LOw Carbon After Life: sustainable use of flooded coal mine voids as a thermal energy source - a baseline activity for minimising post-closure enviromental risks

Research Fund for Coal & Steel

hunosa

LoCAL Deliverable 4.2: Report on benefit/cost and energy efficiency on technologies selected on WP2, and tested on Mieres and Markham sites for preventing corrosion and incrustation affecting heat transfer process

LoCAL WP 4

Partner responsible: HUNOSA

Índice

1 Background

The use of mine water as geothermal resource is one of the best options to get some economic benefit of this water that in some cases must be pump forever. Barredo Shaft is one of those coal collieries that were built in the center of a city some decades ago. The coal exploitation is close and the colliery is flooded but the water level must be kept at 60 meters below the surface to avoid the flooding of Santiago Colliery. Barredo Colliery is in communication with Figaredo Colliery (also flooded) and there is a gallery between Figaredo and Santiago collieries at this level.

The amount of water pumped in Barredo is 4 Hm3/year. Barredo is not only united to Figaredo; they are also united to San Jose and Santa Barbara collieries, the total water pumped from this four old exploitations, all of them flooded, is 15Hm3/year.

Right now we only use 0,7Hm3/year of this water mainly for giving heating and cooling by the heating pump technology to Mieres Hospital, but the benefit of this business is enough to pay the total cost of pumping in Barredo Shaft, 200.000€/year.

But the mine water has a problem, this water flow with Fe, Ca, sulfates, carbonates and other minerals that can cause problems in the circuits. In the following pages the strategy used in HUNOSA to cope with this problem is explained and of course the experience with it.

2 Mine water chemical quality.

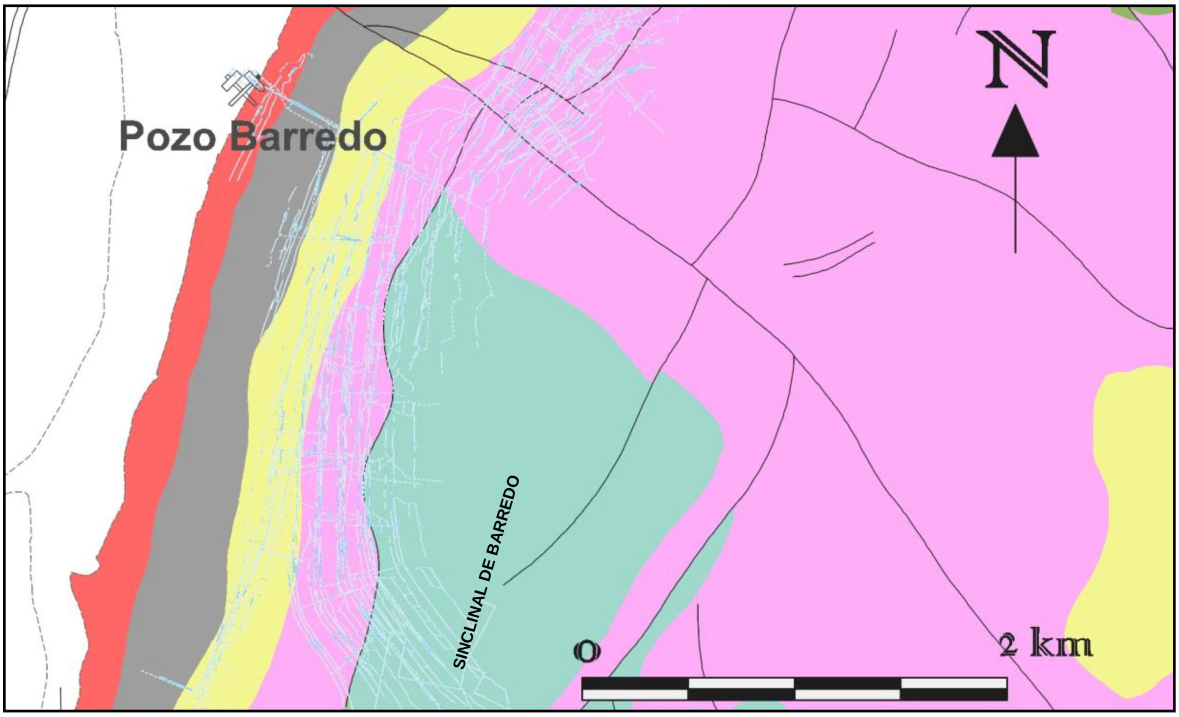

FIGURE 1: Galleries in Barredo Colliery

The mining activity in Barredo colliery started in 1926 and finished in 1993. After closing the exploitation activity de shaft was kept open to give ventilation to Figaredo Colliery and to use some levels as laboratory by the Barredo Foundation. In April 2008 the final flooding was initiated.

The shaft is 362m deep and the mining activity left 147km of galleries. The total volume of voids of galleries and stopes calculated is 1.949.634m3

The mine water pH in HUNOSA collieries is quite neutral, with values between 7 and 8. This is good because with this pH the amount of heavy metals dissolved in the water is very low. Only Ca, Fe, Mg, K and Na in form of sulphates, chlorides and carbonates, are present in the water in significant concentrations.

In table 1 different results of the chemical analysis of Barredo Mine Water just after the flooding are shown:

DATE	pH	T (ºC)	CaCO3 (mg/l)	SO4 (mg/l)	Ca (mg/l)	Fe (mg/l)	Mg (mg/l)	Na+K (mg/l)
1/1/2012	7.49	21	1113,3	1189	318.84	9.05	97.72	478.34
20/1/2012	8.0	21	1015	1120	173	1.4	99	810
19/4/2011	7.4	23	925	1600	174	5.82	102	844,4
11/1/2011	7.4	22	988	1640	184	0.75	118	871.5
17/11/2010	7.8	23	930	1660	180	0.073	109	875.9
8/7/2010	7.6	24	484	737	146	0.03	66	362.03

Table 1: Barredo Mine Water Chemical Analysis

The concentration of this elements change along the year because the water level changes, obviously in winter due to the raining the level is higher and there is an effect of lixiviation, in summer this level is low and the oxygen can affect the chemical substances.

During five years after the flooding the chemical quality of the water was quite low, with concentration of theses ions higher. Right now the quality of the water is better. Usually it is considered that when the total pumped water is six times the total voids in the mine the quality of the water starts to be better.

The precipitation of sulfates and carbonates of Fe, Ca and Mg cause a lot of problems to the conductions of this water. The figure 2 shows an example of the depositions inside a pumping pipe. This precipitation is higher when the oxygen of the air reaches the water just when it is pumped. The redox of this water is negative, so the iron is in form of Fe^{+2}, once this water gets the air, the iron quickly is oxidized to Fe^{+3} with low solubility, and the precipitation starts.

The effects of iron precipitation can go far from the pumping station, in case of calcium the precipitation occurs closer, and usually cause the erosion of the pipes so we need to change them, specially the curved ones.

