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Article

Estimating Limits for the Geothermal Energy Potential of Abandoned Underground Coal Mines: A Simple Methodology

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Abstract: Flooded mine workings have good potential as low-enthalpy geothermal resources, which could be used for heating and cooling purposes, thus making use of the mines long after mining activity itself ceases. It would be useful to estimate the scale of the geothermal potential represented by abandoned and flooded underground mines in Europe. From a few practical considerations, a procedure has been developed for assessing the geothermal energy potential of abandoned underground coal mines, as well as for quantifying the reduction in CO_2 emissions associated with using the mines instead of conventional heating/cooling technologies. On this basis the authors have been able to estimate that the geothermal energy available from underground coal mines in Europe is on the order of several thousand megawatts thermal. Although this is a gross value, it can be considered a minimum, which in itself vindicates all efforts to investigate harnessing it.

Keywords: geothermal energy; mine water; coal mines; abandoned mines

1. Introduction

Large mining areas in Europe are currently being affected by closure processes, which are mainly due to the progress in mining works and changes in mining activities. Mine closure creates negative social, economic, urban and environmental effects on the affected areas. Although mines present high potential for geothermal utilization of low-temperature water, which could be used for heating and cooling purposes, only a few cases have been reported in Europe, Canada, USA or China where this potential geothermal energy from underground mines has been actually detected and used.

In Europe, some cases from The Netherlands, Germany, Poland, United Kingdom, Norway and Spain have been reported by several authors [1–3]. Power obtained from mine water can only be a few kilowatts thermal (kWt) from small installations, like Freiberg (Germany) or Shettleston and Lumphinnans (Scotland, UK); but there are also large installations which extract several megawatts thermal (MWt) from mine waters like those in Heerlen (Netherland), Mszczonow (Poland), and Mieres (Spain). Therefore, a vast geothermal potential is not being exploited; nevertheless, there is always a problem before the start of any project using the geothermal power of a mine. The procedure begins when there is an abandoned mine, as in the two cases shown in Figure 1 (one is an old gallery, and the other is an old shaft). These photos illustrate the reality of the initial stage of these projects: just evidence of the existence of two underground mines which were in operation in the past.

Figure 1. (**A**) Abandoned underground mine, Mariana mine (Asturias); (**B**) Abandoned underground mine, Olloniego colliery (Asturias).

(**A**) (**B**)

Without doubt, there are strong reasons related to sustainability and ecology which make this kind of projects worthy of research; nevertheless, economic viability is always a strong point helping support the project. Thus, the first question that should be solved is: could the use of geothermal power from these mines be profitable? When revising the specialized literature, not many cases have been described. Relevant research has been carried out mainly in Canada [4–10] (the Springhill case is of special interest because it has been operating since 1988) and Europe [11–18]. Another few more cases of geothermal use of mines have also been reported concerning mines in other countries such as the USA [19,20] and China [21–23]. An interested reader can find more complete information about these cases in [1–3] and [16]. In many of these works, hydrogeological models are described. In any cases, a great deal of information is needed to conduct these studies successfully. When the mine is in operation, to find this information is easy. On the contrary, it is difficult to obtain such information when the mine was closed many years ago and the company has disappeared. It is often necessary to study old public administration documents or even visit historic libraries or registries, making this an archaeological and/or industrial patrimony task rather than technical research. Such an amount of work would be only justified in those cases where a significant geothermal energy extraction is expected. The same question can be asked at another level. For example, in countries having a long mining tradition, is it reasonable to carry out actions related to geothermal use from abandoned mines which imply a large investment? How much geothermal energy is expected to be extracted from abandoned mines? In this sense, the main objective of this research work is to develop a method which allows estimating lower and upper limits easily for the geothermal potential of an abandoned underground coal mine. This is important in order to evaluate the possibility of an actual geothermal use of an abandoned mine or of a future use for a mine near closure. The method would help to decide under which conditions it becomes interesting to start a project for using this energy from mines.

In this work, the "geothermal potential" of a mine is the total amount of geothermal energy (or geothermal power) which can be obtained from this mine. It is easy to understand that one of the factors influencing geothermal potential is the volume and characteristics of the voids created by mining activity (*i.e.*, these voids can be stable in the long run and remain open, or they can cave in immediately and be filled with rock debris). This value is directly related to coal output. Our goal is to relate the present geothermal potential of an underground coal mine with the total saleable coal production yielded by the mine through its operation history. The main advantage of this proposal is that the coal output of a mine is a well-known parameter, which is always easy to find because it has been recorded over the years by public administration. On the other hand, wide coal mining experience helps us to establish an easy-to-use method.

Thus, a simple formula is proposed:

$$W_t \approx k \times P_T \quad (1)$$

where W_t is the value for geothermal power of the mine in MW thermal (MWt); P_T is the total saleable coal production in millions of tonnes (Mt); and k is the factor of proportionality which has to be estimated empirically.

Before starting a project for the use of geothermal power of an abandoned mine, it would be very interesting to make a "reasonable estimation" of the minimum and maximum thermal energy which can be recovered from mine water. If the minimum quantity is sufficiently high, a project for its use could be proposed. Nevertheless, under some unfavorable conditions (as for example a mine located far away from inhabited areas) the project could be rejected if it were not economically feasible, even assuming maximum heat recovery.

A "reasonable" maximum and minimum value for the ratio W_t/P_T will be determined in the following. Regarding our mines, the authors have determined that $k_{min} \approx 0.25$ and $k_{max} \approx 1.0$. It is not possible to make accurate predictions using this methodology; nevertheless, if technicians were able to predict a minimum value (or lower limit) for the geothermal potential of a mine and this value is high enough, the development of a project can be justified. On the other hand, if a maximum value of geothermal power is calculated and it is not sufficiently high to support a project, it is clear that it is better not to spend resources in this project.

In order to define this empirical method, coal output and two other parameters of the mine also have to be known: maximum water pumping and average quantity of air flow. Two different mines (different coalfields, history, exploitation methods, hydrogeological conditions…) are described here below. An analysis of these mines helps to understand the method and the value of the characteristic parameters, k_{min} and k_{max}.

It has to be pointed out that the method is only proposed for underground coal mines. As is well known, due to its sedimentary origin, coal usually appears in Nature as coal seams. This fact makes underground coal mines have a more topologically arranged structure than base-metals mines. Consequently, it is easy to find relationships between different parameters which allow the final relationship between geothermal power and total coal ouput to be found. For example, in a given coal field, the total length of galleries is approximately proportional to coal production. In base-metals mines it is more difficult to establish these kinds of relationships due to variable metal concentration in the rockmass. This does not mean that in this kind of mines it could not occur; in fact, a similar formula could probably be established for base-metals mines, but since no data is available a similar empirical law cannot be defined.

