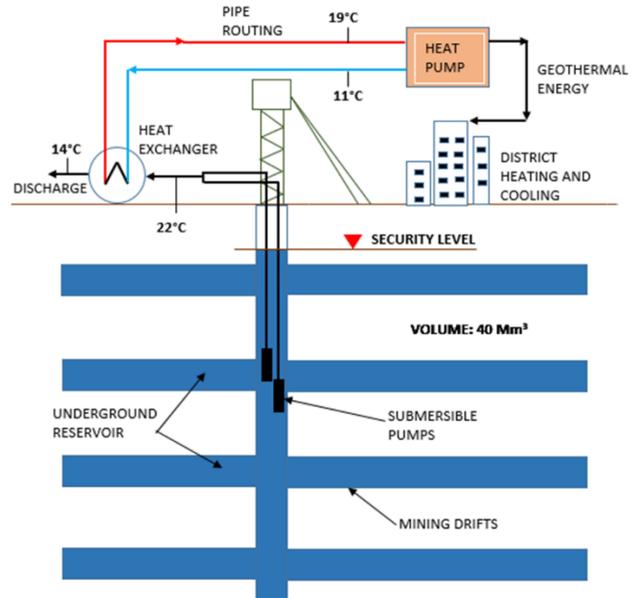

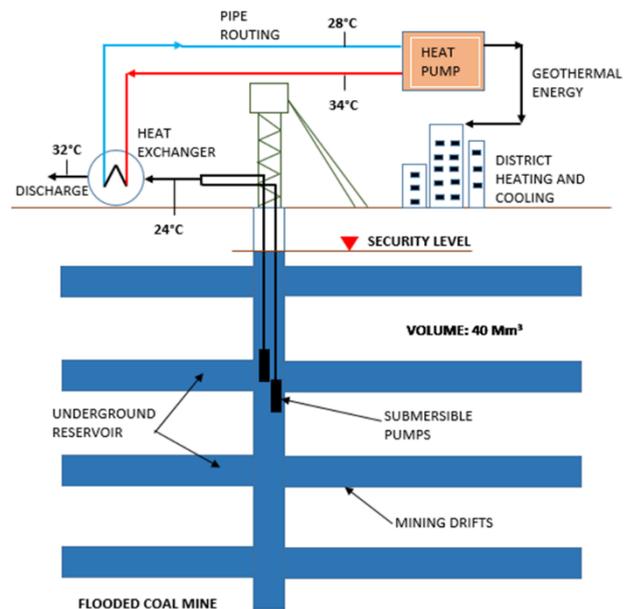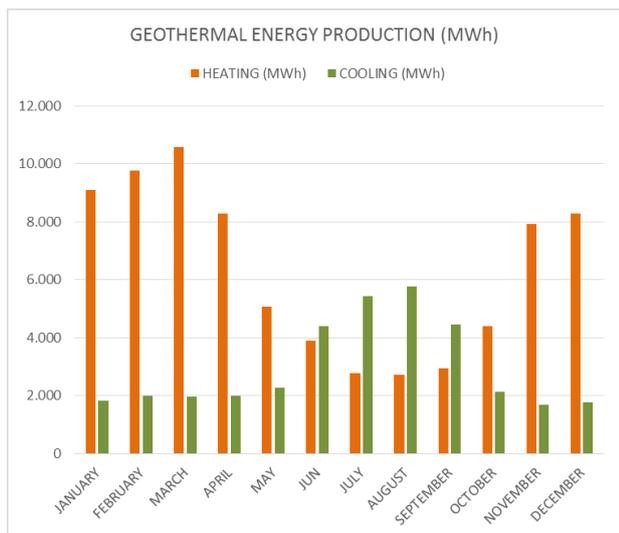**Fig. 3**. Geothermal energy production (heating)

Fig. 4. Geothermal energy production (cooling)

In this study a monthly geothermal energy production model has been made. Depending on the season of the year, the heat pumps can operate in heating mode or cooling mode. The total thermal energy production is 112 GWh/year. The production of energy in heating mode is 76,000 MWh/year and the production in cooling mode is 36,000 kWh/year. Fig. 5 shows the monthly energy production. The electrical consumption in the water recirculation pumps, in the heat pumps and in the submersible pumps located in the vertical well of the underground mine is 14,000 MWh/year.

