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

(LoCAL)

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Low-Carbon After-Life: sustainable use of flooded coal mine voids as a thermal energy source - a baseline activity for minimising post-closure environmental risks (LoCAL)

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

(LoCAL)

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1. FINAL SUMMARY

The LoCAL project aimed at facilitating wider use of thermal energy from mine water for both heating and cooling purposes. In order to achieve that, the international LoCAL project team worked together to bring together the state-of-the-art in modelling and management of abandoned coal mine workings.

One of the LoCAL Project's aims was the provision of bespoke tools for investigating flow and heat transfer in flooded mine workings. For this purpose a new tool for heat transfer modelling in flooded mine workings have been developed. The tool combines flow modelling in the underground mine workings with an updated version of the heat transfer model proposed by Rodriguez and Diaz (Rodriguez R, Diaz MB, 2009). For the purpose of providing evidence required for calibration of this tool, monitoring of specific sites have been undertaken as part of the project, which provided evidence of important mixing processes at the system scale. Once the tools were fully developed they were tested on existing mining systems.

Another aim of the LoCAL project was to overcome the hydrochemical barriers to effective heat transfer from raw and treated mine waters. Ochre clogging is a well-known phenomenon which affects a lot of mine water pipelines. It is particularly important in case of heat transfer from mine water, because ochre can not only affect flow, but also the heat transfer process itself, at least where the mine water used for heat transfer is rich in dissolved iron. Therefore, within LoCAL two types of strategies have been explored. The first comprises preventative methods for ochre clogging of subsurface pumps and pipework during open-loop heat-pump exploitation of mine waters. The second type comprises approaches suited to closed-loop strategies for oxidised, ochre-precipitating mine waters in treatment ponds.

The LoCAL project have not only covered technical and engineering issues, but also provided models for efficiency of energy extraction and distribution. For this purpose technical, legal, managerial and cost-benefit analyses of various types have been performed. Ownership, management and financial models were studied in order to assess the accessibility to subsidies with different ownership models. Responsibility for contamination and licensing aspects with different ownership models have been taken into consideration. Pathways to market uptake of mine water-sourced heat pump systems have also been investigated. As the mine water can potentially serve not only as a source for heating but also as a sink for cooling, models for incorporating cooling into delivery systems have been developed as welll. The project have also provided a web-based toolbox comprising all models and tools developed by the LoCAL project.

Project activities were simultaneously undertaken in mining areas of the UK by research organizations in partnership with industrial enterprises. University of Glasgow in partnership with Alkane Energy Ltd. have implemented pilot applications in UK: Caphouse Colliery, Overton, near Wakefield, Yorkshire and Markham Colliery, Bolsover, Derbyshire. In Spain University of Oviedo and industrial partner HUNOSA have performed pilot implementation at Barredo shaft in Mieres, Asturias, while in Poland Central Mining Institute in partnership with Armada Development have performed pilot application in former Szombierki mine at Bytom, Upper Silesian Coal Basin.

The results obtained by LoCAL project together with the assessment of their usefulness and possible exploitation are summarized and concluded below on a task by task basis.

WP1. Bespoke tools for investigating flow and heat transfer in flooded mineworkings

Task 1.1 A new tool for heat transfer modelling in flooded mine workings

Within Task 1.1 two novel simulation tools were developed in order to provide realistic predictions of flow-coupled heat transfer in flooded mine workings. These tools allowed for two different scenarios of geothermal exploitation to be studied: (1) PANR- Pump and discharge with an open-loop system; and (2) PAAR- Pumped abstraction with reinjection. The tools were used to predict system behavior in response to pumping at the Barredo site (which could be checked against measured observations) and the Manvers site to predict seasonal heating and cooling effects.

Task 1.1 resulted in two predictive tools for determining the sustainability of mine water geothermal resources that were subsequently applied to sites in Spain and in the UK. The LoCAL-

PANR (Pumped Abstraction–Natural Recharge) tool was developed to predict the flow temperatures with time for scenarios utilizing pump and discharge open loop heat exchange, such as the one implemented at Barredo, Spain. The LoCAL-PAAR (Pumped Abstraction–Artificial Recharge) tool was developed to simulate heat transfer in dipole open loop mine water geothermal systems, as is intended for the Manvers site. These tools were subsequently applied to the Bytom site in frame of task 1.3 to predict the performance of geothermal extraction from post-closure mine waters.

The tools developed in Task 1.1 can be used to estimate pumped water temperature and its evolution with time for two separate mine water geothermal exploitation scenarios, pump and discharge and dipole/reinjection, and can there be used to acquire knowledge about the viability and sustainability of a mine water geothermal system. This is further evidence by their successful application to Polish mine water studies in Task 1.3.

Task 1.2 Quantifying important mixing processes at the system scale

Task 1.2 tackled hydrological characterization of mine water bodies. This was mainly achieved through 12 months sampling programs at four study sites across project partner countries. Tuning of analytical equipment for mine waters was achieved via matrix analysis of waters from Florence Mine, West Cumbria. A sampling guide was developed so that all partners followed the same protocol. Stratification in mine workings was investigated using temperature data at the Markham and Barredo sites. These efforts informed the other tasks of WP1 and feed directly into the additional deliverable on CO_2 storage in mine waters. The analytical suite that was developed for task 1.2 has since set the benchmark in terms of both mine water, and geothermal water sampling. One of the major challenges of analyzing these waters is the high concentration of several parameters. For a standard analytical set up for chemistry determination this usually requires dilution of samples which can impact on the accuracy of measurement for lower concentration ions. With increasing interest in minewater geothermal studies, the laboratory facilities in Glasgow are now in an excellent position to become the *de facto* center for minewater analysis in the UK. Task 1.2 have also used data from the Markham and Barredo-Figaredo sites to provide valuable insights into the use of natural tracers. The measured salinity of waters sampled at Markham show distinct values associated with increasing depth in the mine shaft and show a strong indication of at least three separate stratified layers. This is an important observation as it demonstrates the value in salinity tracers for determining stratification maintenance and the extent of hydrological mixing in proximity to the extraction pump interface. The Barredo-Figaredo study shows that mine water temperature in that system is directly, and heavily, influenced by the pumping rate, i.e. the more water that is extracted from the system, the warmer Barredo’s water and the cooler Figaredo’s water. This demonstrates that minewater temperature can play a key role in tracing water origin and flow direction.

Task 1.2 have also investigated the feasibility of CO_2 storage in flooded mine workings. The long-term fate of injected CO_2 is influenced by many variables, including reservoir structure, pressure and temperature conditions, and hydrodynamics and geochemistry of reservoir waters. The extent of the effect of the main migration and CO_2 trapping mechanisms depend on the local conditions formed by these variables in the storage water reservoir and its surroundings. The conditions within storage reservoir waters are also likely to change through time due to a combination of natural processes and engineered induced interactions due to both injection of CO_2 and the introduction of a substantial volume of fluid to the storage location. To gain a real understanding of these processes and to confidently predict the behaviour of injected CO_2 in flooded coal mine systems requires detailed water reservoir characterisation, and accurate modelling and simulation of the fate of injected CO_2. Subsurface CO_2 storage in coal mine systems will likely preclude the most secure type of geological trapping mechanism, residual saturation, and place a large emphasis on solubility trapping. This could have major geochemical ramifications for the geochemistry of the mine water reservoir (including risk of enhanced iron in solution) and would rule it out as a resource for future geothermal application.

The work with Task 1.2 allowed for thorough hydrochemical and isotopic characterization of mine water bodies at four separate sites in three different countries. The understanding developed for the ground water system at each site allowed for unique insights into water mixing behavior and mine water composition stability in response to abstraction. It also allowed for insight into the feasibility of CO_2 storage in mine water systems and the geochemical impact that dissolved CO_2 would have on mine water.

Task 1.3 Demonstration of new tools on a system in development

Task 1.3 focused on application of tools developed in Task 1.1 to simulate mine water flow and heat transfer. The tools were applied to three Polish mine water sites; Szombierki (which also included data from Task 1.2) and Powstańców Śląskich (both in Bytom) as well as Dębieńsko. All of which are abandoned, but still feature active pumping to prevent flooding of active neighboring mines. Simulations consisted of a 200 year timeline in order to gauge the long term impact of the thermal resources. The simulations were informed by activities in Task 1.2 for Bytom, and legacy data for the other two mines. The propagation of cooling effect, represented by the increase of depth of non-dispersed front, is predicted to be only around 50 meters during 200 years of simulation in all three simulated mines. Consequently, no significant depletion of pumped mine water temperature is expected within the simulated 200-year time frame.

Task 1.3 utilized information in the previous tasks to ascertain the sustainability of future geothermal exploitation in three abandoned, but as yet, unflooded Polish mines. The results obtained suggest that all three mine systems could be sustainably used for geothermal energy generation for at least 200 years.

The results of WP1 have been of great relevance to the international mine water geothermal community. The work has so far resulted in seven peer reviewed publications in internationally regarded journals and contributed to a conference proceedings paper and a conference poster.

WP2. Overcoming the hydrochemical barriers to effective heat transfer from raw and treated mine waters

Task 2.1 Preventative strategies for ochre clogging of subsurface pumps and pipework during open-loop heat-pump exploitation of mine waters.

In frame of Task 2.1 field trials to test different methods have been conducted to overcome the ochre clogging issue:

Method 1: Prevent the mine water from coming in contact with air

Method 2: Test the effectiveness of using environmentally benign sodium hydrosulphite in suppressing the ochre formation

For the first method, trials have been made in Markham: mine water is prevented from getting oxygenated, and a prophylactic shell and tube heat exchanger is used to prevent the GSHP from coming in direct contact with mine water. The mine water is extracted and injected back into the same shaft. Periodic analysis of the water samples, filters and heat exchanger have been carried out, while preventing the circulating mine water from coming in contact with oxygen. The testing carried out included additionally monitoring of flow rates on a daily basis and check for any signs of reduction in flow rate due to ochre clogging.

In Caphouse the mine water has an iron content of circa 30 mg/l and is partially oxidised in the pumping shaft, and, due to this, the pumped water is rich in ochre. For these conditions, method 2 was tested in this site, in order to test the effectiveness of the ochre suppression equipment in an open loop heat pump configuration. A pilot plant was installed in order to develop the study.

In Barredo the mine water has an iron content not very high, circa 5 mg/l, and even although the system was redesigned to avoid water being in contact with air, ochre clogging is produced in the filters and in the prophylactic plate exchanger. Periodical maintenances are required because of the reduction in the COP of the geothermal system..

When the mine water quality is good and the total content of iron in water is low, like in Markham where is less than 0.5 mg/l, very little deposition was noticed in filters, pipes or heat exchangers. Thus, in these cases, by preventing the mine water from coming in contact with the oxygen, the ochre clogging can be minimised to a great extent.

When the total iron content increases, for example in Barredo, the results obtained with the use of mine water that has not yet been in contact with the air indicate that under some conditions the clogging is produced. The observation of small ochre particles on sample filters, suggests that the iron in the water could be already partially oxidised underground to form small ochre flocs that produce major aggregates of iron oxy hydroxides and should be the cause that filters, pipes or heat exchangers become clogged, even although they are prevented that be in contact with air. In

Barredo the effects of clogging is clear in plate exchanger while the effects in the tube exchangers is almost negligible.

What concerns to the use of oxidized mine waters in ponds with closed loop heat pump systems, there have been observed that there is a potential minor effect of ochre clogging of the heat exchanger's exterior surfaces. This is indicated by a general very modest decline in experimental heat exchange capacity of the closed loop heat exchanger with progressive accumulation of ochre (and tentative indications of a recovery of exchange capacity following desludging of the aeration lagoon).

The LoCAL project has demonstrated that iron-rich mine water can be used in heat exchange systems provided that it is not allowed to come into contact with atmospheric oxygen (or other oxidising agents), or by the use of chemical reducing agents, in both cases it is intended that iron remains in its soluble ferrous (Fe2+) form.

Not all mine waters are sufficiently chemically reducing to rely on iron always being present in its ferrous form. Indeed, it seems there are mine waters where oxidation of iron has commenced in the underground workings or shafts, such that ochre particles can be observed in the raw water. This can be the cause why ochre clogging occurs, even where access to the atmosphere is precluded in the surface headworks (Caphouse, Barredo).

The presence of modest quantities of ochre particles does not necessarily render a heat exchange scheme unworkable, and can be managed by a degree of maintenance. (e.g. Caphouse, Barredo)

The use of chemical reducing agents, like sodium dithionite, contributes to mitigate ochre precipitation because iron remains reduced and soluble, and it doesn't seem affect environment.

Advection of mine water in a pond where a closed loop heat exchanger is placed increases its heat exchange capacity (Markham), although there is a potential minor effect of ochre clogging of the heat exchanger's exterior surfaces, as indicated by a general very modest decline in experimental heat exchange capacity of the closed loop heat exchanger with progressive accumulation of ochre.

Task 2.2 Closed-loop strategies for oxidised, ochre-precipitating mine waters in treatment systems.

In frame of Task 2.2 laboratory tests with sodium dithionite to inhibit ochre fornation have been carried out with good results. In the laboratory study of Barredo mine water, the results have shown that the use of sodium dithionite doses over 60 mg/l are successful to hinder the oxidation and precipitation of ferric iron. Moreover the sodium dithionite hasn't modified the environmental quality of water before been discharged to river.

For the purpose of studying the effects of the ochre hydrochemical barriers in oxidized mine waters, thermal response tests (using a "GeoCube" rig) were carried out on a closed loop heat exchange system installed in the main aeration treatment pond at the Caphouse site. The results can be used to assist in the interpretation of thermal response tests, monitor mine water pumping and monitor the thermal behaviour of the treatment system over an annual cycle.

Finally, a comprehensive series of laboratory experiments has been undertaken to evaluate the temperature dependent kinetics of ochre (ferric oxyhydroxide) precipitation. A series of experiments at various controlled temperatures have been carried out to investigate the kinetics of ferrous iron oxidation and of ferric iron hydrolysis.

Laboratory analyses have shown iron oxidation and hydrolysis is temperature dependent, with rates increasing as temperature increased in the range 5 – 45°C.

When the mine water quality is fairly good and the total content of iron in water is low, like in Markham where is less than 0.5 mg/l, very little deposition was noticed in filters, pipes or heat exchangers. Thus, in these cases, by preventing the mine water from coming in contact with the oxygen, the ochre clogging can be minimised to a great extent.

The experiments with dosing the mine waters with sodium dithionite ($Na_2S_2O_4$) prior to heat exchange, in an attempt to maintain iron in reduced form in solution have been successful, and these reducing agents can be regarded as relatively environmentally benign

With regards to the dissemination of results, several scientific papers have been published in peer reviewed journals and presented in international conference what facilitates the diffusion of the knowledge

WP3. Models for efficiency of energy extraction and distribution

Task 3.1 Technical, legal and management STEEP/ cost-benefit analysis of various types of decentralised heat pump system, versus centralised plant room system

In frame of task 3.1, two variants of heat systems, centralized and decentralized have been analyzed. As a beginning, a common matrix both for centralized and decentralized system was prepared. As part of the project an analytical model (analytical tool for investors) has been developed that uses the collected data from other tasks, and allows to analyse the cost-effectiveness of thermal energy use from mine waters. The model focuses on the technical possibilities of using mine water for the thermal energy purpose, the financial aspects of the reality of the investment implementation and its profitability, as well as on the identification of economic and environmental reasons, which speak of the ultimate profitability of the investment.

The method developed was used to calculate specific examples. The analysis was made for available solutions by Markham UK and Barredo (ES). Both installations are in different countries, so their analysis takes into account different regional conditions. In addition, both installations are designed on a different rock type. Barredo installation generates several dozen times more annual energy, so both solutions can’t be compared with each other.

The results of the analysis for the Markham installation show that it is an expensive way of thermal energy pumping. This is due to the fact that the installation works on a small scale. With such assumptions, it seems more profitable to remain with the current source of thermal energy. However, there is a high probability that with a large installation producing much more energy, the investment will prove profitable.

The DGC analysis for the Barredo installation shows that it pays to develop this technology on a higher scale. The installation has much higher investment and operating costs, but taking into account its much greater effects (more thermal energy). the investment becomes profitable. The operation of such an installation in the 25-year period seems to be much more profitable than traditional methods of acquiring thermal energy.