2. Brief Description of the Proposed Method

As previously mentioned, the method is reduced to a simple formula (Equation (1)). This formula allows estimation of the geothermal power of the mine W_t (in MW thermal or MWt), from a well-known parameter which is the total saleable coal output P_T (in millions of tonnes or Mt) produced by this mine during operation period. In effect, P_T is easy to find, since it has always been recorded over the years by different administrations. In order to define the method, the parameter k has to be defined or estimated, which implies knowing both the geothermal power and coal output of a mine at a given moment.

In any active mine, there is always a constant flow of two fluids which interchange heat with the rockmass: water and ventilation air. An estimation of the geothermal power which could be supplied by the mine can be deduced from the total heat extracted by these two fluids from the mine.

Assuming that a certain quantity of water flow Q_w (m^3/s) is pumped from the mine and assuming that the temperature of the water has increased in ΔT (°C) in its flow through the rockmass, the heating power W_w (Watts) which heats the water is:

$$W_w = Q_w \times d_w \times s_w \times \Delta T_w \quad (2)$$

d_w and s_w are respectively the density (kg/m^3) and the specific heat (J/kg·°C) of water.

In the same way, if the air flow rate Q_a (m^3/s) is extracted from the mine by the main exhaust fans and its temperature has increased by ΔT_a (°C), the heating power W_a which heats the air is:

$$W_a = Q_a \times d_a \times s_a \times \Delta T_a \quad (3)$$

where d_a and s_a are respectively the density and the specific heat of air.

Nevertheless, the increase of water and air temperature can be produced by other heat sources in the mine which are not related to the heating capacity of the ground. In underground coal mines, the most important artificial heating source is the electrical equipment which also contributes to increasing the water and air temperature.

Assuming a total electrical power E (MW) installed in the mine and an electrical performance of r (%), the total power transferred to the air/water would be:

$$W_e = (100 - r) \times E \quad (4)$$

Under these conditions, the total thermal power effectively released from the rockmass or transferred from the rockmass to water and air is:

$$W_{tmin} = W_w + W_a - W_e \tag{5}$$

This is a real value, since it has been directly obtained from experience and, without doubt, the available geothermal power of this mine is at less equal to it.

In Asturias, the average temperature of water pumped from mines is about 18 °C [24,25] whereas the average temperature of water at the surface is around 12 °C, and consequently, $\Delta T_w \approx 6$ °C. On the other hand, the water density and specific heat are d_w = 1000 kg/m^3 and s_w = 4186 J/kg·°C respectively. The heating power which heats the water, which is a part of geothermal power of the mine, can be estimated by:

$$W_w = 25.1 \times Q_w \tag{6}$$

where W_w is in megawatts thermal (MWt) when Q_w is in cubic meters per second (m^3/s).

In winter, the average temperature of mine air is also about 18 °C and the temperature of the air at the surface is about 7 °C. On the other hand, taking into account that the air humidity within the mine is almost constant and close to 90%, its density and specific heat are 1.18 kg/m^3 and 1020 J/kg·°C respectively; the thermal power necessary to heat the air is thus:

$$W_a = 0.013 \times Q_a \tag{7}$$

W_a is in megawatts thermal (MWt) when Q_a is in cubic meters per second (m^3/s).

On the other hand, assuming an electrical performance of 90%, the total power is:

$$W_e = 0.10 \times E \tag{8}$$

Under these conditions, the total thermal power released from the rockmass or transferred from the rockmass to water and air is:

$$W_t = W_w + W_a - W_e = 25.1 \times Q_w + 0.013 \times Q_a - 0.10 \times E \tag{9}$$

Taking into account the previous explanation, the ratio can be easily calculated as:

$$k = W_t/P_T \tag{10}$$

The analysis of two mines where this ratio reaches low and high values respectively allows us to estimate a minimum and maximum value for k.

The method is useful to perform geothermal resource estimates for given mining regions where coal extraction data are available; nevertheless, it is important to point out that it should not be used to design a geothermal system at a mine site.

The most important factor when using geothermal energy from flooded mines is that there must be a customer for the energy nearby. However, villages or even towns and cities have typically grown due to a mine having started its mining activity nearby. Consequently, a lot of mines in Europe are near populated areas and the geothermal energy can be used directly in district heating or similar systems.

3. Empirical Estimation of Limit Values for Parameter k

3.1. Case History 1: La Camocha Colliery

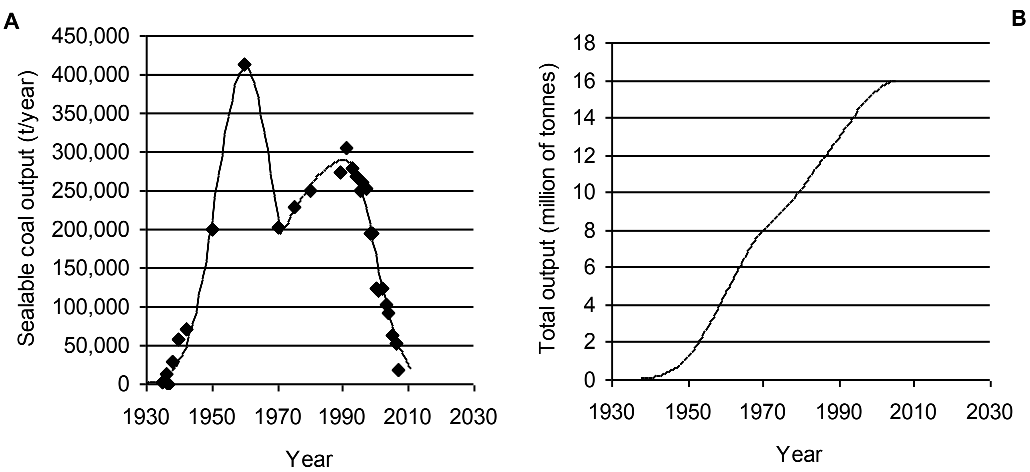
This mine has exploited an independent coal field in the past. Coal seams were mainly very steep (70° dips) and of low-medium thickness (1.5 m in average). The mining method used initially was the traditional inverted steps method (with backfilling) when mining was manual by means of pick hammers. More recently, sublevel caving with explosives has been used successfully.

This is an example of estimating the geothermal power of abandoned coal mine from historic coal output data, air flow rate and quantity of water pumped. As the quantity of water pumped out of this mine can be considered rather low, data will be used for the estimation of a minimum value k_{min}.

In this case, coal output data are known from the first year of the mine until the last year of exploitation. Annual coal production of the mine during its history is represented in Figure 2A.

The exploitation of the mine started during the 1930's. During the Second World War in Europe, the price of coal increased and this caused an increase in coal production. The maximum was reached in 1960 and then, output decreased quickly mainly due to emigration of miners to other coal fields in Europe which offered better working conditions (in this case, to Germany and Belgium). This tendency continued until 1970. However, the energy crisis in the 70s made the production of coal interesting and coal output increased again. Such an increase continued until about 1995. Then, changes in the world market and in European politics caused coal output to decrease drastically until mining ceased, in 2007. Until then, total accumulated production was about 16 million tonnes of saleable coal (Figure 2B).