Figure 2: Depositions inside a pumping conduction

When we built the first geothermal project, we studied the possible effects of the iron in the pipes. This project was the Investigation Center of the University in Mieres Campus. In this case the mine water is pumped directly to the installation in the university; there are two plates heat exchangers and the risk of carbonates precipitation was high so the risk of the reduction in the efficiency of these heat exchangers. According to the concentration of iron we established that at least three times per year it would be necessary to clean the heat exchangers. The following images show how the equipment was the first time we cleaned it.

Figure 3: Filter before cleaning.

Figure 4: Filter after cleaning.

3 Dealing with the iron.

To avoid this problem in the geothermal systems with mine water several strategies must be taken into account. To minimize the possible problems in our installations we have used the following ideas:

- Reduce the circuits with mine water. The heat exchanger is as close as possible to the shaft, so the most part of the installation works with clean water. This can reduce the efficiency of the system but also the maintenance. This is the case of the project for the Mieres Hospital. The distant between the hospital and Barredo Shaft is 2 km, it would be unavailable to use the mine water directly along 2km of pipes. In the final design the exchanger is just near Barredo Shaft and there is a close circuit with to pipes of 400mm of diameter full of clean water that transport the heat between the hospital and the mine water.

Figure 5: Heat exchanger in Barredo Shaft

In the figure 5 we can see the pipes with mine water (in red) and with clean water (in grey). The iron can only precipitate in 20m of pipes.

- Use tubular heat exchangers instead of plate exchangers. In the tubular exchanger the water can go so quickly that avoid the precipitation of solids. This is the design principle for Hospital and FAEN projects. The idea is to avoid the precipitation inside the pipes, so the exchanger efficiency keeps constant. In the figures 6 and 7 it is shown the efficiency and dirt accumulation comparison in tube and plate heat exchanger. It is easy to see that although the plate exchanger seems to be better at the beginning in only 500 hours, due to the quickly accumulation of dirtiness, the efficiency of the plate heat exchanger drops so it is necessary to clean the exchanger, otherwise it would be useless. When this exchanger is installed in a geothermal project this efficiency loss can cause a great loss of the COP and ERR of the heat pump so the heat pump requires more electricity to give the same heat.