**Fig. 5**. Geothermal energy production (heating-cooling)

Fig. 6. shows the amount of thermal energy produced and the monthly electrical energy consumed by the heat pump. The result of the Coefficient of Performance (COP) is a value of 8 kWht/kWhe.
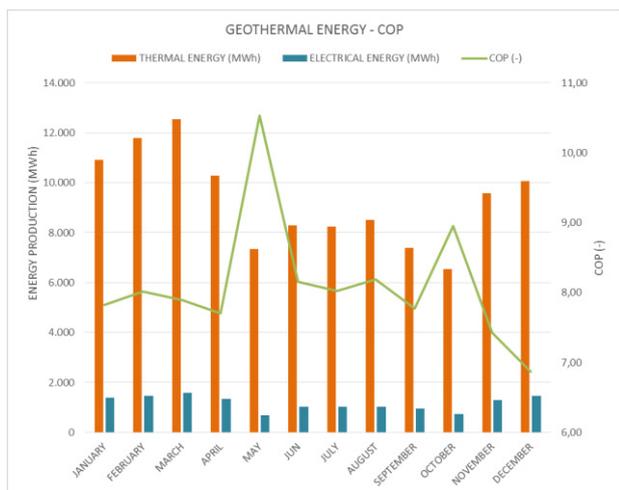
Fig. 6. COP. Geothermal and electrical energy

4.2. CO$_2$ emissions

Fig. 7 shows a comparative study of CO$_2$ emissions for fossil fuels and for geothermal energy produced from mine water. For natural gas, considering a factor of 0.204 kgCO$_2$/kWh, emissions of 20 tCO$_2$/year are produced. For diesel, with 0.287 kgCO$_2$/kWh the emissions reached are 29 tCO2/year. The CO$_2$ emissions produced using the mine water are equivalent to the electric power consumption for the heat pump and water pumps, of 5 tCO$_2$/year. The reduction of emissions with respect to diesel can reach 80%.
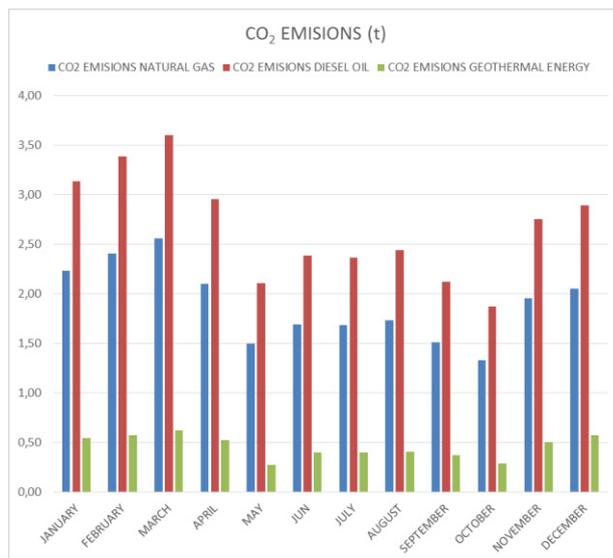
Fig. 7. CO$_2$ emissions. Comparative analysis between fossil fuels and geothermal energy.

5 Conclusions

When the activity in the mines ceases, the pumping works are interrupted and the mining drifts are flooded. Closured and flooded coal mines in the ACCB can constitute mining reservoirs which could be regulated and used as water and energy resource. It is essential to define the hydrogeological model, the water balance, and the volume of voids of the mining reservoir system previously to these applications, which fit with an integrated management of water resources, allowing regulating simultaneously both surface and underground resources.

For security reasons, the ACCB mines cannot be completely flooded. It is necessary to leave the water level between 50-100m from the surface. This makes it necessary to maintain a system of water pumping permanently that can be used for the production of energy by heat exchangers and heat pump. One of the more attractive applications of mine water is to use it as geothermal resource. The energy use of mine water in the ACCB by means of heat pumps is ideal, due to the high performance that can be reached with an average temperature of 20ºC. The water stored in the closed underground mines in the ACCB has a geothermal potential of about 50 MWt of power. The available energy can supply 40,000 inhabitants in the towns located around the mines. The total thermal energy production is 112 GWh/year. The electrical consumption is about 14,000 MWh/year. In addition, the production of thermal energy from low-enthalpy mine water represents an 80% reduction in CO$_2$ emissions compared to fossil fuels that are currently being used.

The development of energy production projects in abandoned mines has a positive impact on depressed mining districts due to the closure of coal mines, with the creation of new stable jobs.

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