Figure 2. Coal production at La Camocha Colliery (Asturias, Spain). (**A**) Coal output, in t/year; (**B**) Cumulative total output from approximately 1932 to mine closure.

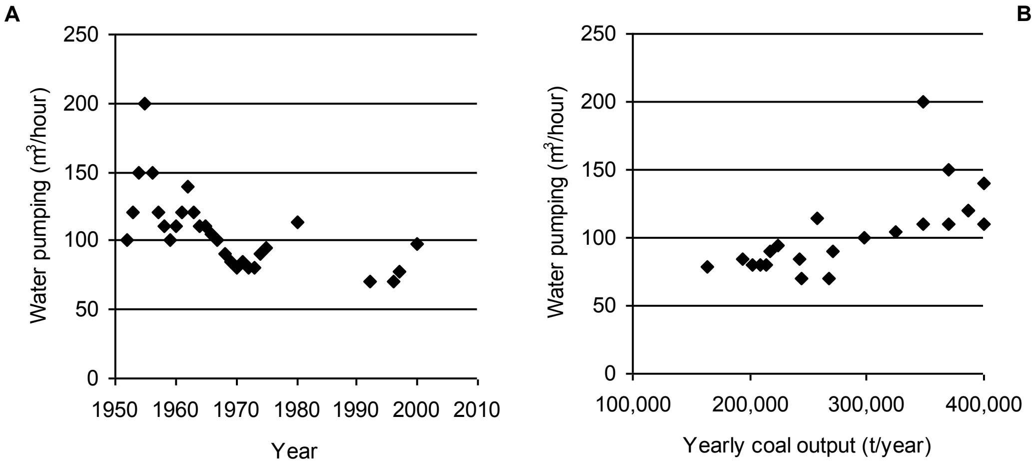


The use of this method implies knowing not only coal output but also another two parameters of the mine: water pumping and quantity of air flow. It is not always possible to obtain the necessary information; nevertheless, in this case, a record for the water pumping over several years has been obtained (Figure 3A).

This is a characteristic curve which decreases over time. There is a initial period of transient regime when the water originally contained in rockmass flows towards the mine. Afterwards, a stationary regime is reached (the water inflow into the mine is equal to the water inflow within the rockmass) and the quantity of water flow remains more constant during the years. The greatest water flow rate pumped was 200 m^3/h.

As can be seen from Figure 3B, water pumping is related to coal output because underground voids created by mining works become channels for water flow. On the other hand, ground movements caused by caving and land subsidence generate an increasing rock mass permeability. But, the relationship between water and coal production is a gross estimation because other significant factors, such as the rainfall, influence the mine water inflow. In many cases, water inflow increases more with the extension of the mine than—for a given extension—with depth.

Figure 3. (**A**) Water pumped at La Camocha colliery per year; (**B**) Water pumped at La Camocha colliery *versus* annual coal output.



The second factor required is the air flow rate in the mine. This parameter does not vary greatly year by year; so, to develop a simple procedure, a unique representative value will be chosen. Thus, the average quantity of air flow extracted from mine by the main fans determined from measurements taken during the last years of the history of the mine is a representative value. Here, air flow rate supplied to the mine by two main exhaust fans was aproximately 60 m^3/s, and was practically constant over the years. When the value of this parameter is not known, it can be deduced from mining experience. Figure 4A,B represent the specific methane emissions in m^3 of methane per raw ton and the average methane flow in m^3 of gas per day for a typical underground mine in Asturias [26–28]. In this mine, the average output in the last 50 years is 300,000 tonnes of saleable coal per year (about 2500 of raw tonnes per day). This mine was not very gassy so, for this output level, the methane flow is of about 10,000 m^3 of gas per day or 0.115 m^3/s. Methane concentration in ventilation return in our coal mines is usually about 0.20%; consequently, the fresh airflow rate is about 60 m^3/s.

The last factor is electrical power. Traditionally, these mines have low mechanisation. We can assume that electrical power of mining equipment in the mine is lower than E = 1.0 MW.

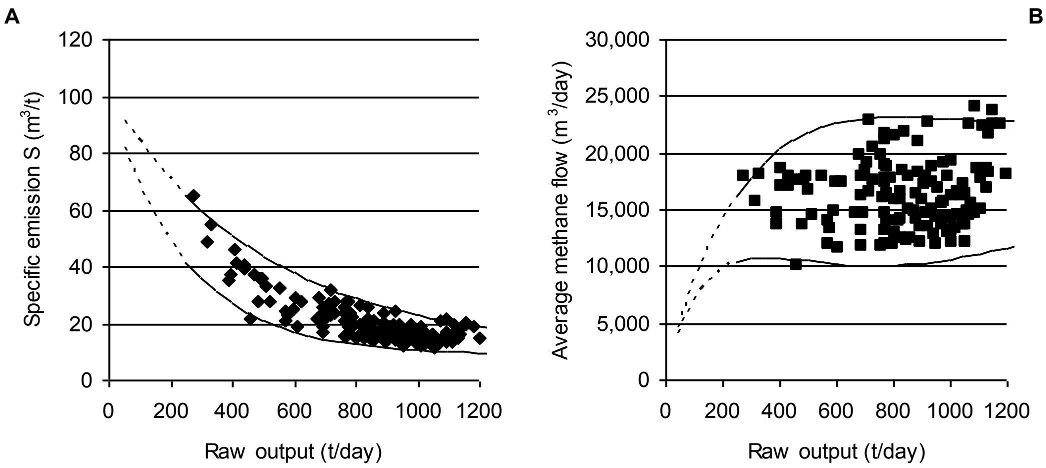
It now becomes easy to estimate k_{min}. The maximum value of recorded Q_w has to be selected. In this case, for 200 m^3/h, Q_w= 0.055 m^3/s. On the other hand, Q_a = 60 m^3/s.

By replacing these values in Equation (9):

$$W_{tmin} = 25.1 \times Q_w + 0.013 \times Q_a - 0.10 \times E = 1.38 + 0.78 - 0.10 \approx 2.1 \text{ MWt} \quad (11)$$

This is a real value for geothermal power that can be extracted from La Camocha mine and, although Q_w is a maximum, W_{tmin} is a minimum because the water inflow in this mine can be considered low.

Figure 4. Typical methane emissions parameters from underground coal mines in Asturias (**A**) Specific emissions; (**B**) Average methane flow.