The CBA analysis was carried out for the available models, because at the stage of conducting analyzes only access to full investment and operating costs was available for these models. The analysis was carried out for a 25-year exploitation period. Includes all operating costs, investment and replacement expenses, as well as economic benefits for the environment resulting from the use of greener sources of thermal energy.

The analyzes carried out in Task 3.1 show that the use of mine water for thermal energy purposes may prove cost-effective from an economic point of view. At this stage of the work, it was diagnosed that the greatest importance for the profitability of investments is the size of the installation, and the actual amount of thermal energy generated by it.

The experience gathered in this task has allowed to build a general model for carrying out financial and economic analyzes for installations for recovering heat from mine waters. As part of subsequent tasks, a tool was created to model any installations, as well as to compare them with the current source of thermal energy.

Interactive tool for investors gives a technical and economic value for potential beneficiaries interested in investments on hydrothermal energy. Results are available via LoCAL web page.

Task 3.2 Pathways to market

The activities of Task 3.2 included: assessment of the TRL level for the LOCAL’s projects in the three countries; workshop to assess route to markets; on-line survey to assess the knowledge and awareness of the technology within local councils, public, academic and industrial organizations and institutions as well as the development of a small-scale simulator to explain the technology and involve university students in the design and implementations.

This task has analysed the possibilities of market implementations. Such analysis intends to bring research and scientific results of LoCAL projects closer to market. We have used established Technology Readiness Level (TRL) appraisal tools, widely used in the EU, to evaluate all the technical results arising from the project, to establish how far up the TRL scale they have reached during the life of LoCAL. As anticipated, all LoCAL outputs have ranked above TRL 5. For systems at TRL8, the industrial partners have participated in a focused workshop on final delivery to market (TRL 9). To support generic development, an on-line survey was developed for companies, students/academics, local councils and the public to capture their knowledge and understanding of the technology to develop a comprehensive commercialisation plan to TRL9. Hence, the industrial partners will then be empowered to take forward the advancement of all outputs to TRL 9.

Task 3.3 Models for incorporating cooling into a delivery system

The task 3.3 has been performed by means of a thorough review report, which includes an examination of the climatic conditions which permit the adoption of free cooling (heat exchanger only) and active cooling (incorporating a heat pump). The report also contains a specific section regarding the means by which cooling has been adopted at the Spanish (Barredo) study site. As it was eventually decided not to incorporate cooling at the Polish study site, two additional real-life studies have been incorporated into the report: that of Heerlen (Netherlands) and Springhill (Canada).

The thermodynamic analysis of the systems has been accomplished by the development of three spreadsheet analytical models. In addition to purely thermodynamic / heat transfer data, these spreadsheets also allow analysis of economic and energetic efficiency of various cooling solutions.

The outputs of the project have been completed in form of a report, comprising two parts:

- Part 1 examines various modes by which a cooling component can be incorporated into mine water heating schemes (passive vs active cooling, reversible heat pumps, district cooling networks, manipulation of mine reservoirs as thermal energy stores).
- Part 2 documents three examples of mine water schemes which have implemented a component of groundwater cooling in practice: Barredo (Asturias, Spain), Springhill (Nova Scotia, Canada) and Heerlen (Netherlands)

Three Excel based spreadsheet models, which assess the thermal and economic performance of various options for incorporating cooling into a mine water (or other groundwater-based) system:

- Model 1. simulates the incorporation of cooling into active (heat pump-driven) systems. The model simulates both heating-dominated or cooling-dominated systems.
- Model 2. simulates both straightforward passive cooling performed by mine water, and the incorporation of an element of passive cooling into an active cooling / heating system.
- Model 3.simulates the use of “chillers” and heat pumps performing cooling and heating simultaneously in a system.

Task 3.3 has resulted in a comprehensive state-of-the-art review of arguably the three largest minewater-based heat pump systems, which incorporate cooling, active in the world today – Barredo, Heerlen and Springhill – and the different means by which heating and cooling are delivered to customers.

The three spreadsheet based models are also all freely available in the public domain via ResearchGate and the Toolbox facility at the LoCAL website (http://www.local.gig.eu/index.php/toolbox).

Task 3.4 Ownership, management and financial models; accessibility to subsidies with different ownership models and responsibility for contamination / licensing aspects with different ownership models

In frame of Task 3.4 an analytical model (analytical tool for investors) has been developed that uses the collected data from other tasks, and allows to analyse the cost-effectiveness of thermal energy use from mine waters. The model focuses on the technical possibilities of using mine water for the thermal energy purpose, the financial aspects of the reality of the investment implementation and its profitability, as well as on the identification of economic and environmental reasons, which speak of the ultimate profitability of the investment.

Task 3.4 produced also the survey questionnaire for potential investors which further became a one of main part of interactive tool for investors (available at: http://www.local.gig.eu/index.php/businessman). Also elaborated algorithms were utilized as an engine for above mentioned tool.

Task 3.5 Toolbox assuring multiplication of the project results

Main result of Task 3.5 is a toolbox which allows to utilize LoCAL project results in "user friendly way".LoCAL Project Toolbox is a web page space containing all tools elaborated within LoCAL project, which are categorized in three categories: Science, Engineering and Economy. LoCAL Toolbox was designed for end-users interested in uptaking heat from minewaters. It's value was tested in real conditions and for technological purpose at the ARMADA pilot site. For analytical purposes three possible paths of Toolbox use has been prepared. Every path is focused on different goal, and shows simple roadmap how to use different tool in specific cases. Suggested paths are addressed to science, business, and official representatives, below main subpages of Toolbox and way of its use were described:

- Scientist's path - path suggested for scientist allows to make full use of elaborated tools.
- Businessman's path - path suggested for business starts from interactive tool for investors (economy) and allows for fast indication of potential value coming from heat extraction from mine waters. Second step of analysis allows to go deeper in technical aspects of cooling and heating process
- Official's path - Suggested path for officials focuses mainly on socio-economic aspects from interactive tool for investors with specific use of CBA analysis that allows to indicate environmental and social aspects of heat extraction from mine water.

Toolbox is free of charge and it is available at: http://local.gig.eu/index.php/toolbox.

WP4. Pilot Implementations

Task 4.1 Pilot implementation at Markham site (UK)

LoCAL project pilot applications in UK have been implemented in: Markham Colliery, Bolsover, Derbyshire and Caphouse Colliery, Overton, near Wakefield, Yorkshire.

Markham

The monitoring and telemetry system developed at this site has enabled detailed data gathering on performance. The use of the plant has also been extended to include heating of a 1.5MWe gas reciprocating engine. Low grade heating is required when the engine is on standby for serving calls from the grid for support generation. Previously this was done with an integral 11KW electric heater but the heat pump system now serves this duty at significantly reduced cost. A further development beyond LoCAL will be to implement heat recovery and storage from when the engine is running to add to the heat resource available for the site.

Caphouse

Operation of both the open loop and closed loop (energy blade) systems have been carried on Telemetry was installed to provide detailed real time monitoring of the system and electronic data gathering. The dosing equipment has been installed to inject sodium dithionate into the raw minewater feed prior to the heat exchangers. The dosing process has been automated based on monitoring of minewater quality parameters. Data have been gathered on the performance of the dosing process in inhibiting the build-up of ochre in the heat exchangers and pipework. Pilot implementation at Caphouse was not planned at the project start, however it have replaced the application at Manvers initially planned in Technical Annex.

Manvers

The experiences at Manvers have illustrated the many and complex issues which need to be resolved to develop a mine water heat project using boreholes. Whereas at Barredo, Caphouse and Markham use existing mine entries (shafts) where the process may be relatively simple, to develop a new project involving drilling of boreholes can be much more complex with various permissions and licences being required, some of which are interdependent. The time and cost resource in seeking to secure these consents may be substantial, and represent a risk of being 'sunk' costs and effort should the project not proceed. Smaller projects, which may be commercially viable in terms of infrastructure costs, may become non-viable if carrying considerable development costs for permits, surveys etc. The cost of such work can add years to the payback period for smaller schemes.

It was not possible to secure the necessary permits from the Coal Authority to enable the Manvers pilot to go ahead within the lifecycle of the project. As well as this being dependent on other permissions being in place (for instance the Coal Authority permit requires planning consent, property rights, Environment Agency permits all to be secured) the key sticking point is that they required Alkane to surrender coal mine methane licence (which relates to core business of the company) prior to issuing the mine water heat consent. Alkane were not prepared to do this as it would have had a significant negative impact on its core business. In addition the requirement for Habitat surveys (birds) also added to the burden of regulatory requirements.

Despite not being able to drill the test borehole, the lessons and experience in seeking to develop the project are valuable in informing other work packages particularly WP3. The fact that the various protection regimes in place are barriers to implementation of a green energy solution is a matter of concern and a lighter touch by Regulators is necessary.

Task 4.2 Pilot implementation at pilot site in Asturias (ES)

Spanish pilot implementation have been performed at Barredo shaft in Mieres, Asturias. In the initial plan only two installations (Hospital and University) were meant to develop this task. But in 2016 another installation was built and it started to operate in May 2016 so the results of this installation were of course very useful to fulfill the objectives of this task. This project was in the FAEN (Asturian Energy Foundation) building very close to Barredo Shaft

From the real experience of three installations in Barredo Shaft in Asturias it was possible to accomplish the following aims:

- Once the final pumping system of the flooded mine is active there are no changes in the COP if the mine water is pumped from different levels.
- When there is enough water it is not useful to use reinjection or use water with different temperature to improve the COP in the geothermal system
- Tubular heat exchangers are without doubt much better than plate heat exchangers. The second ones only are useful in installations of low power and when the working periods are only half year.

The main conclusions of the task can be summarized in the following lines:

- 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 once and it was completely clean.
- In FAEN installation the result is the same, it is in operation since May 2016 and there is no need to clean the heat exchanger. It is different in the University Installation where there is a need 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.
- The great amount of water available in Barredo Shaft helps to control the COP in each installation, so there is no important reduction in the COP during the normal operation when the heat exchanger is dirt with iron.

Task 4.3 Pilot implementation at pilot site in Bytom (PL)

Pilot site is located in Bytom on post mining area where polish project partner - Armada Development, continues its activity of land reclamation as golf course club and housing development. The proximity of mine water discharge from abandoned but still dewatered Szombierki mine was the reason for using renewable energy as the main source for heating at the planned residential area. All main objectives regarding, pilot project, installation and testing were fulfilled.

The designed and implemented heating system in Armada Bytom powered by the heat of mine water works properly, and gives satisfying result. During the low daily temperatures it gives significant cost savings for heating purposes. With the COP of 3 it can be indicated that by the cost of 1 kW of electrical energy 3 kW of heat energy can be obtained. Gathered measurements data from the system indicates also a potential for its optimization. Implemented and tested system is fully multipliable, and will be hopefully implemented by Armada in the future for new house estates promoting the low carbon economy based on flooded coal mines.

Apart from described above pilot implementation at ARMADA site, company due to the proximity of the pipeline with mine water considering the possibility of using heat from the mine water to heat buildings (CO) and water (CWU) in planned multi-family buildings in future housing estates. The planned multi-family housing estate will consist of 29 multi-family buildings, where 685 flats will be built, with a total usable area of 36,479 m^2.

The technical implementation and technical solution for the pilot site resulted from preliminary analysis and were a basis for conducting feasibility study for implementation of such solutions. The pilot site was also equipped with monitoring instrumentation to provide information about the mine water temperature evolution, process efficiency and heat loads delivered. Based on analysis of the pilot site, a report summarizing the results of system implementation and recommendations for future expansion has been prepared.

Installation at Armada site have been equipped with measuring devices for testing its efficiency. Main parameters that have been measured are: circuit temperature, energy consumed from grid and heat energy introduced into heating system.

All local project results are available via project website http://www.local.gig.eu/index.php/results

2. SCIENTIFIC AND TECHNICAL DESCRIPTION OF THE RESULTS

WP1. Bespoke tools for investigating flow and heat transfer in flooded mineworkings

Main objectives

WP1 focused on robust diagnosis of mine water dynamics at the LoCAL field sites, simulation of geothermal energy extraction at LoCAL said sites, and predictive modelling of geothermal energy extraction at further sites under investigation.

The stated objects of WP1 were as follows:

- Develop a modelling tool for advective heat transfer in flooded coal mine workings, building on existing coal mine pond flow algorithms, to enable realistic evaluation of heat and mass transfer during ground-source heat exploitation of coal mine workings.
- Extend existing natural tracer testing approaches (already applied for pollutant migration in flooded coal mines) for the profiling of thermal mixing dynamics in static and pumped flooded coal workings.
- Test the combination of these two tools to a proposed new coal mine water source heat-pump system.

Description of activities and discussion

WP1 comprised of three tasks and eight deliverables which included both physical and simulated investigations into the geothermal resource potential of flooded mine workings and the sustainability of heat extraction from mine water. The findings of WP1 helped inform the pilot projects (WP4), the challenges associated with their operation (WP2) and STEEP analyses (WP3).

Within Task 1.1 two novel simulation tools were developed in order to provide realistic predictions of flow-coupled heat transfer in flooded mine workings. These tools allowed for two different scenarios of geothermal exploitation to be studied: (1) PANR- Pump and discharge with an open-loop system; and (2) PAAR- Pumped abstraction with reinjection. The tools were used to predict system behavior in response to pumping at the Barredo site (which could be checked against measured observations) and the Manvers site to predict seasonal heating and cooling effects. As part of activities Oviedo team member Covadonga Loredo spent 3 months in Glasgow as a visiting researcher.

Task 1.2 tackled hydrological characterization of mine water bodies. This was mainly achieved through 12 months sampling programs at four study sites across project partner countries. Tuning of analytical equipment for mine waters was achieved via matrix analysis of waters from Florence Mine, West Cumbria. A sampling guide was developed so that all partners followed the same protocol. Stratification in mine workings was investigated using temperature data at the Markham and Barredo sites. These efforts informed the other tasks of WP1 and feed directly into the additional deliverable on CO_2 storage in mine waters.

Task 1.3 focused on application of tools developed in Task 1.1 to simulate mine water flow and heat transfer. The tools were applied to Szombierki (Bytom), Powstańców Śląskich and Dębieńsko mines. All of which are abandoned, but still feature active pumping to prevent flooding of active neighboring mines. Simulations consisted of a 200 year timeline in order to gauge the long term impact of the thermal resources. The simulations were informed by activities in Task 1.2 for Bytom, and legacy data for the other two mines.

Main results

WP1 included eight deliverables and produced seven peer reviewed publications, a conference proceedings paper and a conference poster. D1.1 and D1.2 resulted in two predictive tools for determining the sustainability of mine water geothermal resources that were subsequently applied to sites in Spain and in the UK. The LoCAL-PANR (Pumped Abstraction–Natural Recharge) tool was developed to predict the flow temperatures with time for scenarios utilizing pump and discharge open loop heat exchange, such as the one implemented at Barredo, Spain. The LoCAL-PAAR (Pumped Abstraction–Artificial Recharge) tool was developed to simulate heat transfer in dipole open loop mine water geothermal systems, as is intended for the Manvers site. These tools were subsequently applied to the Bytom site to predict the performance of geothermal extraction from post-closure mine waters.

The analytical suite that was developed for D1.3 and D1.4 has since set the benchmark in terms of both mine water, and geothermal water sampling. One of the major challenges of analyzing these waters is the high concentration of several parameters. For a standard analytical set up for chemistry determination this usually requires dilution of samples which can impact on the accuracy of measurement for lower concentration ions. With increasing interest in minewater geothermal studies, the laboratory facilities in Glasgow are now in an excellent position to become the *de facto* center for minewater analysis in the UK.

D1.5 used data from the Markham and Barredo-Figaredo sites to provide valuable insights into the use of natural tracers. The measured salinity of waters sampled at Markham show distinct values associated with increasing depth in the mine shaft and show a strong indication of at least three separate stratified layers. This is an important observation as it demonstrates the value in salinity tracers for determining stratification maintenance and the extent of hydrological mixing in proximity to the extraction pump interface. The Barredo-Figaredo study shows that mine water temperature in that system is directly, and heavily, influenced governed by the pumping rate, i.e. the more water that is extracted from the system, the warmer Barredo's water and the cooler Figaredo's water. This demonstrates that minewater temperature can play a key role in tracing water origin and flow direction.