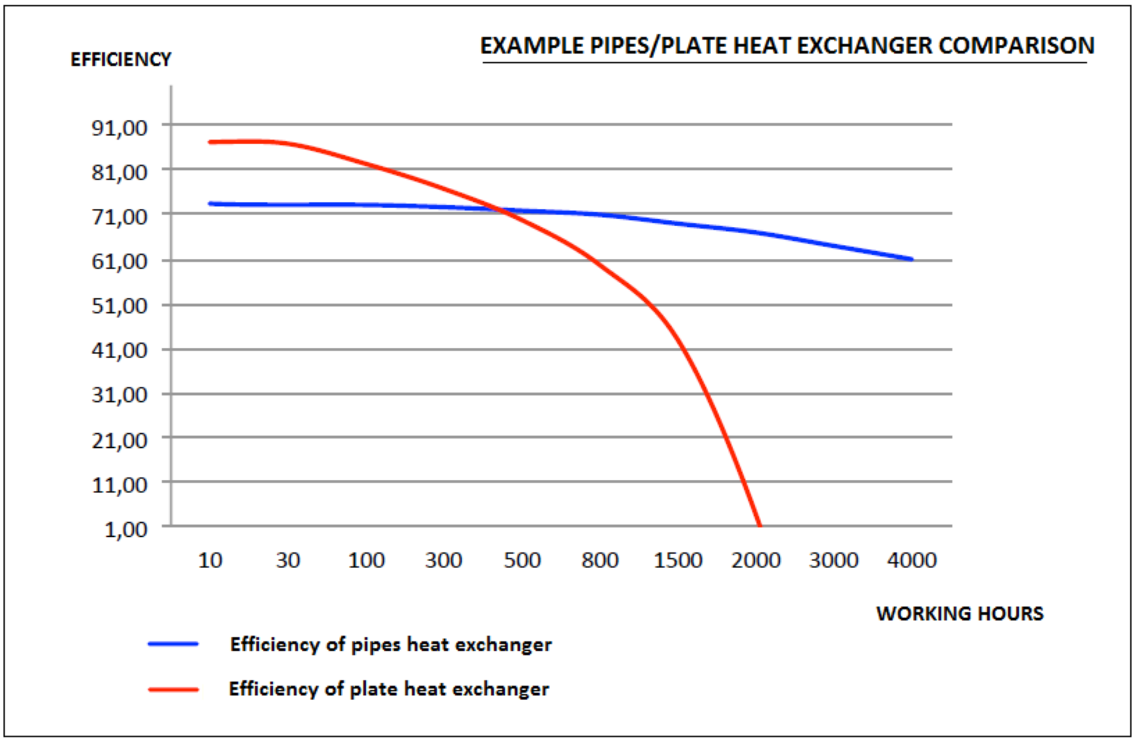

Figure 6: Efficiency of heat exchanger in time

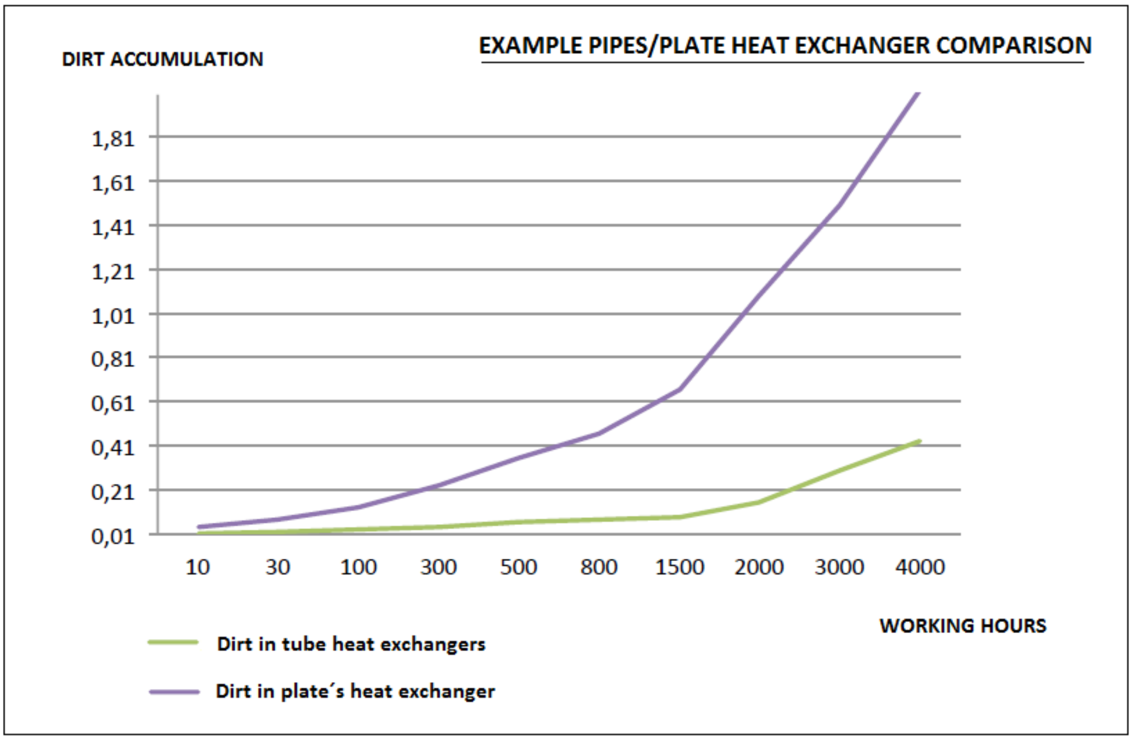

Figure 7: Dirt accumulation in heat exchangers

- Reduce the possibility of the oxygen to reach the mine water. This is easy to achieve, all the pumps are immerse under the water level, and the water goes directly to the heat exchanger, so there is only one surface of 9.6m2 of contact between the air and the water in the bottom of the shaft.

- Maintain the water levels as constant as possible. The objective of this measure is to avoid changes of redox in the ground that helps to put minerals in solution. As Barredo Shaft is united to Figaredo Shaft, to keep constant the level of the water other two pumps were installed in Figaredo Shaft increasing the pumping capability so in winter the level of water is kept constant.

4 FAEN Project.

4.1 Description of FAEN Project.

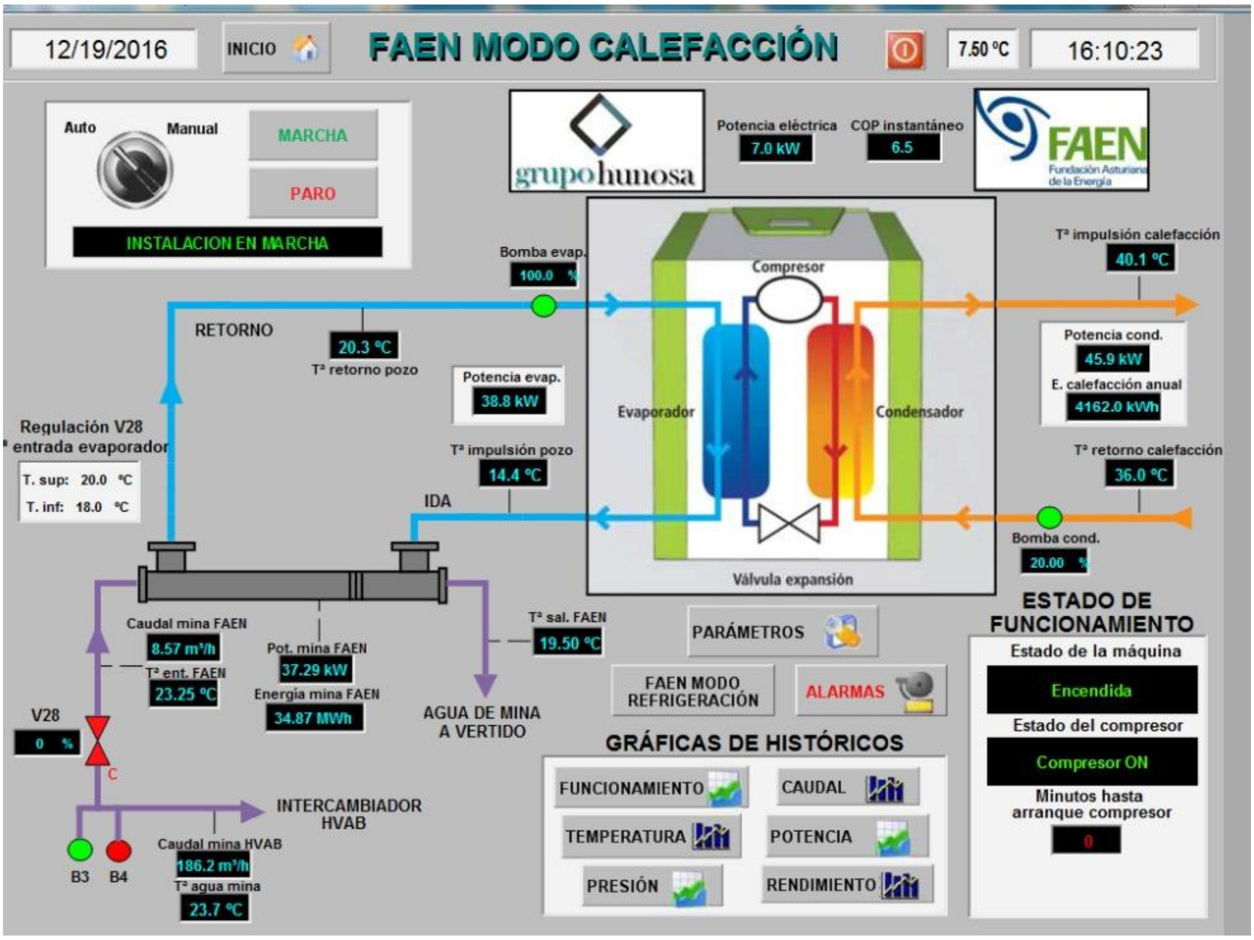

Figure 8: Operation Scheme in Heating Mode in FAEN Project

The nominal working point for the heat exchanger is indicated by the following parameters

Winter Mode

Fluid		Heat pump	Mine Water
Inlet Tª	ºC	16	23
Outlet Tª	ºC	19	19.623
Flow	m3/h	0.598	5.181

Power: 79.8kW

Summer Mode

Fluid		Heat pump	Mine Water
Inlet Tª	ºC	33.5	23
Outlet Tª	ºC	29.5	26.6
Flow	m3/h	0.598	2.181

Power: 89.9kW

The pressure loss in the mine water side for the heat exchanger is shown in Figure 8. The nominal flow is 4.16l/s so the drop in the pressure is 1.529m (15.3kPa).