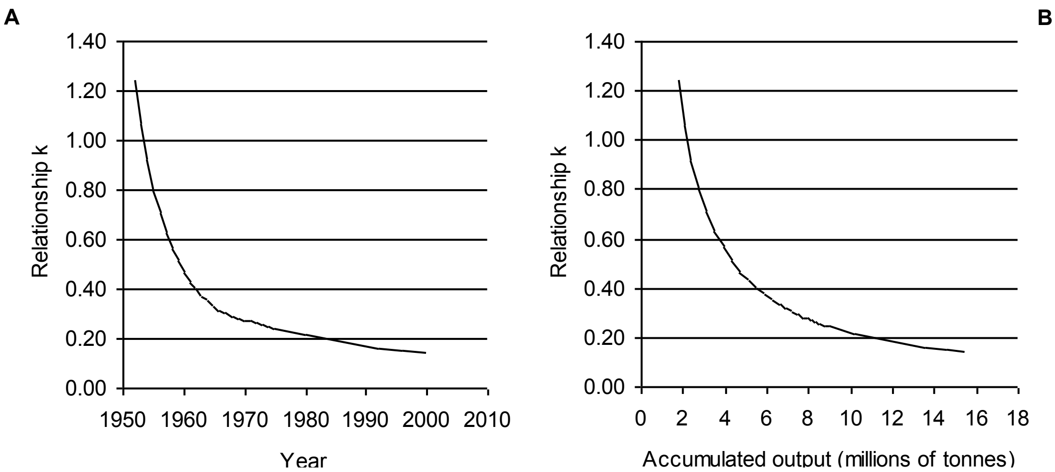


In order to estimate a geothermal power for a given total accumulated coal output, the relationship between W_{tmin} and P_T is calculated for all the years for which P_T is known (Figure 5A and Equation (10)):

$$k_{min}(t) = W_{tmin}/P_T(t) = 2.1/P_T(t) \tag{12}$$

In order to better understand the results, this relationship is represented against the accumulated output P_T in Figure 5B.

Figure 5. (**A**) Relationship between geothermal power and output per year (La Camocha colliery); (**B**) Relationship between geothermal power and output *versus* accumulated output (La Camocha colliery).



3.2. Case History 2: Figaredo Colliery

The second example is similar to the previous one in some aspects; for example, in the latter also vertical coal seams were also mined. However, there are several factors which significantly influence the water inflow into the mine, making it greater than in the former case. One factor is that the longwall method with caving was used more extensively thereby increasing the permeability of the rockmass. The second aspect is that there is a river above the mine and it has been demonstrated that a stream of water had flown from the river into the mine. The last issue is that this mine is connected to three other collieries and could receive water from them. For all these reasons, this practical case will be used to estimate a maximum value of k.

The history of coal production in this colliery is shown in Figure 6. The exploitation of coal started at the end of the XIX century (Figure 6A). It had increased during the second half of the 20th century due to the Second World War and the subsequent petroleum crisis. Peak production was reached in the decade of the 80s and afterwards production felt until the closure of the mine in 2007. Total accumulated production was about 10 million tonnes of saleable coal over more than 100 years (Figure 6B).

Figure 6. Coal production at Figaredo colliery (Asturias, Spain) (**A**) Coal output, in t/year; (**B**) Cumulative total output from 1910 to mine closure.

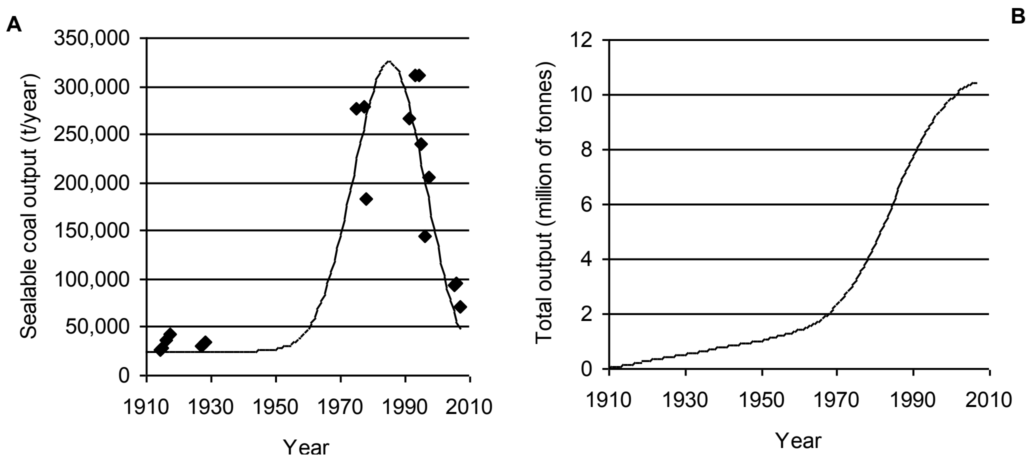
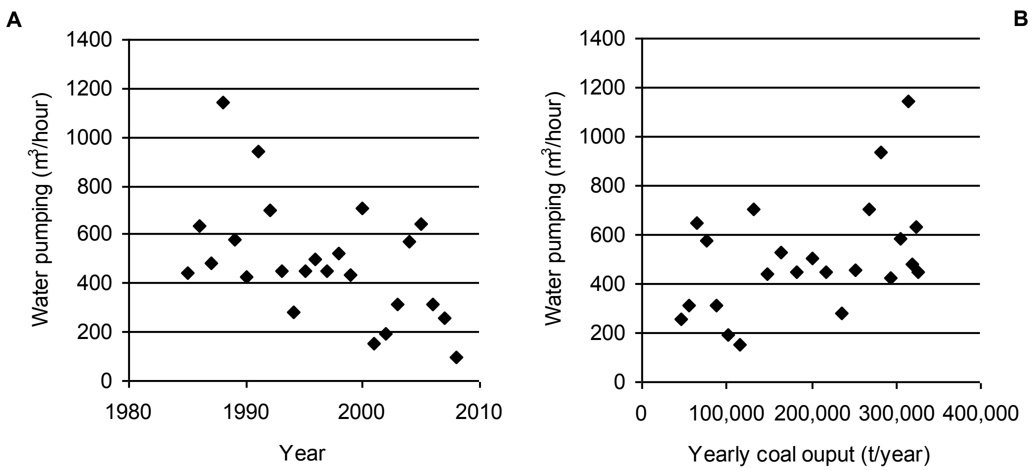


Figure 7A shows the water pumped from the mine for 20 years and, in Figure 7B, water flow rate pumped from the mine is related to the coal output. As can be inferred from Figure 7, water inflow in this mine is greater than in the mine previously analysed, in particular it is as much as five times higher. The maximum quantity of pumped water reached 1000 m^3/h or 0.277 m^3/s. On the other hand, the air flow rate recorded in the last year of the mine was 90 m^3/s and the electrical power of mining equipment is lower than E = 1.0 MW.

Figure 7. (**A**) Water pumped at Figaredo colliery per year; (**B**) Water pumped at Figaredo colliery *versus* yearly coal output.