D1.8 investigated the feasibility of CO_2 storage in flooded mine workings. The long-term fate of injected CO_2 is influenced by many variables, including reservoir structure, pressure and temperature conditions, and hydrodynamics and geochemistry of reservoir waters. The extent of the effect of the main migration and CO_2 trapping mechanisms depend on the local conditions formed by these variables in the storage water reservoir and its surroundings. The conditions within storage reservoir waters are also likely to change through time due to a combination of natural processes and engineered induced interactions due to both injection of CO_2 and the introduction of a substantial volume of fluid to the storage location. To gain a real understanding of these processes and to confidently predict the behaviour of injected CO_2 in flooded coal mine systems requires detailed water reservoir characterisation, and accurate modelling and simulation of the fate of injected CO_2. Subsurface CO_2 storage in coal mine systems will likely preclude the most secure type of geological trapping mechanism, residual saturation, and place a large emphasis on solubility trapping. This could have major geochemical ramifications for the geochemistry of the mine water reservoir (including risk of enhanced iron in solution) and would rule it out as a resource for future geothermal application.

D1.6 and D1.7 strongly depended on the results of the other WP1 tasks, especially Task 1.1. The tools developed in D1.1 and D1.2 were applied to three Polish mine water sites; Szombierki (which also included data from Task 1.2), Powstańców Śląskich and Dębieńsko. The propagation of cooling effect, represented by the increase of depth of non-dispersed front, is predicted to be only around 50 meters during 200 years of simulation in all three simulated mines. Consequently, no significant depletion of pumped mine water temperature is expected within the simulated 200-year time frame.

Conclusions

The tools developed in Task 1.1 can be used to estimate pumped water temperature and its evolution with time for two separate mine water geothermal exploitation scenarios, pump and discharge and dipole/reinjection, and can there be used to acquire knowledge about the viability and sustainability of a mine water geothermal system. This is further evidence by their successful application to Polish mine water studies in Task 1.3.

The work with Task 1.2 allowed for thorough hydrochemical and isotopic characterization of mine water bodies at four separate sites in three different countries. The understanding developed for the ground water system at each site allowed for unique insights into water mixing behavior and mine water composition stability in response to abstraction. It also allowed for insight into the feasibility of CO_2 storage in mine water systems and the geochemical impact that dissolved CO_2 would have on mine water.

Task 1.3 utilized information in the previous tasks to ascertain the sustainability of future geothermal exploitation in three abandoned, but as yet, unflooded Polish mines. The results obtained suggest that all three mine systems could be sustainably used for geothermal energy generation for at least 200 years.

Exploitation and impact of the research results

The results of WP1 have been of great relevance to the international mine water geothermal community. The work has so far resulted in seven peer reviewed publications in internationally regarded journals and contributed to a conference proceedings paper and a conference poster. Publications are listed within specific tasks description.

Task 1.1 A new tool for heat transfer modelling in flooded mine workings

Task leader: UOVE

Main objectives

To create a bespoke tool for realistic simulation of flow-coupled heat transfer in flooded mine-workings.

Description of activities and discussion

A revision of the existent models for flow and heat transfer has been undertaken. Based in this review two new applications specifically designed for mine water geothermal systems have been created: One for systems in an open loop without reinjection configuration (PANR) and other for systems in an open loop with reinjection configuration (PAAR). PANR and PAAR are programmed in MS Excel workbooks and can be found at the LoCAL website together with the user guides.

Main results

Along LoCAL project the tools have been tested in real sites in Spain and UK. In the following paragraphs, the main characteristics and functionalities of the two tools will be described using these applications.

The scope of **LoCAL-PANR** (Pumped Abstraction–Natural Recharge) is to predict the outcoming temperature of the flow and its evolution along the time for open loop without reinjection geothermal systems, as the one implemented at Barredo, Spain (Figure 1).

At this system, with four flooded levels and a significant lateral flow, up to four pumps extract the mine water. This way, the previously horizontal groundwater circulation becomes vertical (from the starting of the pumping) and a risk of thermal depletion arises and should be studied.

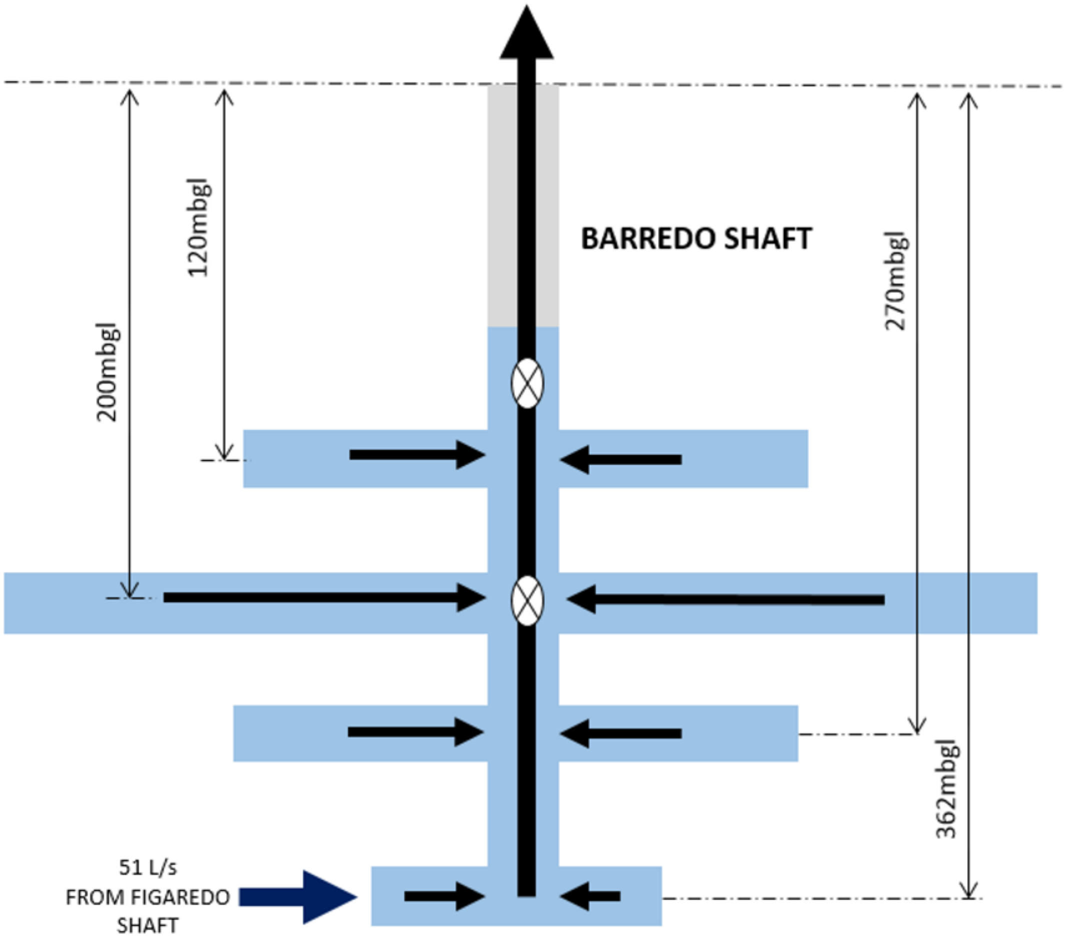
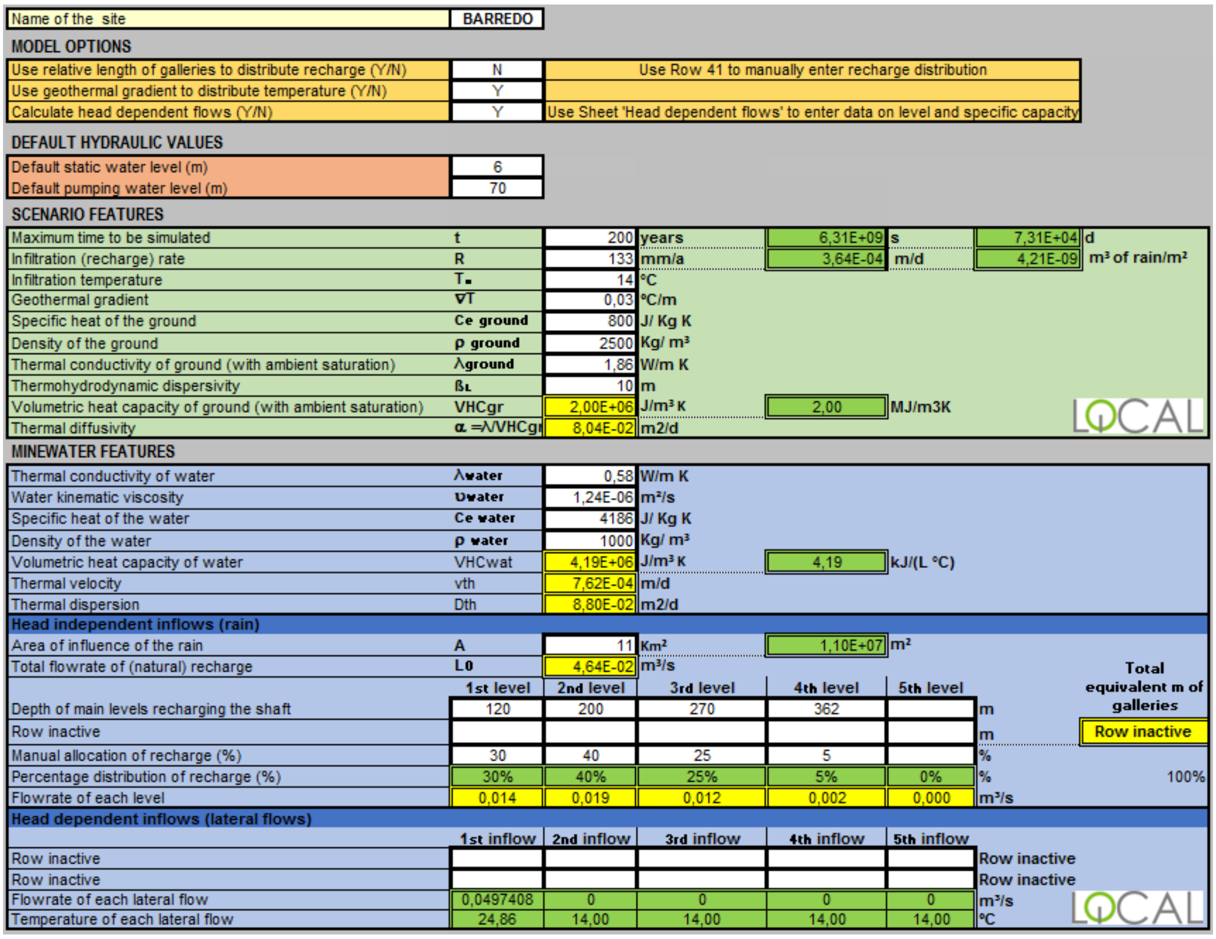


Figure 1. Barredo scheme

Source: University of Oviedo own elaboration

The inputs of the model can be checked at Figure 2, among them a 133 mm/a infiltration rate (rainfall minus evaporation and runoff) at an average temperature of 14ºC, a geothermal gradient of 0.03ºC/m and a 11 Km^2 area of rain influence.



Name of the site	BARREDO

MODEL OPTIONS

Use relative length of galleries to distribute recharge (Y/N)	N	Use Row 41 to manually enter recharge distribution
Use geothermal gradient to distribute temperature (Y/N)	Y	
Calculate head dependent flows (Y/N)	Y	Use Sheet 'Head dependent flows' to enter data on level and specific capacity

DEFAULT HYDRAULIC VALUES

Default static water level (m)	6
Default pumping water level (m)	70

SCENARIO FEATURES

Maximum time to be simulated	t	200	years	6,31E+09	s	7,31E+04	d
Infiltration (recharge) rate	R	133	mm/a	3,64E-04	m/d	4,21E-09	m³ of rain/m²
Infiltration temperature	T	14	ºC				
Geothermal gradient	∇T	0,03	ºC/m				
Specific heat of the ground	Ce ground	800	J/ Kg K				
Density of the ground	ρ ground	2500	Kg/ m³				
Thermal conductivity of ground (with ambient saturation)	λground	1,86	W/m K				
Thermohydrodynamic dispersivity	ßL	10	m				
Volumetric heat capacity of ground (with ambient saturation)	VHCgr	2,00E+06	J/m³ K	2,00	MJ/m3K		
Thermal diffusivity	α =λ/VHCgr	8,04E-02	m2/d				

MINEWATER FEATURES

Thermal conductivity of water	λwater	0,58	W/m K		
Water kinematic viscosity	υwater	1,24E-06	m²/s		
Specific heat of the water	Ce water	4186	J/ Kg K		
Density of the water	ρ water	1000	Kg/ m³		
Volumetric heat capacity of water	VHCwat	4,19E+06	J/m³ K	4,19	kJ/(L ºC)
Thermal velocity	vth	7,62E-04	m/d		
Thermal dispersion	Dth	8,80E-02	m2/d		

Head independent inflows (rain)

Area of influence of the rain	A	11	Km²	1,10E+07	m²
Total flowrate of (natural) recharge	L0	4,64E-02	m³/s		

	1st level	2nd level	3rd level	4th level	5th level		Total equivalent m of galleries
Depth of main levels recharging the shaft	120	200	270	362		m	
Row inactive						m	Row inactive
Manual allocation of recharge (%)	30	40	25	5		%	
Percentage distribution of recharge (%)	30%	40%	25%	5%	0%	%	100%
Flowrate of each level	0,014	0,019	0,012	0,002	0,000	m³/s	

Head dependent inflows (lateral flows)

	1st inflow	2nd inflow	3rd inflow	4th inflow	5th inflow	
Row inactive						Row inactive
Row inactive						Row inactive
Flowrate of each lateral flow	0,0497408	0	0	0	0	m³/s
Temperature of each lateral flow	24,86	14,00	14,00	14,00	14,00	ºC

Figure 2. PANR input data (Barredo)

Source: University of Glasgow own elaboration

With this information, the model calculates a total pumping rate of 96.1 L/s at an initial temperature of 22.5ºC, which is in good concordance with the observations done at the real system. For this flowrate PANR calculates the evolution of the rocks temperature (Figure 3). Here, the striped black line represents the initial temperature profile and the red line the profile at the studied moment. It is possible to see how the thermal wear starts at the shallow horizons and advances vertically within the time.

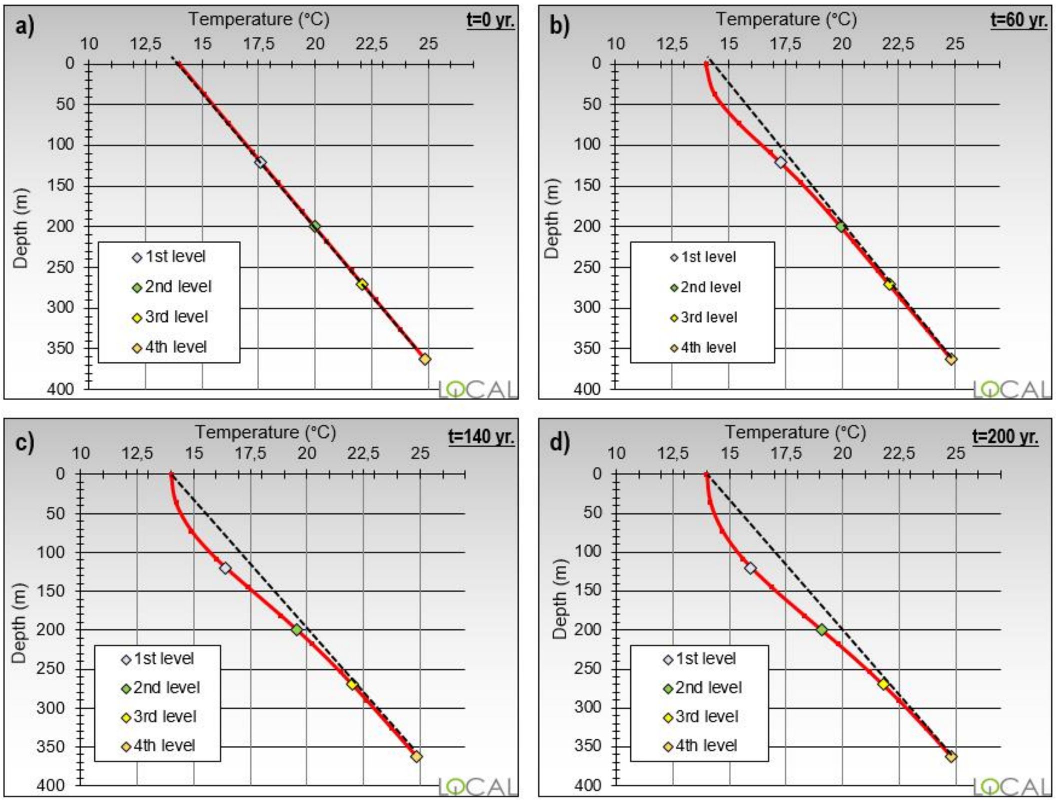


Figure 3. Rocks temperature evolution at a) Initial situation, b) After 60 years, c) After 140 years, d) After 200 years

Source: University of Oviedo own elaboration

The model assumes that within the aquifer the rocks and the mine water are at the same temperature. For this consideration, after a working time of 200 years the temperature decrease would be 0.5ºC (Figure 4) this value, which excess the human horizons, assures the thermal sustainability of the system along the time.