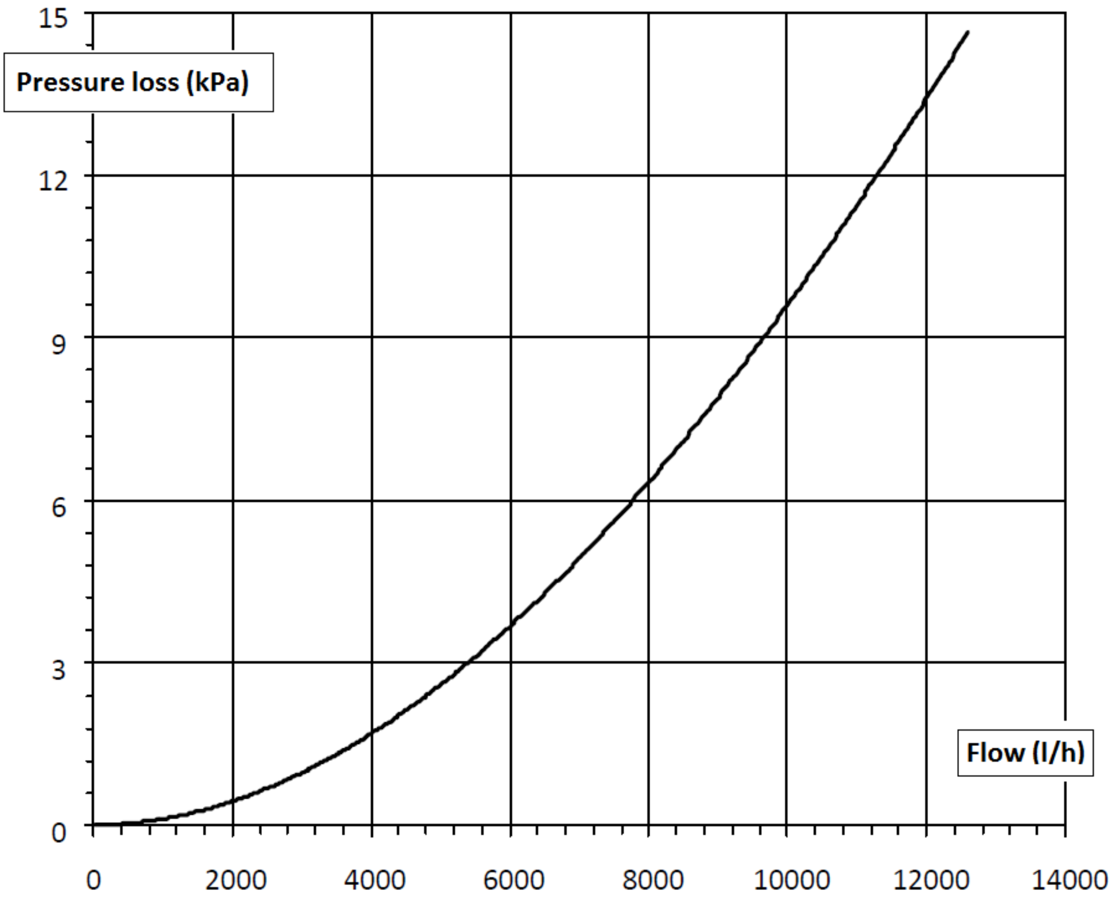

Figure 9: Pressure loss in pipe heat exchanger for FAEN project

For the heat pump, the working point is:

Heat power	kW	25-100
Electrical power	kW	13.3-19
COP		4.49

4.2 Operation conditions.

To keep the heating pump in the optimal operation conditions in the heating mode the regulation process works in the following way:

1.- The temperature in the heating side of the heating pump (right part in the figure 8), that is the water that goes to the fan coils of the building, must be kept at 40ºC. To achieve this there is a pump that control the flow that goes through the condenser, the regulation range is 20-100%. If there is a great necessity of heat from the building, this pump reduce the flow to avoid temperature reduction, only whet more heat is transfer from the mine water this pump increases the flow. If the pump is at 20% and there is no heating supplying to the building the system stops the heating pump. The system knows this when the temperature of the water that goes to the building is the same that the one coming from it.

2.- In the cooling side there is also an optimal range of temperature (16-19ºC), the heating pump can work out of this range (from 3ºC to 23ºC) but the COP drops. And if the temperature reaches 23ºC the systems stops the heating pump and gives us an alarm. This temperature would cause a malfunction of the machine, because over this temperature there is no condensation in the heating side. There is a pump to control the flow in this circuit, but it is no used to control the temperature it only supply more energy to the heating pump coming from the heat exchanger.

3.- The temperature control of the cooling side is in charge of the valve V28 (left side of the figure 8). When the temperature of the cooling side gets 20ºC, the flow of the mine water is reduced by this valve, so the heating pump only can get energy from the temperature of the water accumulated in the circuit of the cooling side. Once the temperature reduces the valve opens again.

If the building needs more heat, the difference of temperature in the heating side increases, so the heating pump reduce the flow until 20%, if the temperature keeps the increment, then the pump of the cooling side increases the flow in this side, this creates a reduction in its temperature. This cause an opening in the valve V28 and the heat begin to pass from the mine circuit to the cooling side, the increment of temperature of the cooling side causes an increment in the heating side and the control pump increases the flow so more heat can go to the building.

When the building needs cooling instead of heating the operation is the similar, in this case is the cooling side what is connected to the building and the heating side is connected to the heat exchanger with the mine water.

This control system causes constant variations in the working conditions so there are constant cycles of adjusting them to the necessities of the building. The Figure 10 shows how the COP is changing along one working day. We can see the eight working periods and how the COP changes between 5 and 7 (blue line); the first period is in the early morning with the building cool so it is the biggest and with a great necessity of heat so this causes a reduction in the COP because the temperature drops (in this case until 8ºC). The red line is the power taken from the water mine by the cooling side of the heat pump; the system tries to keep it constant in the optimal conditions. And the green line is temperature of the water that goes from the heat exchanger to the cooling side of the heating pump. The changes of this temperature a cause mainly by the mine water flow as was explained before.