Proceeding as in the previous case, geothermal power could be obtained from Equation (9):

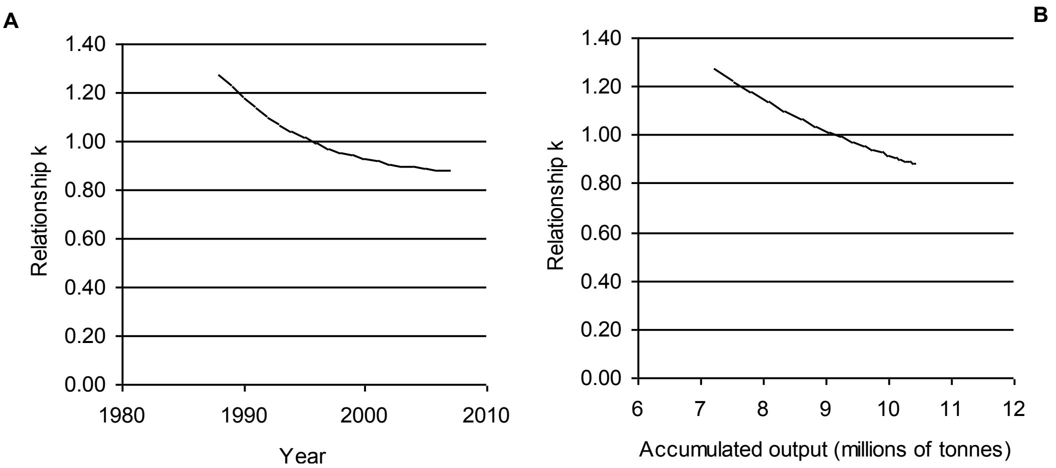
$$W_{tmax} = 25.1 \times Q_w + 0.013 \times Q_a - 0.10 \times E = 6.97 + 1.17 - 0.10 = 8.1 \text{ MWt} \quad (13)$$

This is a real value for geothermal power which can be extracted from the mine and it can be considered as a maximum by comparing it with other mines in Asturias. In order to estimate geothermal power for a given total accumulated coal output, the relationship W_{tma}/P_T is calculated for all the years in which P_T is known (Figure 8A and Equation (10)):

$$k_{max}(t) = W_{tmax}/P_T(t)= 8.1/P_T(t) \quad (14)$$

This relationship is represented as a function of the accumulated output P_T in Figure 8B, in order to better understand the results.

Figure 8. (**A**) Relationship between geothermal power and output per year (Figaredo colliery); (**B**) Relationship between geothermal power and output *versus* accumulated output (Figaredo colliery).



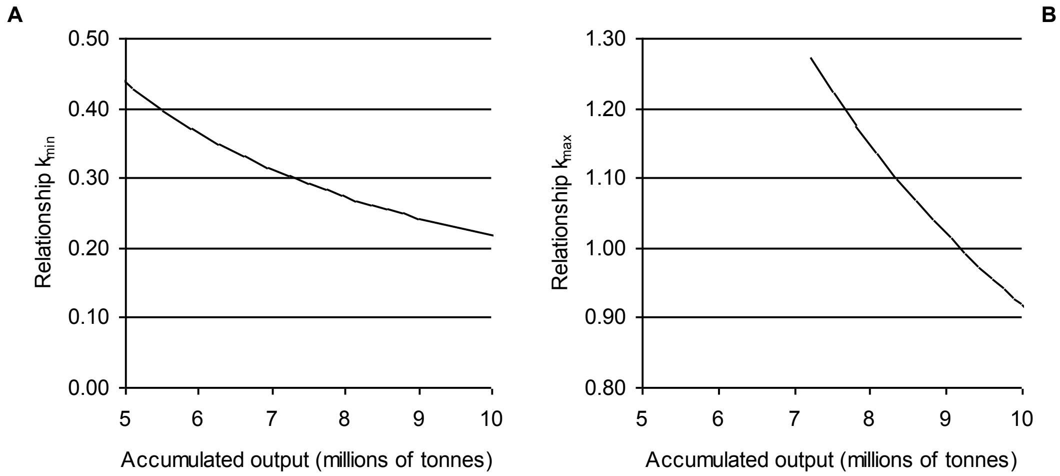
3.3. Determination of Parameter k Based on Experience

In Figure 9, the value of k has been represented as a function of the accumulated coal output for the period of activity of these two representative mines. This method for selecting the proper value of k would be useful for mines producing, at least, 5 million tonnes of saleable coal.

As it can be deduced directly from experience (Figure 9), a reasonable minimum value for k would be $k_{min} = 0.2 - 0.4$ while, a reasonable maximum for the parameter would be $k_{max} = 0.90 - 1.20$.

This means that, with regard to the assessing geothermal power in Asturias, the value k_{min} would be a conservative value and this geothermal power could be actually reached, while k_{max} is an optimistic value and it would be hard (even impossible) to reach the corresponding estimated geothermal power.

Figure 9. (**A**) Minimum relationship between geothermal power and output *versus* accumulated output; (**B**) Maximum relationship between geothermal power and output *versus* accumulated output.



4. Analytical and Semi-Empirical Estimation of Limit Values for Parameter K

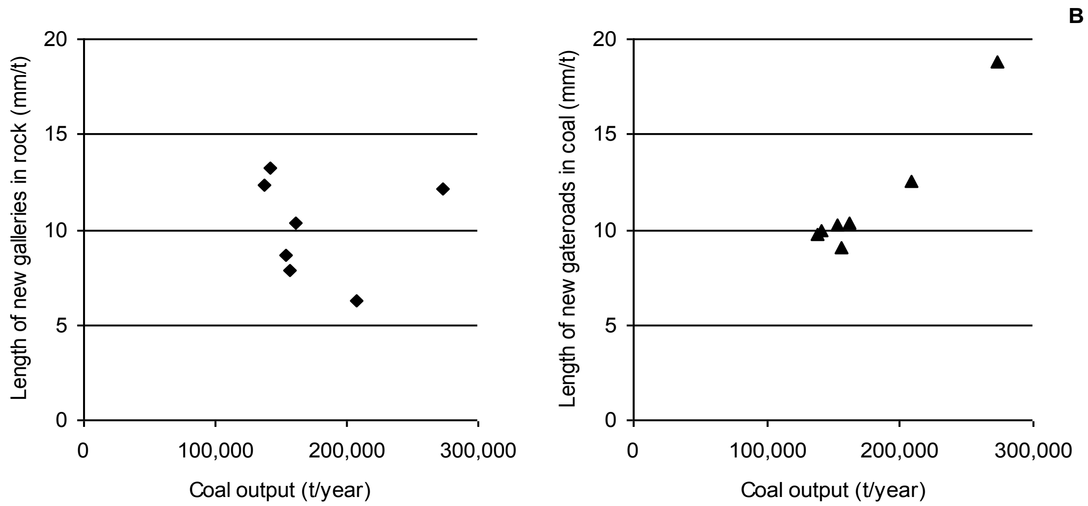
It is not easy to estimate "theoretically" reasonable maximum and minimum values for geothermal power. But a semi-empirical approach could be used if the total length of galleries in the mine is known. If this length parameter is unknown it could be either obtained from historical data or it could also be deduced from coal output as explained below.