The tool includes an energy calculator that for the given flowrate estimates an available thermal potential of 2.7 MW. This quantity would be higher if the system is to provide not only heat but also cold, as occurs in the reality.

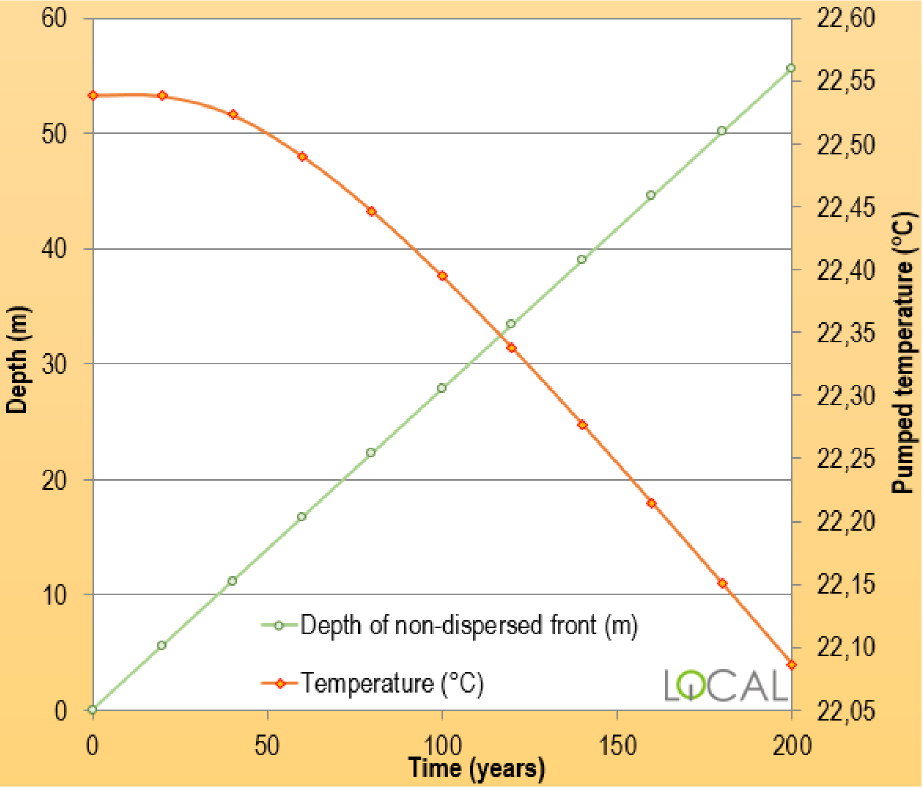


Figure 4. Barredo outflow temperature evolution (PANR)

Source: University of Glasgow own elaboration

The scope of **LoCAL-PAAR** (Pumped Abstraction–Artificial Recharge) is to simulate heat transfer in open loop with reinjection geothermal systems, as the one that could be implemented at Manvers, Figure 5. It should be said that the connections indicated at the figure may be hydraulically sealed but supposing that they are still open, the pathways that the mine water would follow are indicated in red colour at Figure 5 (left).

Figure 5. Map of mining works at Manvers (left) and vertical scheme (right)

Source: University of Oviedo own elaboration

As Figure 5 (right) describes, the mine water would be pump out of the system from the shaft “Nº1/4” and reinjected at the shaft “A”, from here the water would flow by several pathways, along the Swallow Wood seam, towards “Nº1/4” again. In this course, the flowrate will be distributed in a process dominated by the head losses and the water will gain heat in each stretch, proportionally to the flowrate and flow regime.

To do this, the mine roadways geometry (length, radio, distribution) should be indicated by the user at the input data sheet of PAAR (deliverable 1.1, see Annex 1 to the report). With this information, the tool will build the scheme of the pathways and calculate the flowrate distribution and temperature evolution for a given working time.

Supposing that during winter time, a 10 L/s flowrate at 9ºC is injected at the entrance of the system, PAAR calculates the final temperature at the exit of the system (Figure 6).

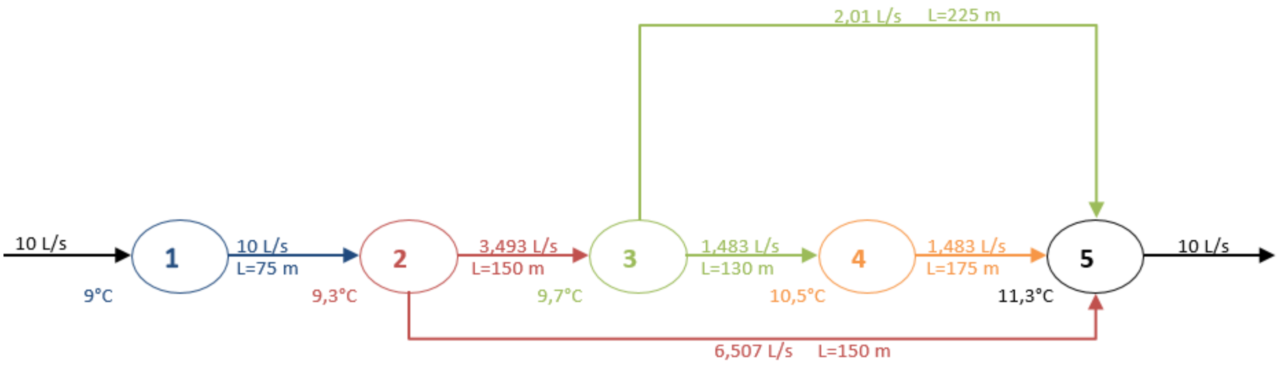


Figure 6. Manvers evolution of the flows and temperatures along galleries (PAAR)

Source: GIG own elaboration

As the outflow temperature will decrease within time it is necessary to simulate working periods with different lengths. By doing this, at Figure 7.a it is visible how initially the outcoming water temperature is about 11.3ºC, this value decreases within time in the first months and stabilises around the fourth month in 10.6ºC.

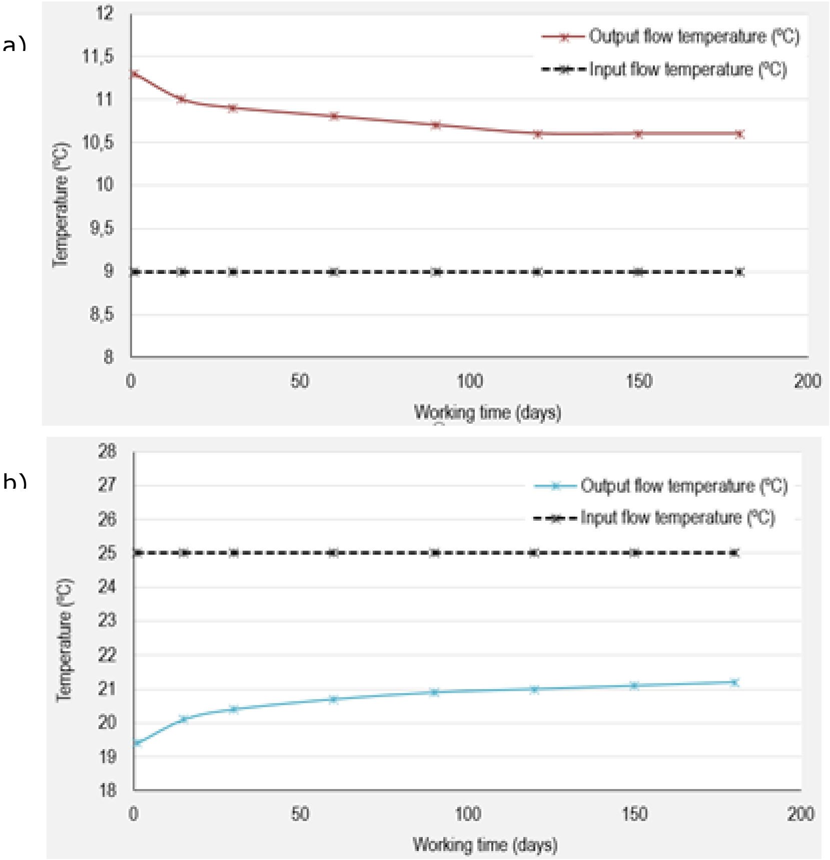


Figure 7. Manvers outflow temperature evolution for a heating season (a) and for a cooling season (b)

Source: University of Oviedo own elaboration

Reinjected systems are specially indicated for work seasonally, i.e. heating in winter (what will thermally deplete the rocks) and cooling in summer (what will thermally charge the rocks).

Following with the example represented at Figure 7.a, after the simulation of a 6 months heating period, the rocks temperature will be about 10.6ºC. Simulating a cooling period, an input flow temperature of 25ºC (temperature that may be attained in an English sunny day) can be assumed. At Figure 7.b it is possible to see how the output flow temperature is cooled initially up to 19 ºC and after 6 months this value increases to 21 ºC, allowing to recover the initially temperature of the rocks (15ºC) and improving the system sustainability.

For the heating season, an energy potential of about 63 KW would be attained (value calculated for a 1.5ºC temperature step). Meanwhile at the cooling season the thermal potential would be around 167 KW (considering a temperature step of 4ºC). It should be remembered that for both cases the use of a heat pump will be required unless free cooling is possible.

Conclusions

The tools developed estimate the outcoming temperature of the flow and its evolution along the time, for different systems of geothermal exploitation, helping to acquire knowledge about the viability and sustainability of a mine water geothermal system.

Exploitation and impact of the research results

The tools designed have been applied to Bytom site, which has allowed to predict the future behavior of the geothermal system after the mine closure. The reported results together with the tools can be found at the CIRCABC web.

A PhD dissertation that includes some of the works elaborated under this task has been done. Besides, in the frame of this task a poster has been presented in a Congress: *Energy and Environment Knowledge Week* 2016 and two publications in indexed journals have been done.

- Loredo, C., Roqueñí N., Ordóñez A., Crespo C., De Cos F.J. The use of mine water in geothermal energy systems: A case study in Asturias. E2KW 2016, 28-29 October 2016, Paris.
- Loredo, C., Roqueñí, N., Ordoñez, A., 2016. Modelling flow and heat transfer in flooded mines for geothermal energy use: A review. Int. J. Coal Geol. https://doi:10.1016/j.coal.2016.04.013
- Loredo, C., Banks, D. & Roqueñí, N. (2017). Evaluation of analytical models for heat transfer in mine tunnels. Geothermics, 69, 153-164. https://doi.org/10.1016/j.geothermics.2017.06.001

Task 1.2 Quantifying important mixing processes at the system scale

Task leader: University of Glasgow

Main objectives

To characterize the hydrological dynamics of flooded mine systems in an effort to better understand water and heat flow behavior.

Description of activities and discussion

Activities focused on the measurement of mine water parameters, investigation of mine water tracing techniques, and latterly assessment of potential for CO_2 storage in mine waters. Practical activities included repeated sampling at four project sites by all partners over a 12 month period and extensive lab work to determine values for several parameters. The analytical suite that was developed for LoCAL has since set the benchmark for mine water analyses. Building on this, natural tracers were utilized to help determine mine water flow behavior in the Markham and Barredo-Figaredo systems. Results of these activities have featured in several highly regarded publications that have raised the profile of the potential for mine water geothermal.

Main results

The two UK sites demonstrate different consistencies with respect to mine water compositions. At Markham, measured composition was consistent throughout the monitoring period. Whilst at Caphouse there was great variation. This is particularly pronounced when comparing recorded data with legacy data from the UK Coal Authority. Cation values have remained relatively constant since 2009. Anion values are a different story: sulphate has decreased in value over time and there has been a relatively recent increase in chloride. There is a marked decrease in SO_4 levels from c. 1200 to 800 mg/l from 2004 to 2007, and a steady decrease from 2007 to modern day values of c. 600 mg/l. Prior to 2015, chloride values typically exhibit concentrations of 120-150 mg/L. During 2015, the proportion of this water appears to have increased, with the chloride concentrations rising above 300 mg/L.

Data recorded from the Barredo-Figaredo and Bytom mines systems, allowed form a more comprehensive lokk and comparison of mine waters from different shafts and mine levels and surface waters that have hydraulic connections to the mines. Mine waters from the Barredo and Figaredo mines are dominated by sodium and bicarbonate/sulphate and very distinct from river waters, which are dominated by calcium and chloride. Interestingly the Mariana mountain mine (situated above the local water table), has a similar cation value to surface waters and similar anion value to mine waters.

In the Bytom System the water chemistries strongly depend on their local source and interactions with other water bodies. Sulfate-rich waters with high concentrations of calcium and magnesium inflow to mine workings of Bolko pumping station in Triassic abandoned Zn-Pb workings (Type I waters). Measurements of mine water quality on each level in the Szombierki mine revealed two main types of water – so called ‘natural inflow’ to level 510 m and 630 m (Type II waters) – sulphate-rich with relatively high concentrations of calcium, mixed water from ZG Bytom II and from bulk pumping station waters at the 630 m level. Discharge from the Centrum mine (Type III waters) consisted of sulfate-rich water with high concentrations of chloride and sodium.

Measurements taken from Caphouse and Barredo-Figaredo demonstrated evidence of mine water quality recovery during flooding of the mines after abandonment. For Caphouse this was mainly manifest through decreasing salinity with time, whilst sulphate and iron measurements at Barredo-

Figaredo demonstrated a clear spike after closure and flooding of the mines before a gradual water quality recovery from 2008 to 2014 (Figure 8).

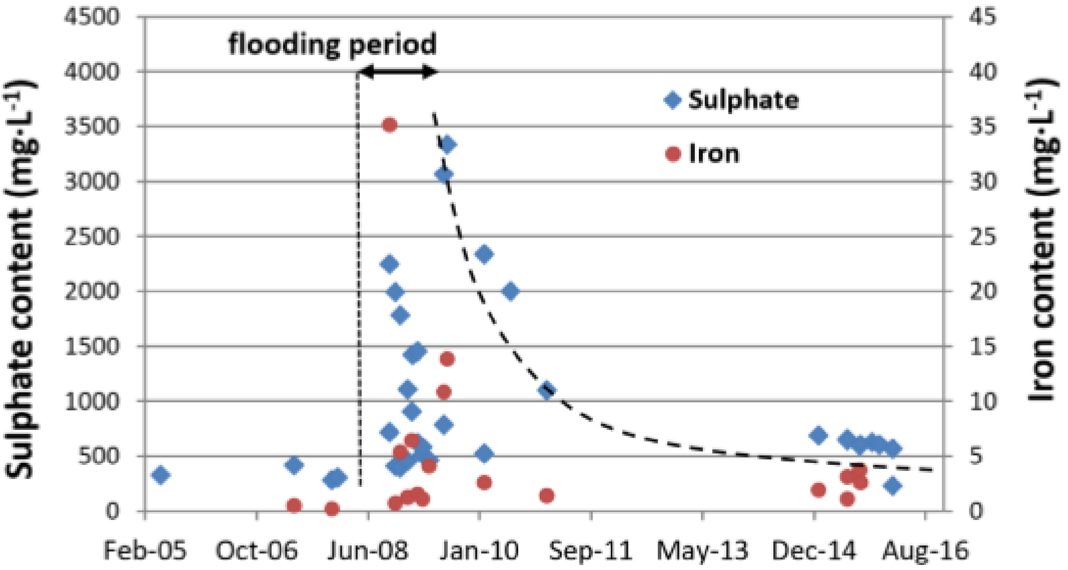


Figure 8. Time evolution of sulphate and iron content in Barredo and Figaredo mine waters.