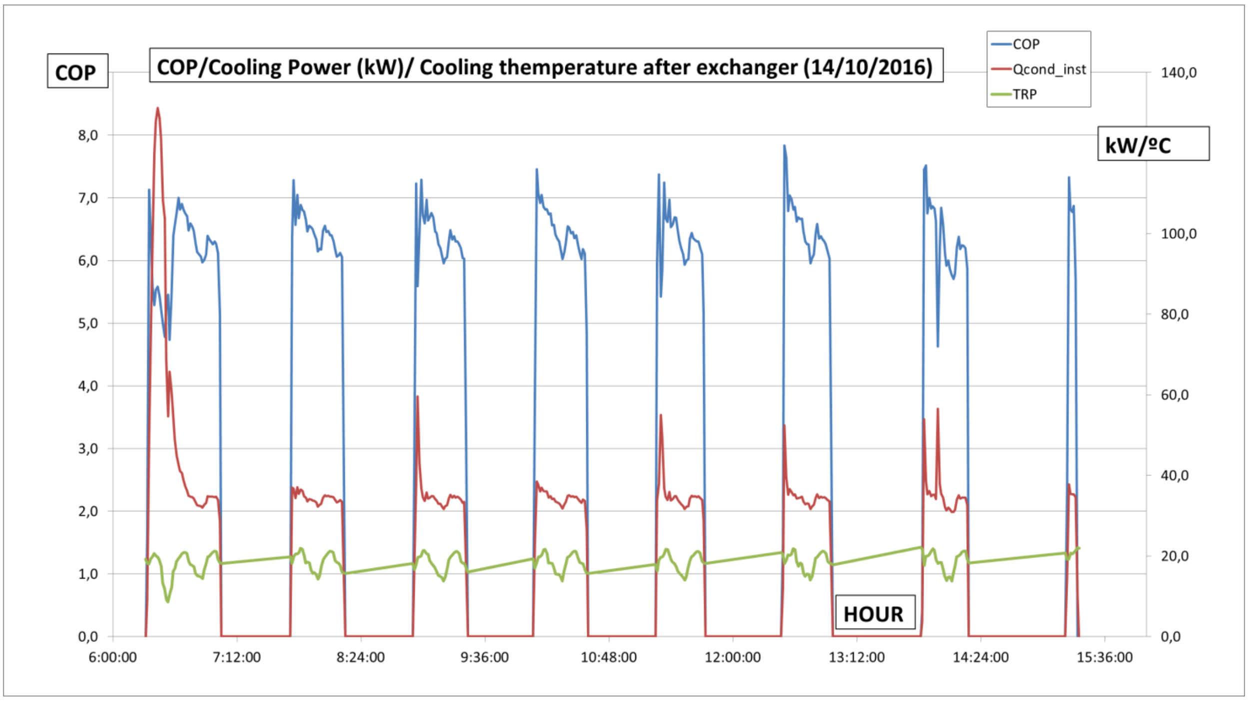

Figure 10: Example of operation conditions for 14/10/2016

There is enough mine water so this control system can cope with changes. For example the mine water temperature, if there is a reduction the system would supply more water, obviously the opposite is also possible. When the heat exchanger gets dirty by the iron the effect is the same, the valve V28 allows more water to flow to it. But of course this compensation effect would have a limit. If the heat exchanger is very dirty the valve would open until 100%, but the flow would not be enough and the cooling side of the heating pump would reduce its temperature, so to give the same heating power the heating pump would use more electrical power reducing the COP until the temperature of the cooling side gets 3ºC creating frozen inside the heating pump. Of course there is a security system to avoid this, but not to avoid inefficient operation points.

The FAEN installation is working since last march, and the COP is more or less the same. There is now a better COP due to a better regulation of the V28 valve. In the following lines some data demonstrates that the heat exchanger is clean, there is no iron precipitation inside it after 9 months.
As far, we have not done any maintenance to the pipe exchanger.

4.3 Results

There is an easy indicator to check if there is iron precipitation in the heat exchanger. The pressure of the mine water is always the same in the circuit, so if the heat exchanger increases its hydraulic resistance due to iron precipitations the flow when the V28 valve is 100% opened would be different. The following table shows different values along these months.

Date	Flow (V28)
11/05/2016	21,6
16/05/2016	20,5
20/05/2016	21,22
28/07/2016	27,4
08/08/2016	27,9
30/08/2016	27,7
08/09/2016	27,12
16/09/2016	27,7
23/09/2016	27,5
28/09/2016	27,5
04/10/2016	27,39
12/10/2016	27,4
14/10/2016	27,4

The flow when the valve is totally open is the same so the flow resistance keeps constant and the mine circuit keeps clean.

Other indicator is the medium COP that is the energy supplied to the building by the electrical energy used. The following table shows these values for different days.

DATE	COP med	Supplied energy kWh	Electric energy kWh
11/05/2016	5,47	200,2	36,5
13/05/2016	5,44	164,8	30,3
16/05/2016	5,45	247,1	45,3
20/05/2016	5,3	78,6	14,8
04/10/2016	6,16	122,8	19,9
12/10/2016	6,1	96,1	15,7
13/10/2016	6,11	114,2	18,7
14/10/2016	6,22	143,46	23,1

This table shows an increasing in the COP (the mine water temperature was constant) due to a better control of the valve V28. There is no effect of the iron in the efficiency of the installation. But according it was said previously to notice the effect the iron precipitation should be important, to check this we can look for another indicator; the amount of heat we can extract from the mine water.

We can know the amount of water that was used to supply this energy to FAEN building, so we can calculate the amount of energy extracted from this water. The iron effect would cause a reduction of this indicator because more water would be necessary to supply the same energy. This can be seen in the following table.

In this case the result is the same; more energy is extracted from the water in October (13W per every cubic meter of water) than in may (3W/m3). A better regulation of the valve V28 allow the use of less water to get the same energy.

DATE	Supplied energy kWh	Amount of water (m3)	kW/m3 of water
11/05/2016	200,2	6527,7	0,0033
13/05/2016	164,9	4996,5	0,0041
16/05/2016	247,1	6971,4	0,0030
20/05/2016	78,7	2145,7	0,0128
04/10/2016	122,9	1638,0	0,0170
12/10/2016	96,1	1341,7	0,0206
13/10/2016	114,3	1763,0	0,0154
14/10/2016	143,5	2101,0	0,0132

It is not possible determine the real efficiency of the heat exchanger because measurement equipment is in the heating pump. There are 28m between the heating pump and the heat exchanger and part of the circuit is underground so there is an effect of storing energy along this circuit.

5 Investigation Center project

5.1 IC Project Description.

This was the first in geothermal technology with mine water and it was design with these parameters:

Parameter	Value	Units
Heating consumption	586.819	kWh/year
Cooling consumption	745.253	kWh/year
Amount of mine water needed	409.479	m3/year
Heating pumps	2x362	kWh heating power
Distance (Barredo- CI)	250	m

Production in heating mode

	Heating side 30/35		
Cooling side T (ºC)	**Heating (kW)**	**Electricity (kW)**	**COP**
5/10	375	75	5,0
7/12	399	77	5,2
9/14	424	79	5,4
16/21	511,5	86	5,9

	Heating side 35/40		
Cooling side T (ºC)	**Heating (kW)**	**Electricity (kW)**	**COP**
5/10	363	80	4,5
7/12	386	82	4,7
9/14	411	85	4,8
16/21	498,5	95,5	5,2

	Heating side 40/45		
Cooling side T (ºC)	**Heating (kW)**	**Electricity (kW)**	**COP**
5/10	352	87	4,0
7/12	374	89	4,2
9/14	397	91	4,4
16/21	477,5	98	4,9

Although the installation is prepared to give heating and cooling right now the University only wants to get heating service. Figure 11 shows the control system during the heating mode.

In this case the mine water goes from the shaft to the building through a 200mm diameter pipe, the water pass throw a plate heat exchanger an then goes to the same pouring point with the rest of the mine water. The different of level between Barredo Shaft and the Installation is 10m so there is no need of pumping.

In this case the temperature in the cooling side must be below 18ºC, so the regulation system use the mine water flow to keep this temperature between 16-18ºC. When the building requires more heat, there is a reduction in the temperature of the cooling side, so the valve V26 opens and more mine water passes to the exchanger.

Plates heat exchangers are quite affected by iron precipitation (see figure 6) in the past we have several problems cause by the blockage of the filter (see figures 3 and 4), with reductions of the flow to the exchanger and of course reductions of the temperature of the cooling side, so the heat pump stops.