After a study carried out in Spain in 1990 [29], the length of galleries excavated in rock in Spanish coal mines varies from 4 to 9.5 km per million of saleable tonnes. In the case of gateroads or galleries advanced in coal seams this value ranges from 6 to 12 km. The report gave data from a total of about 25 underground mines in Spain (pit-coal, anthracite and lignite). In this period, a number of large-scale mines were in operation and these values can be taken as representative for any mine. In the following, a minimum value for the gallery length excavated in rock and a maximum value for the total length of excavated galleries (rock + coal) will be necessary. Taking into account the above, limits of 5 km and 20 km per million of tones have been chosen.

Figure 10 shows the total yearly length of galleries excavated in rock and gateroads excavated in coal seams for several mines in Asturias. The value is related to the yearly coal output and it is given in mm per ton (equivalent to kilometre per million tonnes). These Figures illustrate that these values, 5 and 20 km, could be accepted for mines in Asturias rather than show data from which these values could be deduced mathematically.

In order to define a procedure, a typical mine in Asturias with a total output of about 10 million of saleable coal has been assumed. The total necessary gallery length would be about 200 km. This value is in agreement with real data, since the total length of galleries excavated in Figaredo Colliery has been about 254 km.

Figure 10. (**A**) Yearly ratio of length of new galleries excavated to coal output; (**B**) Yearly ratio of length of new gateroads excavated to coal output.



After research in a typical mine in Asturias [30], it has been found that the potential geothermal power of a 1 km gallery is approximately 50 kWt = 0.050 MWt. This means that the total geothermal power of a mine which has produced P_T tonnes along its life would be:

$$W_{tmax} = 0.050 \times 20 \times P_T = 1.0 \times P_T \quad (15)$$

Therefore the value of k which can be taken as a maximum would be a constant:

$$k_{max}(t) = W_{tmax}/P_T(t) = 1.0 \quad (16)$$

This value has to be considered a "maximum" because the factor 50 kW/km was deduced from data of galleries at a depth of 500 m, where rockmass temperature was about 28 °C. It is clear that galleries at a lower depth would have smaller geothermal potential. On the other hand, it is assumable that most of the galleries excavated in rock maintain their section, with no significant convergences. Another assumed factor is that the distance between galleries is enough to allow extraction of the maximum heat from the rockmass, which is not always realistic. Finally, in order to recover this amount of heat, large quantities of water should be used (which is not always possible).

A more conservative value can be estimated if it is assumed that gateroads (galleries following coal seams) would collapse and water could not flow through them. In this case, only galleries excavated in rock are stable in the long term and only these galleries could behave as paths for water flow. Moreover, the smaller ratio of galleries' length excavated in rock to coal output is chosen. Consequently, only 5 km of galleries are useful per million of coal tonnes:

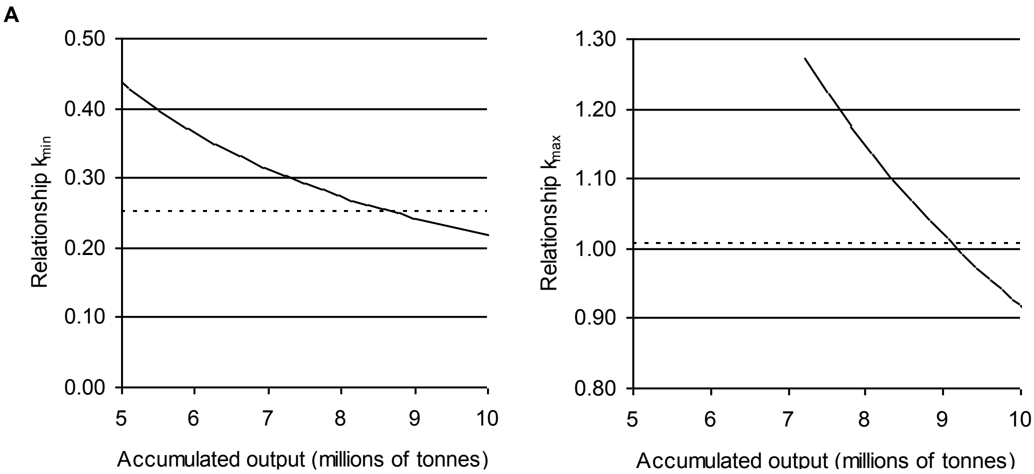
$$W_{tmax} = 0.050 \times 5 \times P_T = 0.25 \times P_T \quad (17)$$

Consequently the value of k which can be taken as a minimum is constant and its value is:

$$k_{min}(t) = W_{tmin}/P_T(t) = 0.25 \quad (18)$$

These theoretical results are represented in Figure 11, in a graphical output similar to the one that shows the more experimental results previously deduced (in Figure 9).

Figure 11. (**A**) Minimum relationship between geothermal power and output *versus* accumulated output; (**B**) Maximum relationship between geothermal power and output *versus* accumulated output.



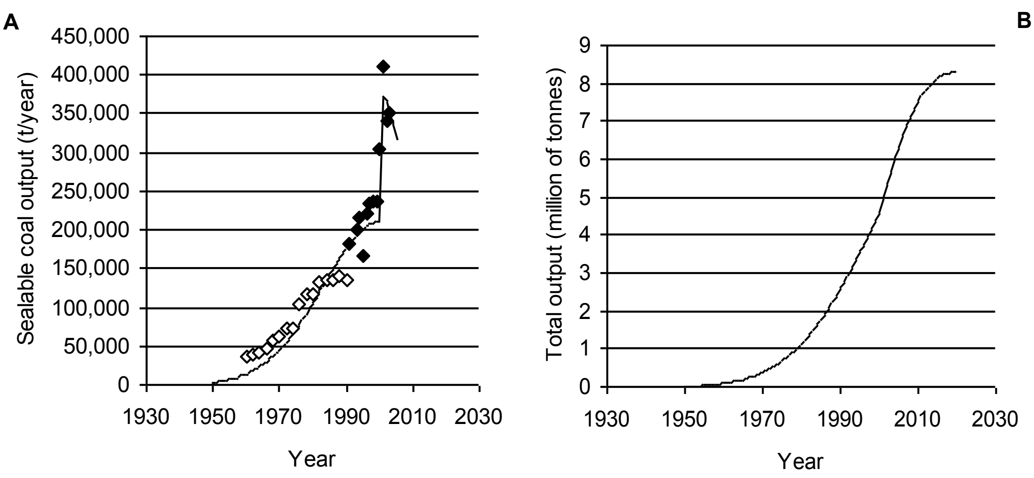
5. Using the model

5.1. Estimation of the Geothermal Power of a Mine

It now becomes easy to estimate the geothermal power potential of any mine in Asturias, by applying the above-described method.