Source: University of Oviedo own elaboration

O and H stable isotope results of pumped waters from the UK sites provided insight into the origin of the waters (Figure 9). Sample sites include both Markham and Caphouse mine waters and surface waters from the local Holme Brook stream in Chesterfield. Samples were compared to the long term weighted mean value for meteoric water recorded at the nearby Keyworth weather monitoring station. Both mine waters have a similar signal that is unique from surface water values. However, they are very similar to the long term meteoric mean value recorded at Keyworth. It is therefore likely that the mine waters represent a bulk sample of recent (decades) meteoric waters. δ34S data across LoCAL sites demonstrated that each mine, and sections of mines, can display a unique signature. This is especially evident at the Bytom site, which provided the most comprehensive data set (Figure 10).

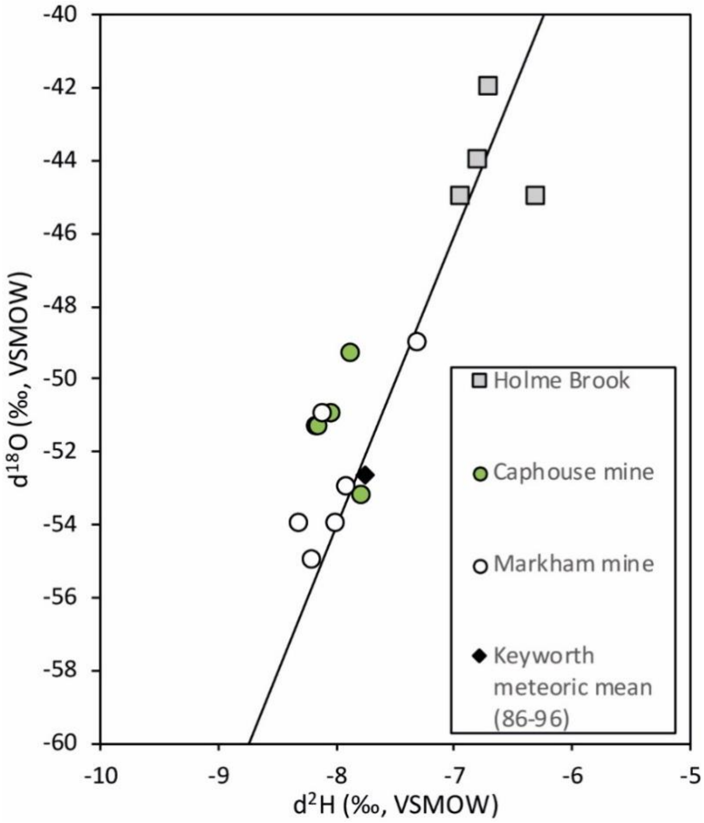


Figure 9. Plot of δ^{18}O versus δ^{2}H isotope values for the second half of the UK sampling regime (December 2015 to June 2016). The solid trend line represents the Global Mean Meteoric Water Line (GMWL).

Source: University of Glasgow own elaboration

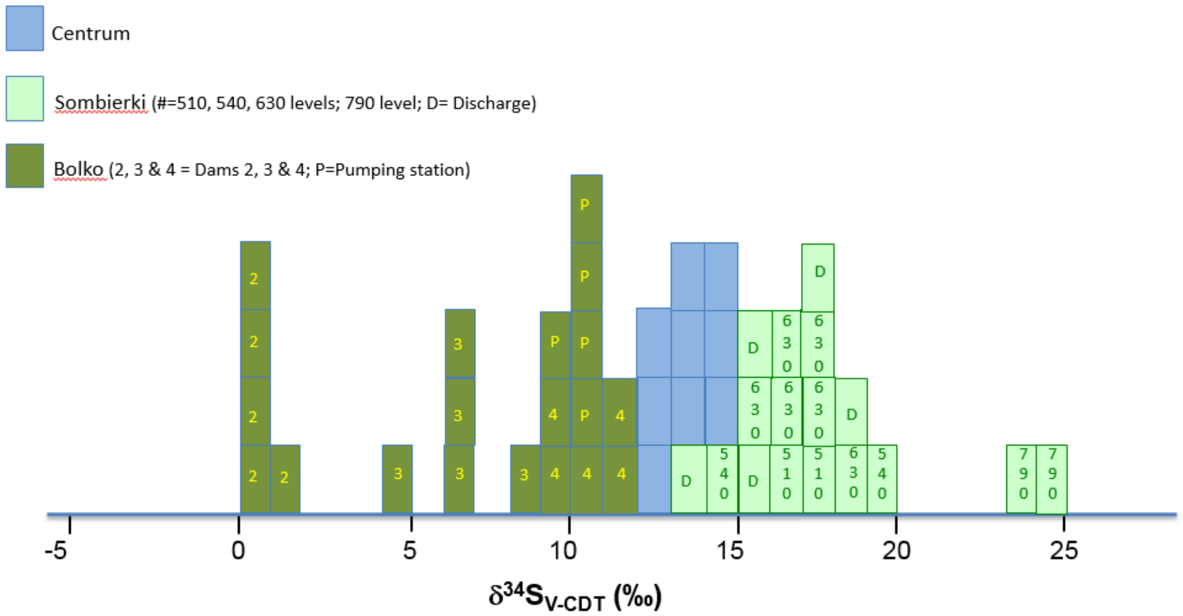


Figure 10. Chart of δ^{34}S values for the Bytom system

Source: University of Glasgow own elaboration

The usefulness of natural and synthetic tracers is highly dependent on the chemical composition and pH of the resident mine waters. Due to their ubiquitous nature, natural tracers can be used over large areas and long timescales. Physical measurements, such water temperature, are comparatively easy to measure and therefore can play a major role in mine water investigations. Natural tracers were investigated at both the Markham and Barredo-Figaredo sites. Salinity measurements at Markham demonstrated distinct values for three separate pumping depths and highlight the usefulness of this parameter for determination of stratification and flow boundaries within the shaft's water column (Figure 11).

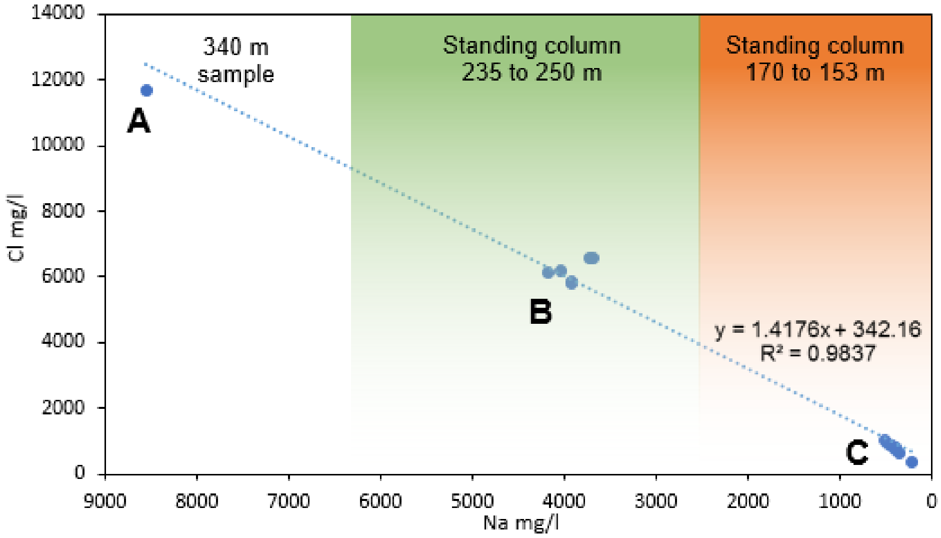
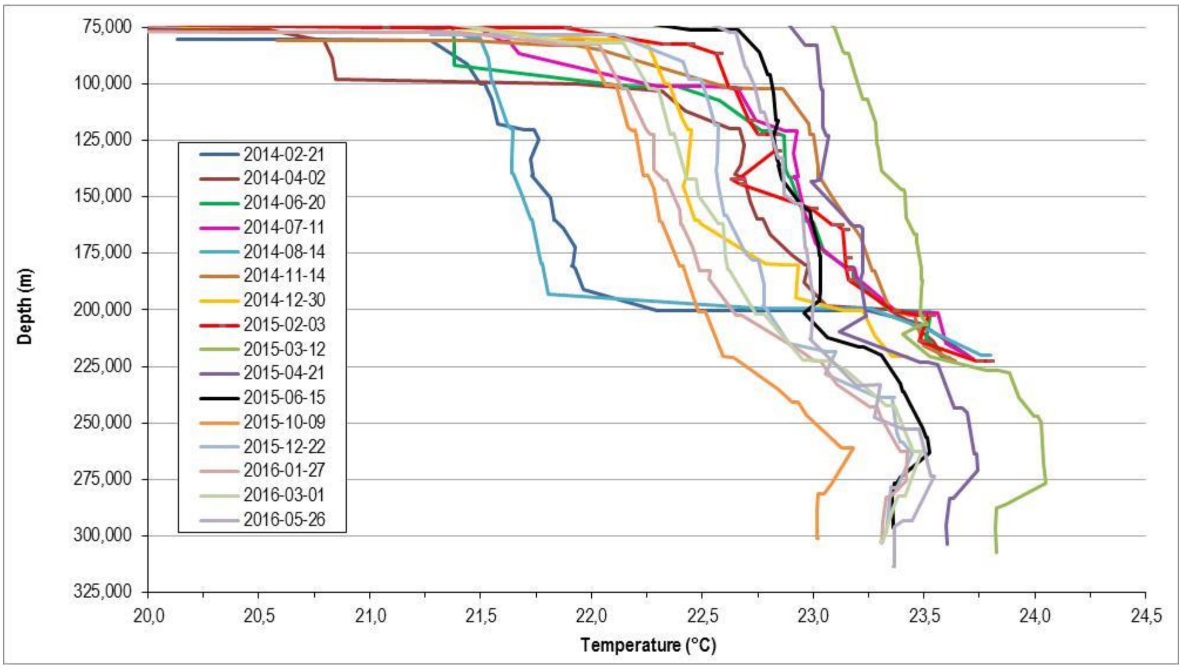


Figure 11. Plot of salinity (Na vs. Cl) evolution throughout alteration of pump depth at Markham. Water types: A- October 2011, B- January 2013, and C- September 2015.

Source: University of Glasgow own elaboration

Temperature measurements at Barredo-Figaredo demonstrate clear impacts of pumping regime in each shaft and indicate increased influence from connected workings as pumping progresses (Figure 12). Barredo has four hydraulic pumps, three of them are placed at 100 m bgl and one (Pump 3) is placed at 200 m bgl. When measuring the thermal profiles, the number of activate pumps was noted, so that the influence of each pump on measured mine water temperatures could be recorded. When Pump 3, the deepest one, is used in isolation, a clear thermal response was evident. This is likely due an increased influence of flow connection between Figaredo and Barredo which leads to an increase of mine water temperature around the connection area at the bottom of Barredo shaft.



	21/02/2014	02/04/2014	20/06/2014	11/07/2014	14/08/2014	14/11/2014	30/12/2014	03/02/2015	12/03/2015	21/04/2015	15/06/2015	09/10/2015	22/12/2015	27/01/2016	01/03/2016	26/05/2016
Pump 1	0	0	0	0	0	0	0	1	1	1	1	0	1	1	1	0
Pump 2	0	0	0	0	0	0	1	0	1	1	1	0	0	0	0	1
Pump 3	1	0	0	0	1	0	0	0	1	1	1	0	1	1	0	0
Pump 4	0	1	1	1	0	1	1	1	1	1	0	1	0	0	1	1

Figure 12. Barredo thermal profile alterations in response to different pumping strategies. Sole use of Pump 3 is highlighted in orange.

Source: University of Oviedo own elaboration

Planned active pilot projects on mine water as a heat source are themselves aimed at obtaining a low-carbon energy source from the remains of the high-carbon past, but also in terms of the CO_2 capture agenda they could, if deep enough, be considered as potential CO_2 storage zones (Figure 13).

The safest way to geologically store CO_2 is in the supercritical, dense phase. The critical point, or saturation line, for supercritical CO_2 is 31.1°C and 73.8 bar, storage temperatures and pressures must be beyond these values to maintain dense phase behaviour. Vertical pressure is equal to the product of substance density, depth and acceleration. Utilising typical density values for water (ca. $1g/cm^3$) and an acceleration equal to gravity (ca. $10m/s^2$), hydrostatic pressure gradient is typically 100 bar /km. This means a depth of greater than 740 m is required for supercritical CO_2 in most cases.

Geothermal gradients are more variable and are there for highly site specific. In the case of the Markham Colliery the geothermal gradient is 28°C/km and the mean surface temperature is 10°C, so a depth of at least 820 m would be required for storage of supercritical CO_2. For practicality, a greater depth would be required to keep clear of the phase transition boundary.

As CO_2 dissolves in brine it decomposes into H^+ and HCO_3^- via carbonic acid which would have a direct effect on the geochemical environment within a flooded coal mine system, which is already undergoing dramatic changes in response to post-abandonment flooding. The addition of large volumes of CO_2 for storage could potentially lead to far greater quantities of dissolved iron in solution and impede natural acid mine recovery. In turn this would pose problems for any future use of the flooded mine system as a geothermal resource, as there would be a high risk of ochre precipitation during pumped extraction.

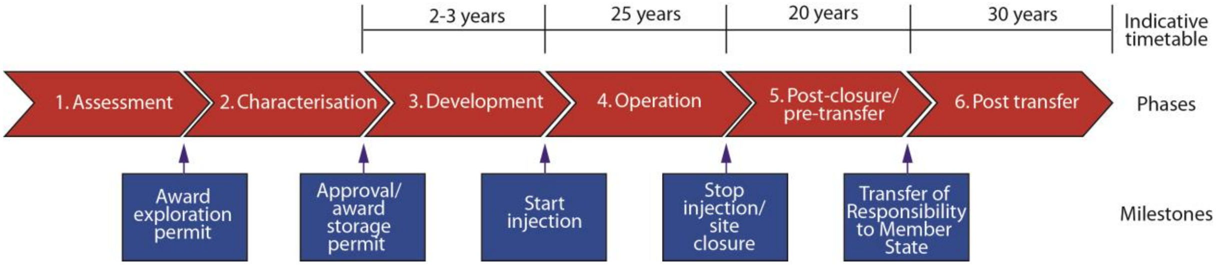


Figure 13. Phases and milestones of the European Commission Directive on the Geological Storage of Carbon Dioxide (2009/31/EC) with indicative timetable for a storage operations.

Source: European Commission Directive on the Geological Storage of Carbon Dioxide (2009/31/EC)

Conclusions

Achievements made within this task include thorough characterization of mine water bodies at four separate sites in three different countries. The understanding developed for the ground water system at each site allowed for determination of water mixing behavior and baseline assessment of sustainable resource extraction. It also allowed for insight into the feasibility of CO_2 storage in mine water systems.