We established a schedule to clean the exchanger and the filter; at least three times per year these elements must be cleaned.

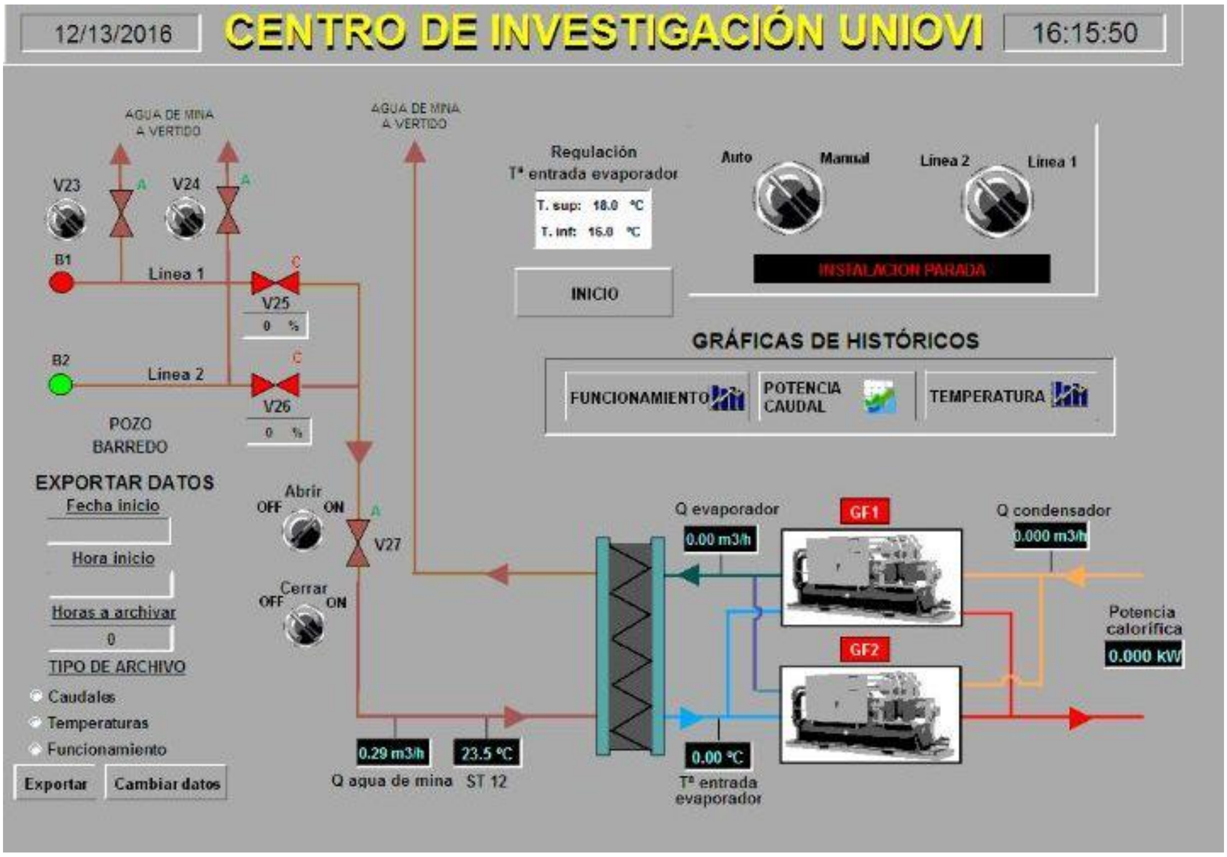

Figure 11: University in heating mode

5.2 Results

In the same way that in the FAEN project, the regulation system can cope with the dirtiness in the heat exchanger and it is difficult to see if the changes in the operating parameters came from this problem of from others changes like the consumption of the building, the external climate, etc. But in the figure 12 it can be seen how the iron deposits increase the necessity of mine water.

The values represent the electrical energy consumed by the heat pump (blue line) and the amount of water in m3 used every day to supply the geothermal heat. The electrical energy grows with cold weather but also if there is iron in the plates of the exchanger (this cause loss in heating transmission). The amount of water also rises by the same reasons; in case of dirtiness the installation requires more water.

In the first heating period winter of 2014/2015, the electrical consumption of the heating pump decreased from December to April due to better external climate conditions, but the amount of water needed by the installation increased when it should have decreased too, obviously this was by the iron deposits.

In the second heating period (2015/2016) we can see how the heating necessities increase along the winter and the spring (this year the spring in Asturias was quite cold), in may we can see a reduction of the electricity use by the heat pump when the good weather started but the amount of water needed kept rising. This is another case of dirtiness.

In the current winter period (this year the weather conditions are colder), we can see how the heating pump uses more electricity without important increments of the amount of water, that is because the heat exchanger is still clean.

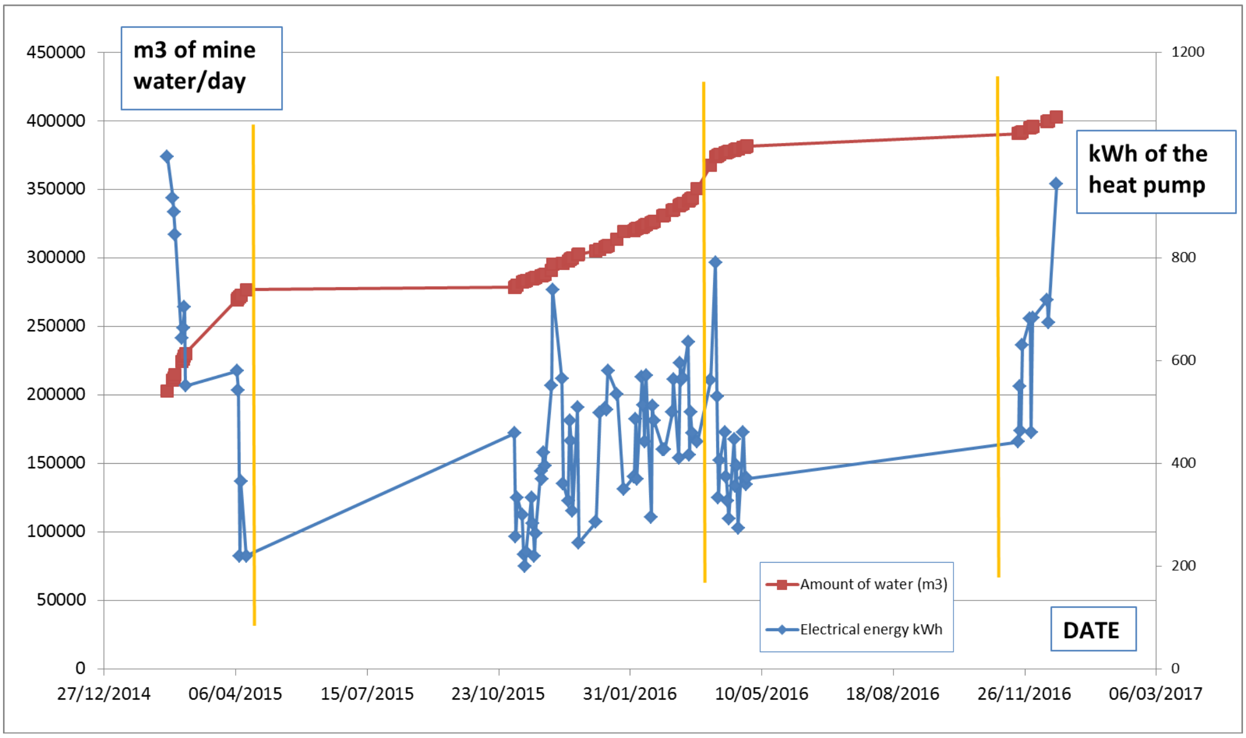

Figure 12: Use of mine water and electricity by the installation

It is easy to see how the installation of the University Investigation Center gets dirty in three or four months (it is off between June and November) while the installation in FAEN is still clean after eight month in continuous operation.