The case example selected to validate the method is a coal mine having mainly low, steep coal seams at a moderate depth of 400 m. The coal is anthracite, without methane and the exploitation method is longwall with caving. This coal field did not have easy access to the rest of the region, so its mining history starts about the middle of the 20th century, when a power station was built near the coalfield (Figure 12). Production drastically increased in 2000, due to the mechanisation of the works in order to mine a 4 m thick coal seam by the longwall method [31].

Figure 12. Coal production of an underground mine in Asturias (**A**) Coal output, in t/year; (**B**) Cumulative total output from approximately 1954 to present time.



Studies conducted during 2003 have provided some valuable information, which can be used to validate the approach. Up to this date, the mine had produced about $P_T = 5 \times 10^6$ tonnes of saleable coal. Taking the value $k_{min} \approx 0.25$, the minimum expected geothermal power of the mine would be:

$$W_{tmin} = 0.25 \times 5 = 1.25 \text{ MWt} \tag{19}$$

This minimum value can be verified from real data obtained from the mine. In 2003, the total water inflow into the mine was $Q_w \approx 162$ m^3/h = 0.045 m^3/s while the air flow rate was $Q_a \approx 25$ m^3/s [24,32]. In this case, it can also be assumed that the electrical power of mining equipment is about E = 1.0 MW.

Consequently, a realistic value for geothermal power would be:

$$W_t = 25.1 \times Q_w + 0.013 \times Q_a - 0.10 \times E = 1.13 + 0.32 - 0.10 = 1.35 \text{ MWt} \tag{20}$$

This value is greater than the previously calculated minimum value.

Taking $k_{max} \approx 1.0$, the upper limit for geothermal power (which is not expected to be reached) would thus be:

$$W_{tmax} = 1.0 \times 5 = 5.0 \text{ MWt} \tag{21}$$

Nevertheless, in opposition to estimation of the minimum parameter, the assessment of the maximum value cannot be proved.

5.2. Estimation the Geothermal Power for Several Mines in the Same Coalfield

This section shows the typical problem of estimating the geothermal power potential of many abandoned mines for a given coalfield in Europe, applying it to Asturian mines. The total underground coal output in Asturias during the last 200 years is shown in Figure 13. It is a fairy moderate production of only 110 million tonnes. Actually, the output is about 1 million tonnes per year. Data is only referred to pit-coal produced in the Central Coal Basin.

Actual data from 1980 and 2004 allow verification of the simplified method. In 1980, total coal ouput of mines in Asturias was about 89 million tonnes of saleable coal ($P_T = 8.9 \times 10^7$ tonnes). This production was obtained mainly from 25 collieries, so the average saleable production reached was about 3.5 Mt per mine facility. So, at the present time these mines could be considered “old mines” and the approach could be used.

For the following minimum and maximum values, $k_{min} \approx 0.25$ and $k_{max} \approx 1.0$, the minimum and maximum expected geothermal power of the mines would thus be:

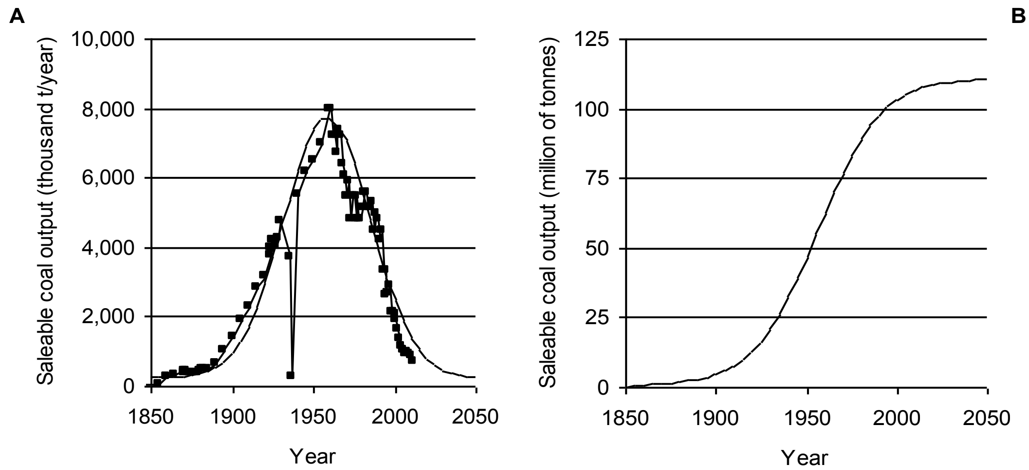
$$W_{tmin} = 0.25 \times 89 = 22.2 \text{ MWt} \tag{22}$$

$$W_{tmax} = 1.00 \times 89 = 89.0 \text{ MWt} \tag{23}$$

It can be estimated that the total mine water evacuated from underground mines in Asturias was more 4.0×10^7 m^3 per year or $Q_w = 1.2$ m^3/s, as a study about mine water carried out in 1980 reports [33]. On the other hand, following the procedure explained above, coal output for this year was 5.5×10^6 tonnes, and the total air flow rate supplied to the mines would be more than 1500 m^3/s. With this input data, the actual geothermal power could then be estimated as:

$$W_t = 25.1 \times Q_w + 0.013 \times Q_a = 30.1 + 19.5 = 49.6 \text{ MWt} \tag{24}$$

Figure 13. Total coal production of underground mines in Asturias (**A**) Coal output, in thousand t/year; (**B**) Cumulative total output from 1850 to present time, in million tonnes.



This value is higher than the minimum geothermal power estimated before and, it is obviously lower than the maximum one. In 2004, the total coal output of mines in Asturias was about 104 million tonnes of saleable coal (P_T = 1.04 × 10^8 tonnes). Taking the values $k_{min} \approx 0.25$ and $k_{max} \approx 1.0$, the minimum and maximum expected geothermal power would be:

$$W_{tmin} = 0.25 \times 104 = 26.0 \text{ MWt} \quad (25)$$

$$W_{tmax} = 1.00 \times 104 = 104.0 \text{ MWt} \quad (26)$$

A study carried out in 2004 [25] demonstrated that the total mine water pumped from underground mines in the Central Coal Basin in Asturias was more than 36 × 10^6 m^3 per year or $Q_w = 1.1$ m^3/s. On the other hand, following the procedure developed in this research, for a yearly coal output of approximately 1.8 × 10^6 tonnes, and a total air flow rate supplied to the mines of more than 500 m^3/s in 2004, the estimated geothermal power is:

$$W_t = 25.1 \times Q_w + 0.013 \times Q_a = 27.6 + 6.5 = 34.1 \text{ MWt} \quad (27)$$

A value which is also between the minimum and maximum values previously estimated.