Exploitation and impact of the research results

The results of Task 1.2 have been of great relevance to the UK Coal Authority, who are looking to develop mine water geothermal projects at several of their sites. They have also fed into investigations of the flooded mine water system beneath the University of Glasgow. The work has so far resulted in five peer reviewed publications in internationally regarded journals and contributed to conference proceedings papers:

- Banks, D., Steven, J. K., Berry, J., Burnside, N. and Boyce, A. J. (2017) A combined pumping test and heat extraction/recirculation trial in an abandoned haematite ore mine shaft, Egremont, Cumbria, UK. Sustainable Water Resources Management, (doi:10.1007/s40899-017-0165-9) (Early Online Publication)
- Loredo, C., Ordóñez, A., Garcia-Ordiales, E., Álvarez, R., Roqueñi, N., Cienfuegos, P., Peña, A. and Burnside, N.M. (2017) Hydrochemical characterization of a mine water geothermal energy resource in NW Spain. Science of the Total Environment, 576, pp. 59-69. (doi:10.1016/j.scitotenv.2016.10.084)
- Burnside, N.M., Banks, D., Boyce, A.J. and Athresh, A. (2016) Hydrochemistry and stable isotopes as tools for understanding the sustainability of minewater geothermal energy production from a 'standing column' heat pump system: Markham Colliery, Bolsover, Derbyshire, UK. International Journal of Coal Geology, 165, pp. 223-230. (doi:10.1016/j.coal.2016.08.021)
- Burnside, N., Banks, D. and Boyce, A. (2016) Sustainability of thermal energy production at the flooded mine workings of the former Caphouse Colliery, Yorkshire, United Kingdom. International Journal of Coal Geology, 164, pp. 85-91. (doi:10.1016/j.coal.2016.03.006)
- Janson, E., Boyce, A. J., Burnside, N. and Gzyl, G. (2016) Preliminary investigation on temperature, chemistry and isotopes of mine water pumped in Bytom geological basin (USCB,Southern Poland) as a potential geothermal energy source. International Journal of Coal Geology, 164, pp. 104-114. (doi:10.1016/j.coal.2016.06.007)
- Gzyl, G., Banks, D., Younger, P., Głodniok, M., Burnside, N., Garzon, B. and Skalny, A. (2016) Low Carbon After-Life – overview and first results of project LoCAL. In: International Mine Water Association (IMWA) Conference 2016: Mining Meets Water – Conflicts and Solutions, Leipzig, Germany, 11-15 Jul 2016, pp. 593-599. ISBN 9783860125335

Task 1.3 Demonstration of new tools on a system in development

Task leader: GIG

Main objectives

The objective of this task was to apply the tools developed in frame of task 1.1 in forward mode to investigate the likely behaviour of a proposed new mine water heat pump system. The primary application site was former coal mine Szombierki in Bytom (Poland).

Description of activities and discussion

The coupled model for mine water flow and heat transfer being developed in frame of Task 1.1 have been applied in Poland, in frame of Task 1.3. Primarily, the model have been applied to Szombierki mine in Bytom. Szombierki mine is closed down, while necessity of dewatering is due to interconnections between active Centrum and Bobrek mines. To compare results from modelling in Szombierki mine, coupled model has been also applied to nearby mines Powstańców Śląskich and Dębieńsko. These mines are also located in *Upper Silesian* Coal *Basin (*USCB), and their geological and technical structure are in relation to Szombierki mine. Figure 14 shows the location of USCB and the mines of concern.

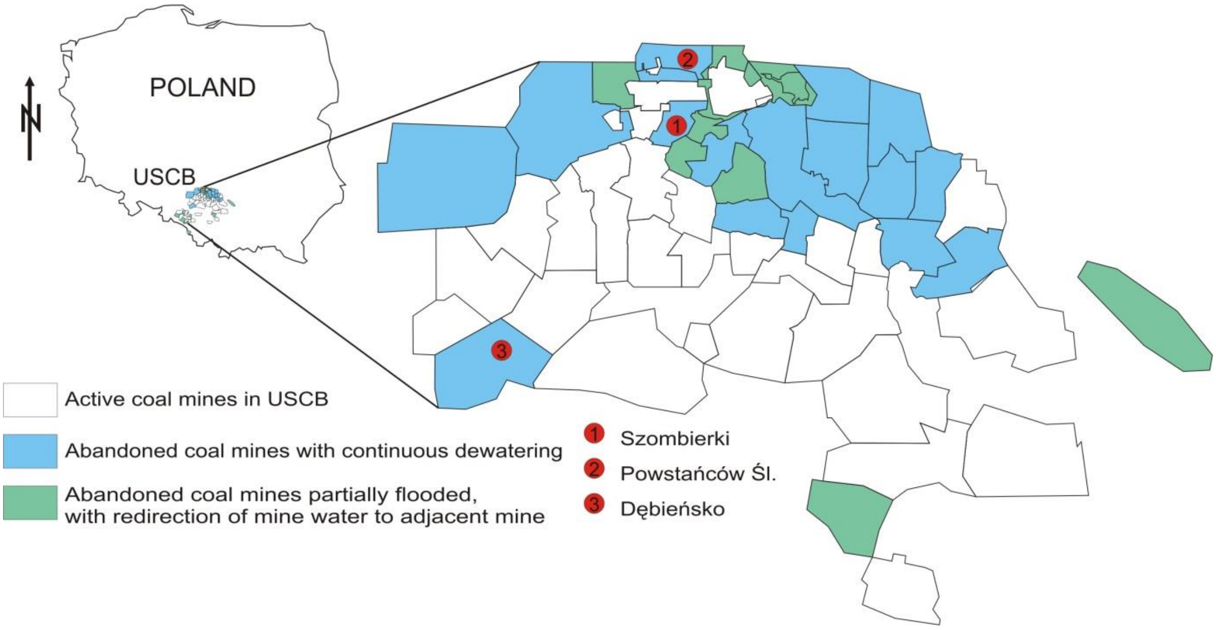


Figure 14. Location of Upper Silesian Coal Basin (USCB) over a contour map of Poland and location of mines of concern within USCB

Source: GIG own elaboration

Main results

The results of the modelling tool application to Szombierki mine indicate that the propagation of cooling effect, represented by the increase of non-dispersed front depth is predicted to be about 46 meters after 200 years of simulation (Figure 15). This parameter is directly proportional to the simulation time i.e. for the same site but a simulation time of 100 years, the non-dispersed front depth is 23 meters). Logically, as the pumping horizons are deeper than the thermally affected area (510, 630 and 790m) the pumped flow temperature shows no variation within time.

Thus, according to the simulations a 80.80 Ls-1 pumped flow of a constant 24.27ºC temperature is expected for this system.

Besides the temperature evolution, this tool provides an estimation of the system energy potential. In this case, supposing a COP of 4 and a temperature step of 5ºC in the heat pump evaporator (both values typical for geothermal heat pumps), the available thermal potential will be 2.25 MW. This value considers only heat supply and can be increased if the heat pump purpose is to provide both heat and cold.

Nevertheless, as maintaining deep pumping horizons is highly expensive, it is a common practice in mine post-closure to rise the pumps up in order to reduce costs.

According to the results a temperature of about 19.3ºC and 18ºC (200m and 100m respectively) could be obtained from the pumped flow in this hypothetical situations.

Powstańców is another example of abandoned mine with deep dewatering (500, 650 and 760m). As the pumped flowrate quantity is smaller than in Szombierki, the thermal potential will be lower. In this site, for a solely use of the heat pump as a heater, 1.38MW can be expected.

If compared with Szombierki and Powstańców, Dębieńsko has slightly higher pumping horizons and a more significant pumping rate (159.48L/s). This is the reason that explains the rise of the heat potential, up to 4.45MW, and the decrease of the pumped flow temperature, about 17.5ºC

Conclusions

The main achievement of task 1.3 is a demonstration of model developed in frame of task 1.1 in Poland at three different mines: Szombierki, Powstańców and Dębieńsko. The results were compared in between the three mines. The evolution of the depth of non-dispersed front in Dębieńsko and Powstańców is exactly the same, as the same infiltration rate have been measured (108 mm/a). In Szombierki this value is slightly higher (110mm/a) so a slightly higher advance of the non-dispersed front can be observed (Figure 15)

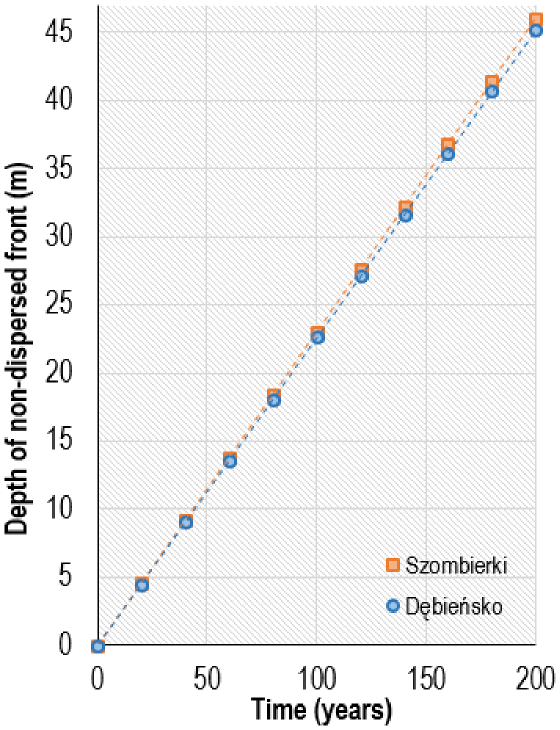


Figure 15. Comparison of the depth of non-dispersed front evolution in Szombierki and Dębieńsko sites

Source: University of Oviedo own elaboration, based on GIG analyses

In Figure 16 the relation between the thermal energy potential against the mine water flowrate for each of the studied mines is shown. This fact, is partially driven by the supposition of same COP and temperature gap at the heat pump for the tree cases, but anyhow it reveals the importance of having a high flowrate in order to assure a raised thermal potential.

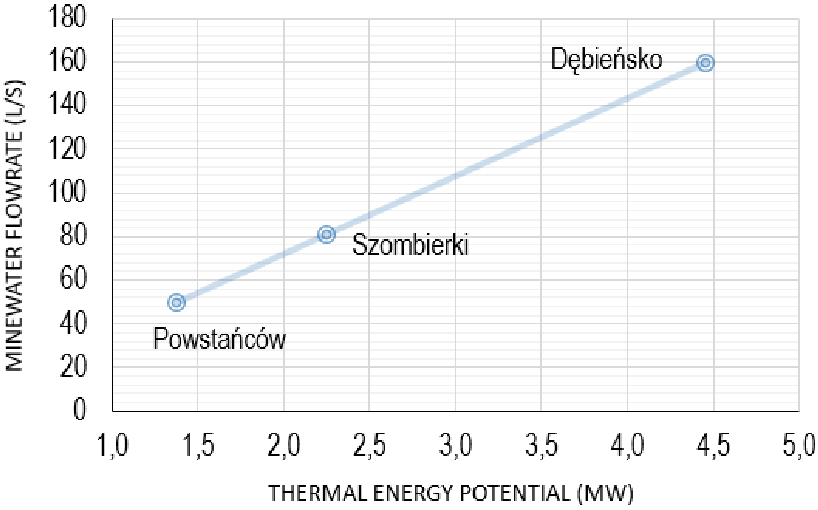


Figure 16. Thermal energy potential against the mine water flowrate for each of the studied mines

Source: University of Oviedo own elaboration, based on GIG analyses

More detailed description of main achievements of task 1.3 is also included into deliverable 1.7 (see Annex 7 to the report).

Exploitation and impact of the research results

The task 1.3 included a demonstration of a tool developed under task 1.1, therefore the exploitation of the research component of task 1.3 is basically the same as for task 1.1 already described above. However, on top of that, the results of task 1.3 provide also important practical evidence of potential for use of mine water in USCB, Poland for heating purposes.

Lessons learned have been presented during IMWA conference in 2017:

- Janson E., Gzyl G., Głodniok M., Markowska M.: *Use of Geothermal Heat of Mine Waters in Upper Silesian Coal Basin, Southern Poland – Possibilities and Impediments* [in:] C.Wolkersdorfer, L. Sartz, M. Sillanpää i A. Häkkinen (eds.): *Mine Water & Circular Economy,* vol I, s. 415-422; IMWA conference materials, Lappeenranta, Finland 2017.

At one of the tested mines – Szombierki in Bytom the real mine-water-driven heating project have been applied in frame of LoCAL project. The further activities of Central Mining Institute after LoCAL project will concentrate on encouraging the further uses of the heat from the mine water in the region. The evidence provided by results of task 1.3 will be very helpful in that process.

WP2. Overcoming the hydrochemical barriers to effective heat transfer from raw and treated mine waters

Main objectives

This work package is mainly focused on investigating the hydro chemical variables that lead the processes of ochre clogging and on developing strategies for mitigation the iron precipitation of mine water in geothermal systems. These preventative strategies will be tested in open-loop and closed loop heat-pumps in order to know how the performance of the geothermal systems can be affected.

The stated objectives of WP2 (project proposal) are:

- To investigate those hydrochemical changes affecting mine waters (especially ochre clogging) that are potentially inimical to the use of these waters in effective thermal exchange processes
- To develop strategies for minimization of deleterious effects of these hydrochemical barriers to heat transfer for the two cases of:
  - (i) Raw mine water that has not yet been oxidized
  - (ii) Partly or fully oxidized mine waters, both in underground infrastructure (shafts, pumps, rising mains) and in oxidation and settlement ponds at surface.

Description of activities and discussion

Field trials to test different methods have been conducted to overcome the ochre clogging issue:

Method 1: Prevent the mine water from coming in contact with air

Method 2: Test the effectiveness of using environmentally benign sodium hydrosulfite in suppressing the ochre formation

For the first method, trials have been made in Markham: mine water is prevented from getting oxygenated, and a prophylactic shell and tube heat exchanger is used to prevent the GSHP from coming in direct contact with mine water. The mine water is extracted and injected back into the same shaft. Periodic analysis of the water samples, filters and heat exchanger have been carried out, while preventing the circulating mine water from coming in contact with oxygen. The testing carried out included additionally monitoring of flow rates on a daily basis and check for any signs of reduction in flow rate due to ochre clogging.

In Caphouse the mine water has an iron content of circa 30 mg/l and is partially oxidised in the pumping shaft, and, due to this, the pumped water is rich in ochre. For these conditions, method 2 was tested in this site, in order to test the effectiveness of the ochre suppression equipment in an open loop heat pump configuration. A pilot plant was installed in order to develop the study.

In Barredo the mine water has an iron content not very high, circa 5 mg/l, and even although the system was redesigned to avoid water being in contact with air, ochre clogging is produced in the filters and in the prophylactic plate exchanger. Periodical maintenances are required because of the reduction in the COP of the geothermal system. The observation of small ochre particles on sample filters, suggests that the iron in the water could be already partially oxidised underground to form small ochre flocs that produce major aggregates of iron oxy hidroxydes and should be the cause that filters, pipes or heat exchangers become clogged.

Laboratory tests with sodium dithionite to inhibit ochre fornation have been carried out with good results. In the laboratory study of Barredo mine water, the results have shown that the use of sodium dithionite doses over 60 mg/l are successful to hinder the oxidation and precipitation of ferric iron. Moreover the sodium dithionite hasn’t modified the environmental quality of water before been discharged to river.

For the purpose of studying the effects of the ochre hydrochemical barriers in oxidized mine waters, thermal response tests (using a “GeoCube” rig) were carried out on a closed loop heat exchange system installed in the main aeration treatment pond at the Caphouse site. The results can be used to assist in the interpretation of thermal response tests, monitor mine water pumping and monitor the thermal behaviour of the treatment system over an annual cycle.

Finally, a comprehensive series of laboratory experiments has been undertaken to evaluate the temperature dependent kinetics of ochre (ferric oxyhydroxide) precipitation. He then carried out a series of experiments at various controlled temperatures to investigate the kinetics of ferrous iron oxidation and of ferric iron hydrolysis.

Main results

When the mine water quality is good and the total content of iron in water is low, like in Markham where is less than 0.5 mg/l, very little deposition was noticed in filters, pipes or heat exchangers. Thus, in these cases, by preventing the mine water from coming in contact with the oxygen, the ochre clogging can be minimised to a great extent.

When the total iron content increases, for example in Barredo, the results obtained with the use of mine water that has not yet been in contact with the air indicate that under some conditions the clogging is produced. The observation of small ochre particles on sample filters, suggests that the iron in the water could be already partially oxidised underground to form small ochre flocs that produce major aggregates of iron oxy hydroxides and should be the cause that filters, pipes or heat exchangers become clogged, even although they are prevented that be in contact with air. In Barredo the effects of clogging is clear in plate exchanger while the effects in the tube exchangers is almost negligible.

What concerns to the use of oxidized mine waters in ponds with closed loop heat pump systems, there have been observed that there is a potential minor effect of ochre clogging of the heat exchanger’s exterior surfaces. This is indicated by a general very modest decline in experimental heat exchange capacity of the closed loop heat exchanger with progressive accumulation of ochre (and tentative indications of a recovery of exchange capacity following desludging of the aeration lagoon).

It has been noted at Caphouse that the submerged heat exchanger becomes progressively fouled by accumulating ochre deposits in the aeration basin. We have, however, not been able to demonstrate that this, in itself, adversely affects heat capacity (the underperformance noted was likely due to inadequate heat transfer fluid flow rates).

Laboratory analyses have shown iron oxidation and hydrolysis is temperature dependent, with rates increasing as temperature increased in the range 5 – 45°C.