6 HOSPITAL Project.

This is a great Project, when we designed it we already knew the effect of the iron in plates heat exchangers so we decided to use a pipe exchanger from the beginning. The cost was 227.000€ and the cost for the equivalent plates exchanger (175.000€), it is quite a difference but it was a good decision.

The installation was designed to supply 3.3MW of heating and 3.7MW of cooling to the hospital. The total energy consumption of the hospital is 7GWh per year. The figure 13 is a basic scheme where the main elements are the following:

1.- The heat exchanger (in the left side of the figure), in blue is represented the circuit of the mine water. It is a small part so the maintenance caused by the iron is quite simple. The mine water goes very quickly along the pipes in the exchanger so the risk of iron precipitation is low.

2.- The circle circuit of clean water that transport the heat between the exchanger in Barredo Shaft and the hospital is 2010m length, the two pipes a 400mm made of PVP.

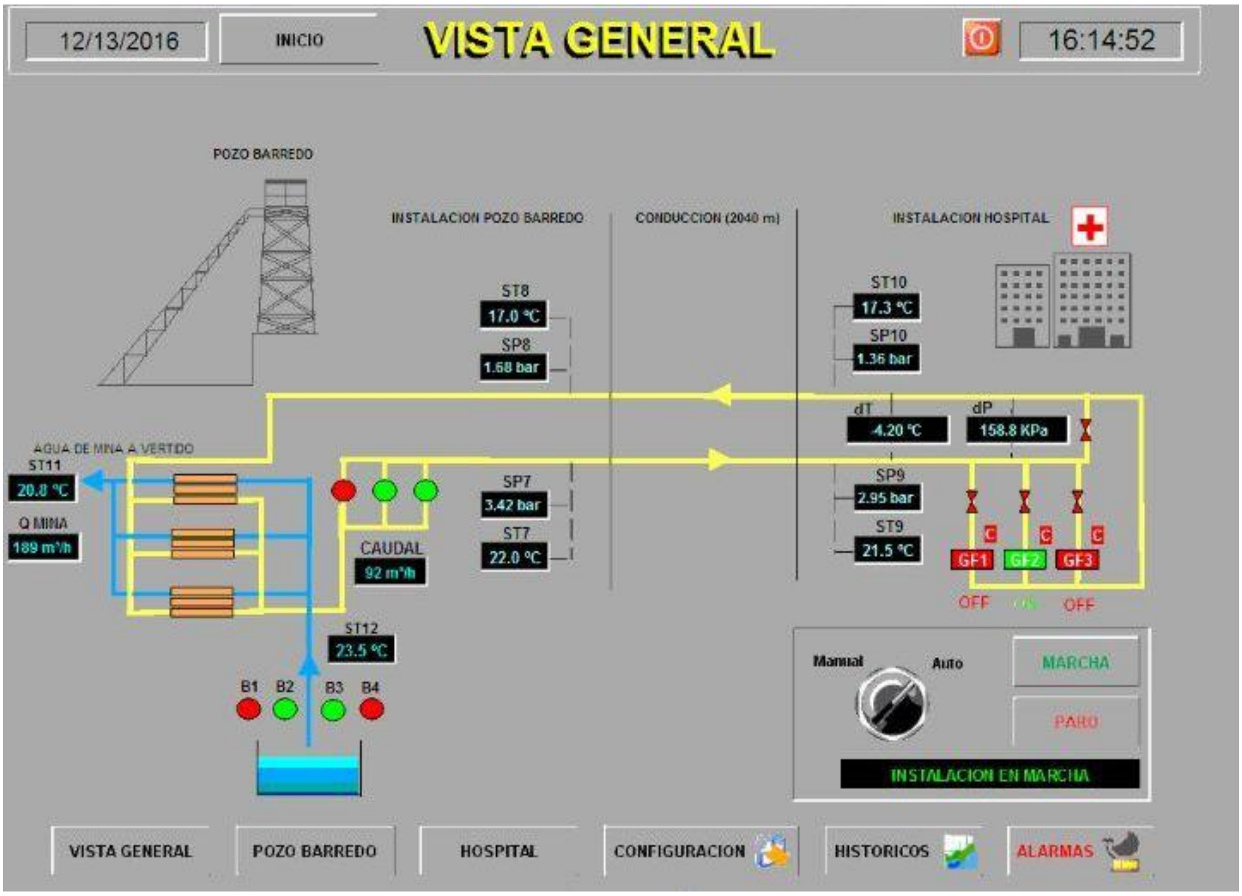

Figure 13: geothermal scheme of the hospital project

3.-The flow of water in the circle circuit is kept by three pumps of 55kW and 200m3/h. The number of the pumps in operation is related to the necessity of the hospital.

4.- Three heating pumps are in charge of extract the heat coming from the mine and transfer it to the hospital circuit. Two of them are equal (B1152) and they will work transferring the heat and the third one (B652) will work in "compensation", that is transferring the heat between different areas of the hospital (when cooling and heating are necessary at the same time). In the following tables different working points of the heating pumps are shown.