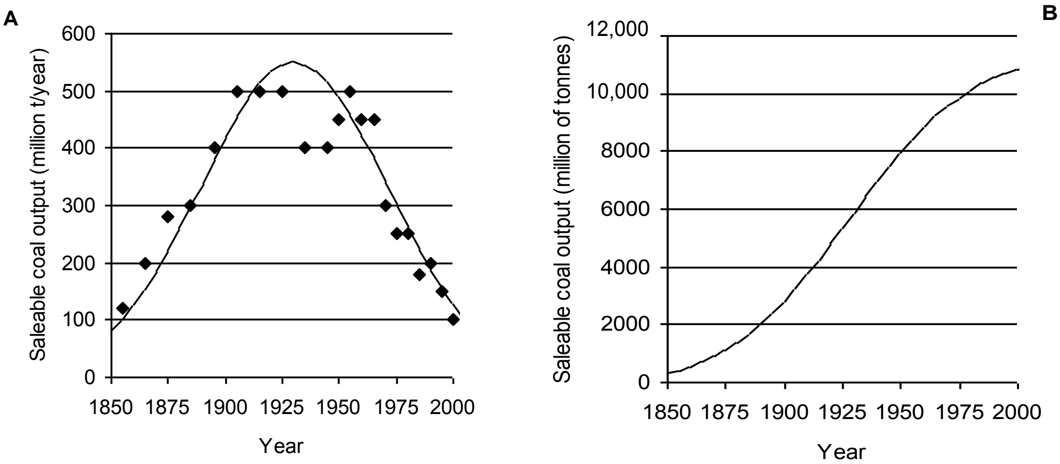
It is important to point out that, as recorded in [25], the population of villages and towns close to these mines reaches 500,000 inhabitants which could directly use this geothermal power.

5.3. Could the Total Geothermal Power of Abandoned Mines in Europe be Estimated?

An accurate quantification of the geothermal power of abandoned mines in Europe would not only contribute to making the right decisions but also help to find proper uses for existing funds. This is obviously an interesting problem which cannot be solved at this stage of research; the main but not the only reason, is that at the present time, thousands of mines remain abandoned in Europe with no information available and without reported data; nevertheless, at least, an attempt to estimate the potential of abandoned coal mines could be made by applying the proposed method.

The graphical output in Figure 14A shows a gross estimation of the total coal production in the European Union for the last 150 years [34,35]. The accumulated coal output could reach the value of 11,000 million tonnes (Figure 14B).

Figure 14. Estimation of total coal production of underground mines in Europe (**A**) Coal output, in million t/year; (**B**) Cumulative total output from 1850 to 2000, in million tonnes.



Taking the value $k_{min} \approx 0.25$, the total geothermal power potential in Europe could be assessed:

$$W_{tmin} \approx 0.25 \times P_T = 0.25 \times 11000 = 2750 \text{ MWt} \quad (28)$$

This is, about 3000 MWt could be extracted only from abandoned underground coal mines. The conclusion is that, as stated above, a vast geothermal potential from abandoned mines is not being exploited in Europe.

Furthermore, at this point, it would be interesting to make a gross estimation of hypothetical reduction in CO_2 emissions due to the use of this unexploited geothermal power.

Assuming that W_t = 3000 MWt, and for a coefficient of performance COP = 4, the useful thermal power is:

$$W_u = W_t \times COP/(COP - 1) = 3000 \times 1.33 \approx 4000 \text{ MW} \quad (29)$$

Assuming that the power is used h = 24 h/day and d =30 days/month during m = 6 months/year, the total energy would thus be:

$$E_u = W_u \times (12 - m) \times d \times h = 4000 \times 6 \times 30 \times 24 \approx 17{,}280{,}000 \text{ MWh/year} = 17.3 \text{ TWh/year} \quad (30)$$

The ratio between tonnes of CO_2 emissions and MWh produced depends on the source. In order to produce 1 MWh of thermal energy, it is necessary to emit 0.850, 0.450 or 0.200 tonnes of CO_2 to the atmosphere depending on wether electrical, fuel or natural gas has been used as a primary energy source [30]. Assuming an average ratio of 500 t/MWh the production of 17.3 TWh/year would imply a total emission of more than 8.5 million tonnes per year.

The value of this ratio is 0.170 for geothermal power by means of heat pumps. Consequently, in this case, CO_2 emissions would be only 3 million tonnes per year, thus yielding a reduction of CO_2 emissions of about 5 million of tonnes/year.

Finally, it is important to point out that this 3000 MWt could be extracted only from abandoned coal mines. It is unquestionable that a quantity of similar magnitude could be extracted from base-metals mines. So, the total amount of geothermal energy which could be recovered from underground mines in Europe could be as much as 6000 MWt. This value is equivalent to the energy supplied by 6000 eolic generators or equivalently, to the energy supplied by a wind power park with more than 150 generators for each country in the European Union. For this reason, promoting the widespread use of this source of renewable energy is of the most importance.

6. Conclusions

The following conclusions can be deduced from research carried out so far:

- Although mines present a high potential for geothermal utilization, there are only few cases known in Europe where this potential has been detected, and accurately used.
- A method has been developed to allow a non-complex estimation of the limits for the geothermal potential of an abandoned underground coal mine, from the value of its total production.
- The method is useful for making geothermal resource estimates for given mining regions where coal extraction data are available; it should not be used to design a geothermal system at a mine site.
- The specific maximum and minimum values, $k_{min} = 0.25$ and $k_{max} = 1.0$, could also be applied in coal regions similar to Asturias. Many parameters can influence these values, as for example thermal properties and hydrogeological characteristics of the rockmass, average temperature of virgin rock and gradient of temperature with depth, climate and average temperatures of the air and the river water and mining methods…*etc*. Consequently, values of k_{min} and k_{max} could be different in other regions.
- Assuming that the application of the formula has a high level of uncertainity, it has been estimated that an underground coal mine has a geothermal power of approximately 2.5 MWt per each 10,000,000 of tonnes produced.
- At least approximately 3000 MWt could be used from underground coal mines in the European Union, without including base-metals mines; the potential for coal mines is equivalent to 3,000 eolic generators or thereabouts, to the energy supplied by a wind power park with 90 generators for each country in the European Union.
- If this energy potential were used, an important reduction in CO_2 emissions of approximately 5 million tonnes of CO_2 per year could be reached.
- A good practice in mining management would be to make some mine-measurements, such as recording air flow rates, quantity of water actually pumped or air and water temperatures; this data would be of the most interest for future studies, especially when approaching the mine closure date.

Author Contributions

Rafael Rodríguez conceived and developed the idea behind the present research and he proposed the methodology and analytic procedure. Rafael Rodriguez and María B. Díaz have carried out the literature review and manuscript preparation including the searching and study of historical data of mines used in the definition of k_{min} and k_{max}. Final review, including final manuscript corrections, was done by Rafael Rodríguez.

Conflicts of Interest

The authors declare no conflict of interest.

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