Conclusions

- The LoCAL project has demonstrated that iron-rich mine water can be used in heat exchange systems provided that it is not allowed to come into contact with atmospheric oxygen (or other oxidising agents), or by the use of chemical reducing agents, in both cases it is intended that iron remains in its soluble ferrous (Fe^{2+}) form.
- Not all mine waters are sufficiently chemically reducing to rely on iron always being present in its ferrous form. Indeed, it seems there are mine waters where oxidation of iron has commenced in the underground workings or shafts, such that ochre particles can be observed in the raw water. This can be the cause why ochre clogging occurs, even where access to the atmosphere is precluded in the surface headworks (Caphouse, Barredo).
- The presence of modest quantities of ochre particles does not necessarily render a heat exchange scheme unworkable, and can be managed by a degree of maintenance. (e.g. Caphouse, Barredo)
- The use of chemical reducing agents, like sodium dithionite, contributes to mitigate ochre precipitation because iron remains reduced and soluble, and it doesn’t seem affect environment.
- Advection of mine water in a pond where a closed loop heat exchanger is placed increases its heat exchange capacity (Markham), although there is a potential minor effect of ochre clogging of the heat exchanger’s exterior surfaces, as indicated by a general very modest decline in experimental heat exchange capacity of the closed loop heat exchanger with progressive accumulation of ochre.

Exploitation and impact of the research results

Conclusions obtained from the results achieved in this work package are directly applicable to real systems, because depending on the iron content and on the type of heat pump scheme, different strategies for prevention ochre formation have been identified.

The study has tested the effectiveness of some ochre clogging prevention strategies to avoid problems on open loop geothermal systems and has demonstrated the application of a closed loop heat exchanger in a mine water treatment basin, with documented performance data.

With regards to the dissemination of results, several scientific papers have been published in peer reviewed journals and presented in international conference what facilitates the diffusion of the knowledge

Task 2.1 Preventative strategies for ochre clogging of subsurface pumps and pipework during open-loop heat-pump exploitation of mine waters.

Task leader: Alkane

Main objectives

The stated objectives of Task 2.1 (project proposal) are:

- Use updated knowledge in relevant literature to formulate a generic conceptual framework of aspects of dissolved load behaviour that have potential to affect open-loop use of deep mine waters: influence of dissolved gas content (especially CO2 and O2), iron content, pH or temperature will be studied.
- We will also do preliminary laboratory tests followed by full-scale field trials of the use of environmentally benign (bio)chemical reducing agents (especially sodium dithionite), without compromising the suitability of the water for discharge. The aim is to test its longer term prophylactic use during ongoing pumping, under the range of pressure and temperature ranges induced by heat pumps

Description of activities and discussion

A literature review of experiences of ochre clogging has been undertaken with special emphasis on case studies in participant countries. This study seeks to formulate a conceptual framework of different aspects that governs the ochre precipitation process, with special emphasis on the role of dissolved gases, pH, temperature dependence and effects of reducing agents.

The installation of pilot oxidation suppression equipment at Markham and Caphouse Collieries has allowed testing the effect of different parameters in the precipitation of iron. In Barredo shaft, mine water used in the geothermal system that provides heat to a University of Oviedo building produces frequent ochre clogging deposits that are studied in depth.

In Markham, a prophylactic shell and tube heat exchanger was installed to prevent the GSHP from coming in direct contact with mine water, and the installation was designed to avoid ochre clogging. A periodic analysis of the water samples, filters and heat exchanger have been carried out. Results have been evaluated in order to check if avoiding the circulating mine water from coming in contact with oxygen prevents the ochre clogging.

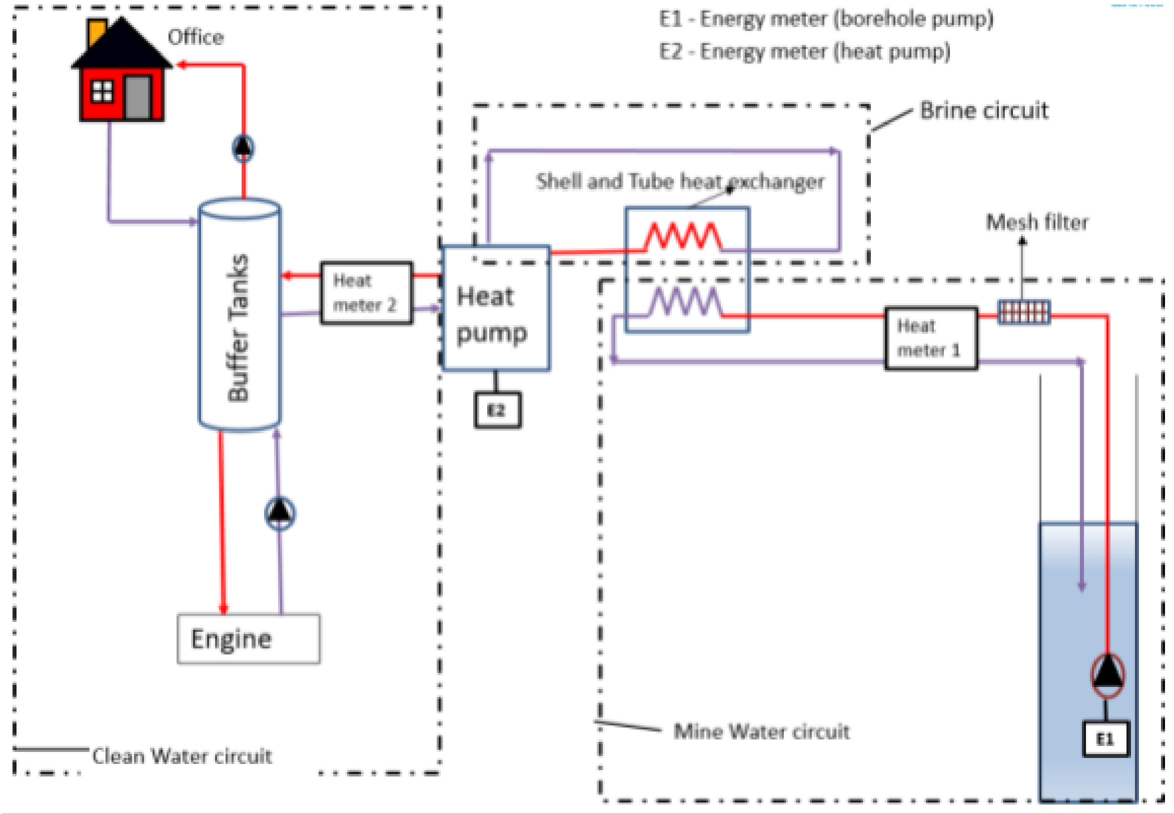


Figure 17 Scheme of the close loop system at Markham

Source: Alkane own elaboration

In Caphouse a pilot plant was designed and put into operation to check the effectiveness of using an environment friendly reducing agent in suppressing the ochre formation. A dousing pump to introduce the reducing agent (*Sodium dithionite*) was installed in addition to the use of a filter and a prophylactic heat exchanger. First results obtained in the pilot plant have been analysed, and after them trials with different sodium dithionite dose rates have been carried out.

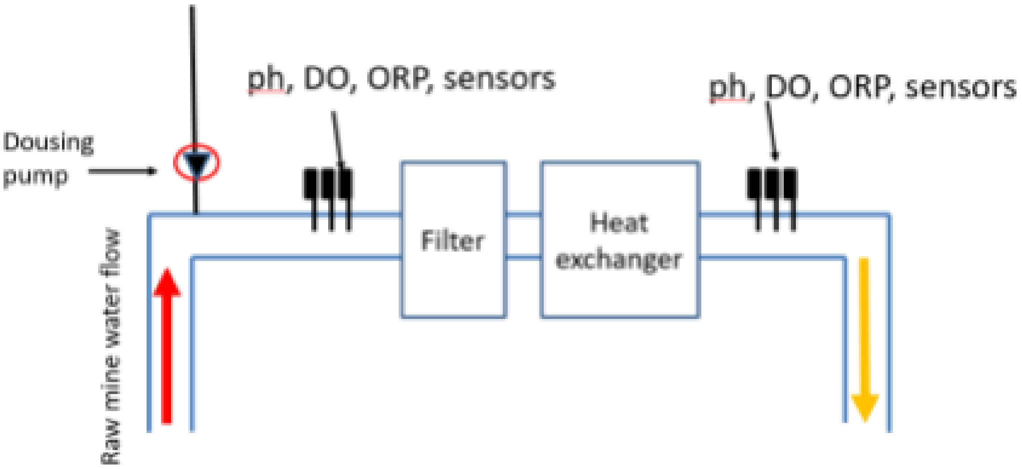


Figure 18 Dousing kit schematic diagram

Source: Alkane own elaboration

In Barredo the geothermal system of the University is working in the way that mine water is pumped through a filter and a prophylactic plate heat exchanger before coming into the heat pump, in an open loop system. The filters and the plates become soon clogged, and periodically maintenances are required. Other schemes used with Barredo mine water, as that of the Mieres hospital, have shell and tube heat exchangers and there have not been major issues with ochre clogging, suggesting that shell and tube heat exchangers are less susceptible to ochre clogging than parallel plate heat exchangers.

Effects of ochre clogging in the performance of the heat pump were studied. Samples of the iron oxi hydroxide deposits in the filter and in the plates of the exchanger were collected to study their composition and the variables that could influence in the precipitation. Water samples have been taken at the exit of the mine shaft and before the entrance to the prophylactic heat exchanger in order to know their geochemical composition.

Laboratory tests have been done to study iron precipitation rates under different doses of sodium dithionite addition.

Main results

Based on the literature review, a report on influence of gas pressures on ochre clogging processes was completed, and produced as LoCAL project deliverable.

In Markham the mine water quality is fairly good and the total iron content in the water is less than 0.5 mg/l. The water quality has actually improved ever since the borehole pump was raised, because previously the total iron content was circa 3.2 mg/l. The filters, pipelines and heat exchangers were removed and checked for any ochre deposition and very little deposition was noticed, during 1.5 years of operation. Thus by preventing the mine water from coming in contact with the oxygen the ochre clogging can be minimised to a great extent.

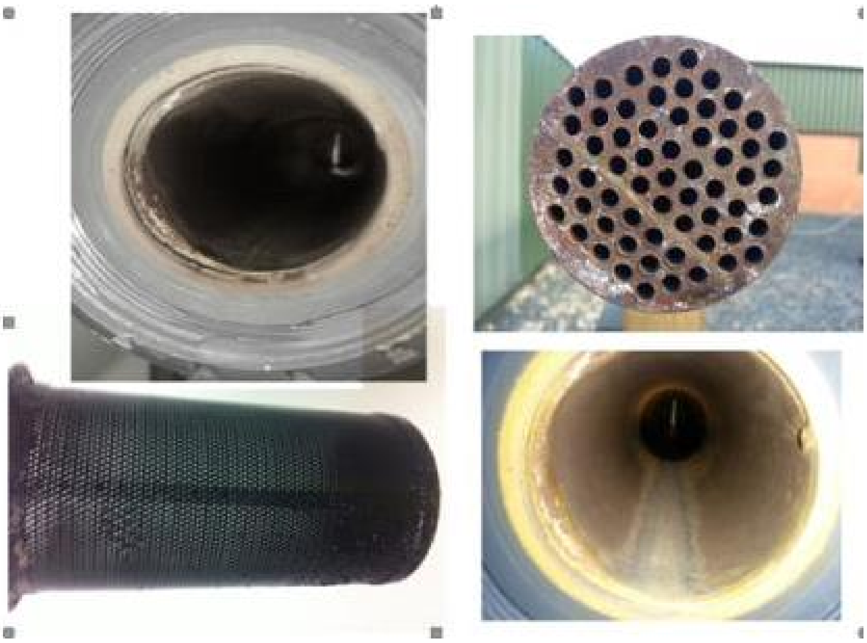


Figure 19 Inspection of pipelines at Markham

Source: Alkane archive

At Caphouse as expected there is a lot of clogging of the heat exchanger and the filter requires frequent cleaning. The dousing of sodium dithionite is being done; slight difference in ochre clogging is being seen.

Figure 20 Caphouse filter after dousing of sodium dithionite

Source: Alkane own elaboration

In Barredo, although the maximum concentration of 5.2 mg/l was found in the water pumped, the filter and the plate exchange have shown problems with clogging which produces periodically stops in the operation of the geothermal installation to clean them. The mine water can be oxidizes after coming out of the shaft but the observation of small ochre particles on sample filters in pumped water, suggests that the iron in the water could be already partially oxidised underground to form small ochre flocs that produce major aggregates of iron oxy hydroxides in the prophylactic plate exchanger.

Figure 21 Ochre deposition in a filter and in a plate of the exchanger in Barredo

Source: Alkane own elaboration

Results of the trials adding different doses of sodium dithionite to Barredo mine water allows to see how the reduction agent successes inhibiting the ochre precipitation with concentrations higher than 50 mg/L, as shows in Figure 22. The reactions that reduce Fe^{3+} into Fe^{2+} that is soluble, are obtained of the literature review, and it is probable that are:

$$Na_2S_2\,O_4 + 3\,H_2O = Na\,HSO_4 + Na\,HSO_3 + 4\,H^+$$

$$Na\,HSO_3 + Fe^{3+} = Na\,HSO_4 + Fe^{2+}$$

Figure 22 Mine water response to the addition of different doses of sodium dithionite. Concentrations of 75 and 100 mg/l keep the iron completely dissolved as Fe^{2+}

Source: Alkane own elaboration

The addition of sodium dithionite seems to sequestrate the dissolved oxygen as is seen in the evolution of it concentration shows in Figure 23. Once the iron is dissolved, if the water is not exposed to atmospheric oxygen iron remained reduced and soluble and no reversion in the reaction that inhibits iron precipitation is observed for a long time.

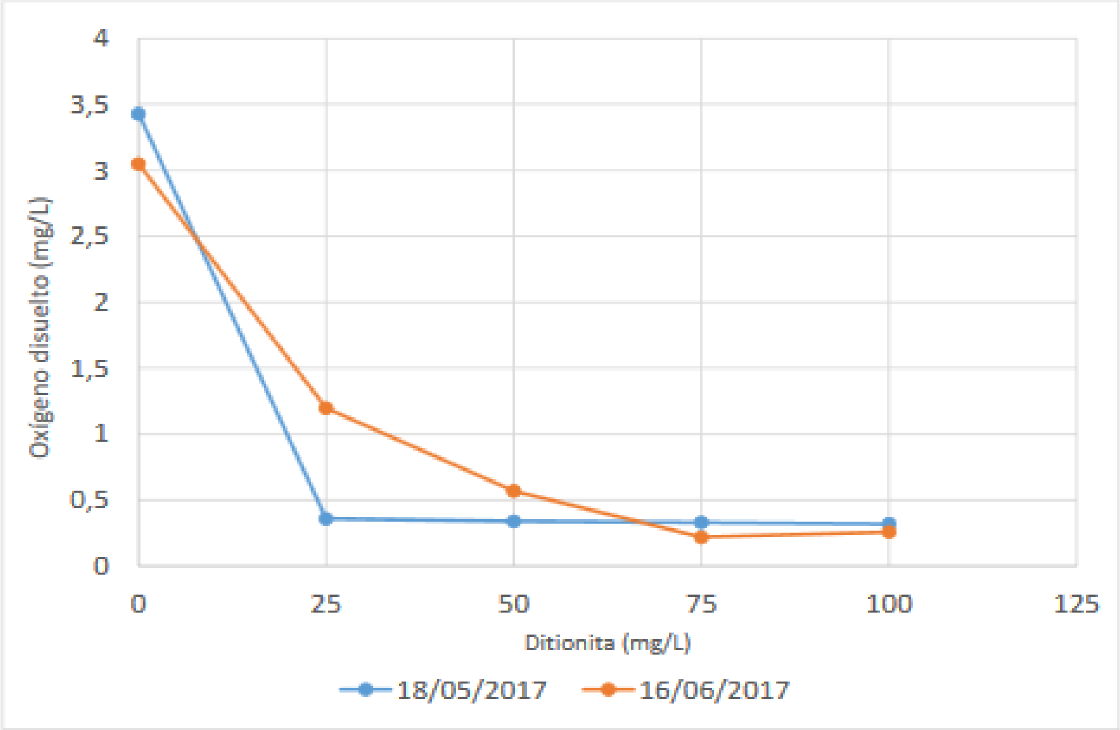


Figure 23 Evolution of dissolved oxygen in mine water at different concentrations of the reducing agent

Source: University of Oviedo own elaboration, based on Alkane analyses

The addition of the reducting agent doesn’t produce environmental problems as is seen in the chemical analyses of water with different dithionite concentration.