B1152	Power (kW)			Rendimientos	
Point	cooling	heating	electricity	EER	COP
1118134046	1242,7	1509,5	272,2	4,56	5,54
1218134045	1252	1512,9	266,2	4,7	5,68
1318133945	1254,2	1513,8	264,8	4,74	5,72
2113084045	1071	1332,4	266,8	4,01	4,99
2215104045	1140,8	1402,1	266,7	4,28	5,26
2315103945	1142,8	1402,8	265,3	4,31	5,29
3112072833	1141,4	1329,8	192,2	5,94	6,92
3212072834	1135,7	1327,7	195,9	5,8	6,78
4112073238	1098,7	1315,5	221,3	4,97	5,95
4212073035	1126,2	1324,3	202,1	5,57	6,55
5112074045	1037,4	1298,9	266,8	3,89	4,87
5212074046	1029,7	1297,1	272,9	3,77	4,75

B1152	Evaporator			Condensator		
Point	T out	T in	flow (l/s)	T in	T out	flow (l/s)
1118134046	13	18	59,43	46	40	60,71
1218134045	13	18	59,87	45	40	73
1318133945	13	18	59,98	45	39	60,86
2113084045	8	13	51,09	45	40	64,29
2215104045	10	15	54,48	45	40	67,65
2315103945	10	15	54,58	45	39	56,4
3112072833	7	12	54,42	33,2	28,2	63,93
3212072834	7	12	54,15	34	28,2	55,03
4112073238	7	12	52,38	38,2	33,2	63,34
4212073035	7	12	53,7	35	30	63,71
5112074045	7	12	49,46	45	40	62,67
5212074046	7	12	49,1	46	40	52,16

The use of mine water with a temperature of 23ºC, make the heating pump work at better conditions, in the table the best is the first one with 18ºC entering in the evaporator (cooling side) that gives a COP of 5.54, so better COP is achieve by the heating pump.

B652	Power (kW)			Rendimientos	
Point	Cooling	Heating	Electricity	EER	COP
1118134046	714,5	872,6	161,5	4,42	5,4
1218134045	722,1	877,1	158,3	4,56	5,54
1318133945	724,5	878,6	157,4	4,6	5,58
2113084045	604,5	758,8	157,7	3,83	4,81
2215104045	649,9	804,4	157,9	4,12	5,1
3112072833	677,4	790,4	115,4	5,87	6,85
3212072834	672,5	787,4	117,4	5,73	6,71
4112073238	638,2	767,3	131,9	4,84	5,82
4212073035	663,5	727	121,1	5,48	6,46
5112074045	582,7	737	157,6	3,7	4,68
5212074046	576	733,5	160,9	3,58	4,56
2315103945	651,7	805,5	157	4,15	5,13

B652	Evaporator			Condensator		
Identificador	T out	T in	flow (l/s)	T out	T in	flow (l/s)
1118134046	13	18	34,17	46	40	35,1
1218134045	13	18	34,54	45	40	42,33
1318133945	13	18	34,65	45	39	35,32
2113084045	8	13	28,84	45	40	36,62
2215104045	10	15	31,04	45	40	38,82
3112072833	7	12	32,3	33,2	28,2	38,01
3212072834	7	12	32,06	34	28	32,64
4112073238	7	12	30,43	32,8	33,2	36,95
4212073035	7	12	31,64	35	30	37,62
5112074045	7	12	27,78	45	40	35,56
5212074046	7	12	27,47	46	40	29,5
2315103945	10	15	31,13	45	39	32,39

The installation has been in operation for three years, in this period we only opened the heat exchanger ones to check the iron deposits inside and it was completely clean.

6.1 Results

The figure 14 shows the relation between the energy supplied to the hospital and the amount of water used in one day for different days during one year.

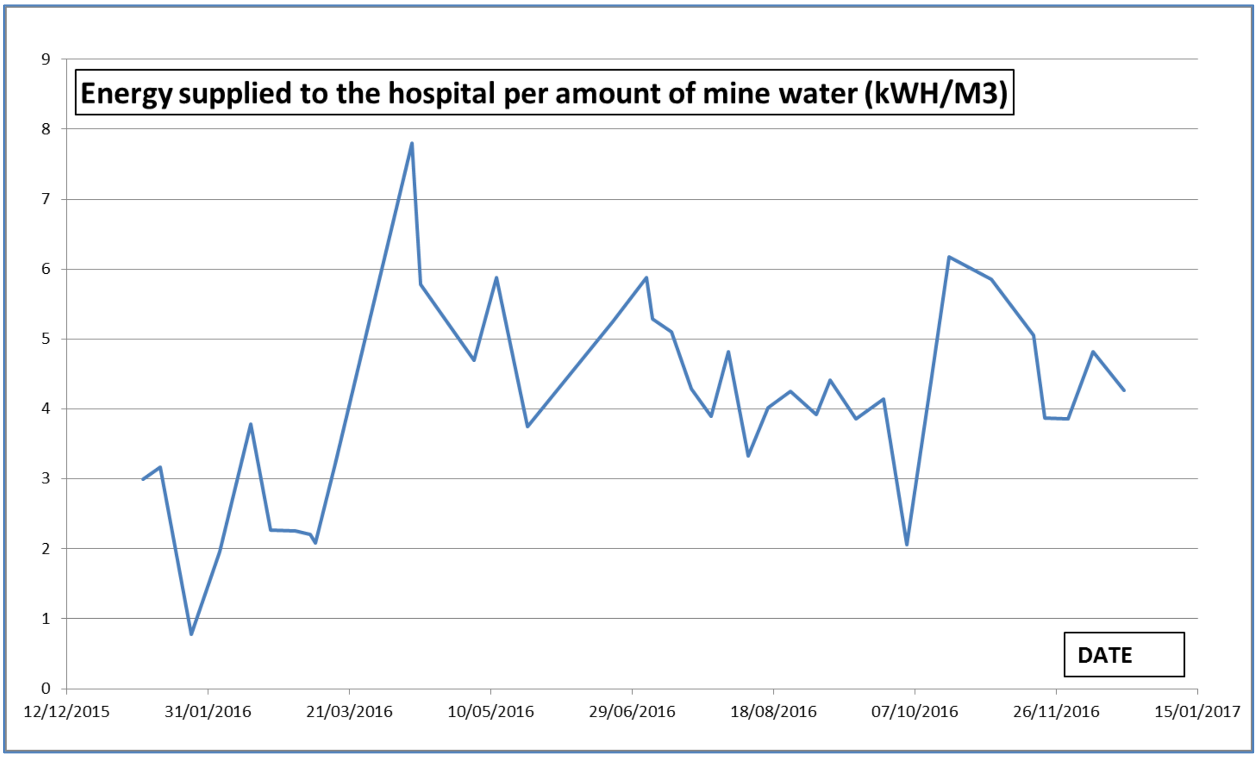

Figure 14: Energy supplied to the hospital per amount of mine water.

Like in the previous cases this relation can show the effect of iron depositions inside the heat exchanger. With more iron less exchange of heat and more water would be needed to supply the same energy.

We can see that there is no a descending trend in the values along one year. The reason of the increment in march is due to the changes in the regulation conditions of the installation that allow us to keep the geothermal system keep the operation all day (before that we sometimes kept when the gas system was in operation instead the geothermal system).

7 Conclusions.

The pipe heat exchangers have a very good behavior when the water can cause problems with iron. The installation in the hospital has a great pipe exchanger of 4MW that has been working during three years in perfect conditions. It was only opened one time and we could check it was completely clean.

In FAEN installation the result is the same, it is in operation since March and there is no need to clean the heat exchanger. The contrary happens in the University Installation where we have to clean the plate exchanger twice per year, and the results show how quickly the energy extracted from the mine water reduce in time that is as the iron is precipitating in the heat exchanger.