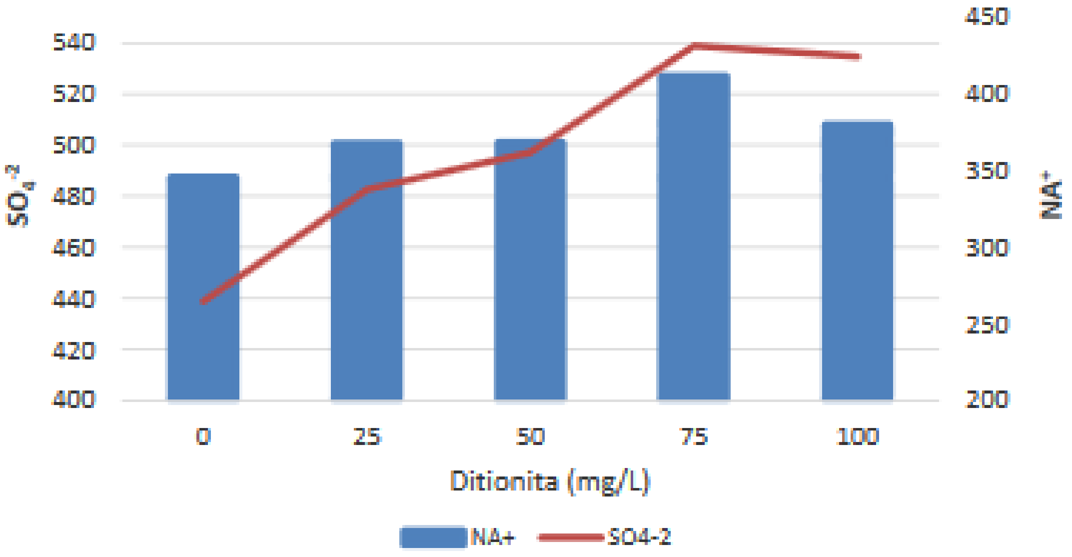


Figure 24 Sulphate content in water after addition of sodium dithionite

Source: University of Oviedo own elaboration, based on Alkane analyses

In the laboratory study of Barredo mine water, the results have shown that the use of doses of sodium dithionite over 60 mg/l are successful to hinder the oxidation and precipitation of ferric iron. Moreover the sodium dithionite hasn't modified the environmental quality of water before been discharged to river.

Conclusions

When the mine water quality is fairly good and the total content of iron in water is low, like in Markham where is less than 0.5 mg/l, very little deposition was noticed in filters, pipes or heat exchangers. Thus, in these cases, by preventing the mine water from coming in contact with the oxygen, the ochre clogging can be minimised to a great extent.

The experiments with dosing the mine waters with sodium dithionite (Na2S2O4) prior to heat exchange, in an attempt to maintain iron in reduced form in solution have been successful, and these reducing agents can be regarded as relatively environmentally benign.

Exploitation and impact of the research results

The study has tested the effectiveness of some ochre clogging prevention strategies to avoid problems on geothermal systems.

The findings have been published in several peer reviewed journal:

- Athresh, A.P., Al-Habaibeh, A. and Parker, K. (2016). The design and evaluation of an open loop ground source heat pump operating in an ochre-rich coal mine water environment. International Journal of Coal Geology. DOI:10.1016/j.coal.2016.04.015
- Burnside, N.M., Banks, D., Boyce, A.J & Athresh, A. (2016). Hydrochemistry and stable isotopes as tools for understanding the sustainability of minewater geothermal energy production from a ‘standing column’ heat pump system: Markham Colliery, Bolsover, Derbyshire, UK. International Journal of Coal Geology doi:10.1016/j.coal.2016.08.021
- Loredo, C., Ordóñez, A., Garcia-Ordiales, E., Álvarez, R., Roqueñí, N., Cienfuegos, P., Peña, A.; Burnside, N. M. (2017). Hydrochemical characterization of a mine water geothermal energy resource in NW Spain. Science of The Total Environment, 576, 59–69. DOI:10.1016/j.scitotenv.2016.10.084
- Banks, D., Athresh, A.P., Al-Habaibeh, A. And Burnside, N. (2017) Water from abandoned mines as a heat source: practical experiences of open- and closed-loop strategies, United Kingdom. Sustainable Water Resources Management. DOI:10.1007/s40899-017-0094-7

The laboratory findings carried out in the University of Oviedo are published in a Bachelor's thesis:

- Rodriguez Van Riet, L. (2017) Sostenibilidad del uso del agua de mina como recurso geotérmico: Influencia de la calidad del agua en el rendimiento de un sistema real (Sustainability in the use of mine wáter as a geotermal resource. Influence of water quality in system performance).

There will be, probably, a future possible publication on *Practical experience of using sodium dithionite as an ochre suppression agen*t.

Task 2.2 Closed-loop strategies for oxidised, ochre-precipitating mine waters in treatment systems.

Task leader: UoG

Main objectives

The stated objectives of Task 2.2 (project proposal) are:

- Thermal exchange testing in an existing mine water treatment pond in the UK using a GeoCube thermal response testing rig coupled to submerged loops. We will also repeat thermal tests at 6-monthly intervals over the life of LoCAL, allowing us to compare responses at different degrees of ochre coating on the pipes (which will remain in the ponds for the duration of the experiments, with the GeoCube being brought to site just for the testing days).
- We will also perform high-precision temperature measurements in lab and field systems subject to differing degrees of ochre precipitation, and apply thermodynamic modelling codes to assess the net thermal energy availability as a function of iron oxidation / hydrolysis rates.

Description of activities and discussion

The closed loop system (Energy Blade) installed in the first aeration pond at Caphouse Colliery has been regularly used by the National Coal Mining Museum of England to heat a visitor exhibit at the Inman Shaft building.

The first round of thermal response testing of the submerged "Energy Blade" heat exchanger was successfully undertaken in October 2015. The second round of thermal response testing took place during March-April 2016.The March 2016 test had to be aborted (although the results were still found to have some value), and was thus repeated (successfully) in April 2016. The fourth and final round of testing took place in January 2017.

The mine water treatment system at Caphouse was monitored throughout the project period using four submerged "Diver" units, continuously monitoring water temperature, head and electrical conductivity, and also one atmospheric logger. The results can be used to assist in the interpretation of thermal response tests, monitor mine water pumping and monitor the thermal behaviour of the treatment system over an annual cycle.

Finally, a comprehensive series of laboratory experiments has been undertaken as part of the LoCAL project by Mr Adam Raftery, as a collaborative study between the Universities of Birmingham and Glasgow. Mr Raftery reviewed available literature on the temperature dependent kinetics of ochre (ferric oxyhydroxide) precipitation. He then carried out a series of experiments at various controlled temperatures to investigate:

- The kinetics of ferrous iron oxidation, using the ferrozine blue method
- The kinetics of ferric iron hydrolysis.
- The overall kinetics of ferrous iron oxidation / ferric iron hydrolysis combined, using time lapse photography.
- The evolution of particle size during ferric iron hydrolysis, in a Zetamaster zeta potential analyser.

Main results

The results of all four thermal response tests) have been fully analysed. An example is shown below:

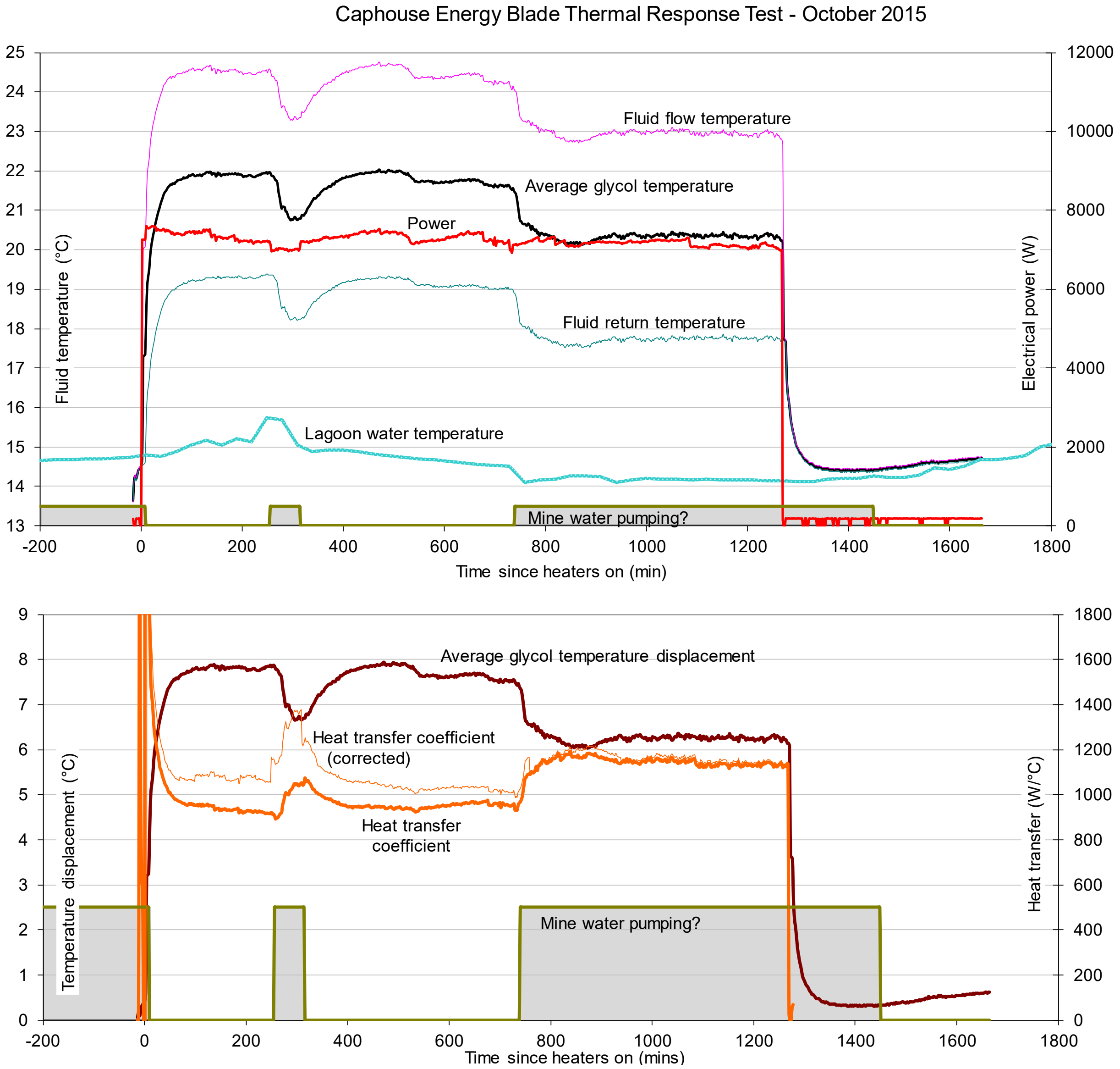


Figure 25. Thermal response test on aeration lagoon heat exchanger, October 2015

Source: University of Glasgow own elaboration

The upper diagram shows the calculated electrical heater power (W), the glycol flow and return temperatures, the average glycol temperature, the lagoon water temperature from logger 1 and whether the mine water was pumping (shaded on/off). The lower diagram shows the glycol temperature displacement, relative to a baseline of 14.1 °C, the calculated heat transfer coefficient, relative to a lagoon baseline of 14.1 °C, a "corrected" heat transfer coefficient relative to the actual logged lagoon temperature, and whether the mine water was pumping (on/off).

The results show

- That advective flow of minewater through the aeration lagoon increased heat transfer coefficients (typically by up to 15-20 W m^{-2} K^{-1}, or around 20-25%), compared with the static water condition.
- The "Energy Blade" is not achieving the heat exchange capacity advertised by the manufacturer. This is most likely due to the installed circulation pump not being able to achieve a sufficiently high flow for transient-turbulent conditions in the heat exchanger.

- The museum's experiences of the closed-loop Energy Blade system have been overwhelmingly positive, and it was by far preferred over the "open loop" option.
- There is a potential minor effect of ochre clogging of the heat exchanger's exterior surfaces, as indicated by a general very modest decline in experimental heat exchange capacity of the closed loop heat exchanger with progressive accumulation of ochre (and tentative indications of a recovery of exchange capacity following desludging of the aeration lagoon).

The installed "divers" have been very efficient at collecting temperature, level and conductivity data throughout the mine water treatment system.

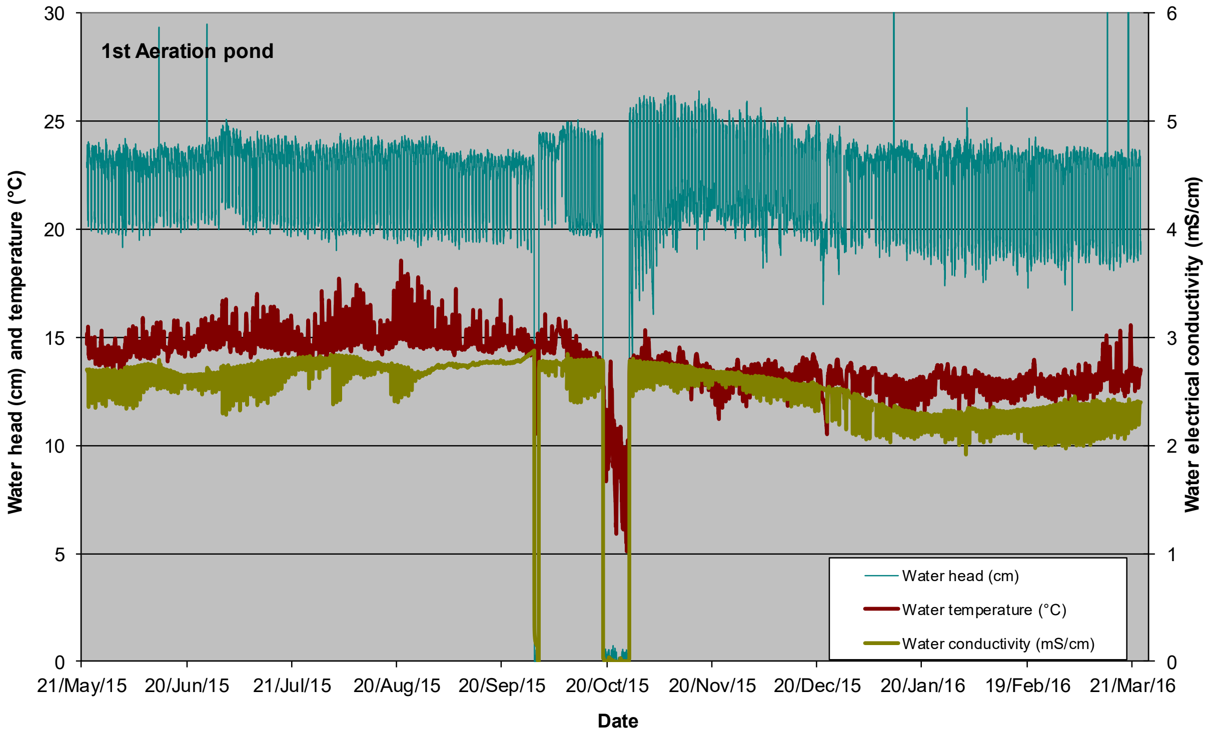


Figure 26. Water level, temperature and conductivity data from Aeration Pond 1, Caphouse mining museum.

Source: University of Glasgow own elaboration

For example, the data clearly illustrate that the water in aeration pond 1 maintains a relatively constant temperature throughout the year (around 15°C in summer and 13°C in winter, relative to a minewater temperature of c. 14°C. Moreover, it can be seen that water levels increased in response to increased mine water pumping, in late autumn 2015, and that mine water mineralisation decreased following this peak pumping episode.

The University of Birmingham / Glasgow LoCAL study by Mr Adam Raftery unequivocally confirmed that iron oxidation and hydrolysis is temperature dependent, with rates increasing as temperature increased in the range 5 – 45°C. This is best visualised in a sequence of time-lapse photography experiments (Figure below).

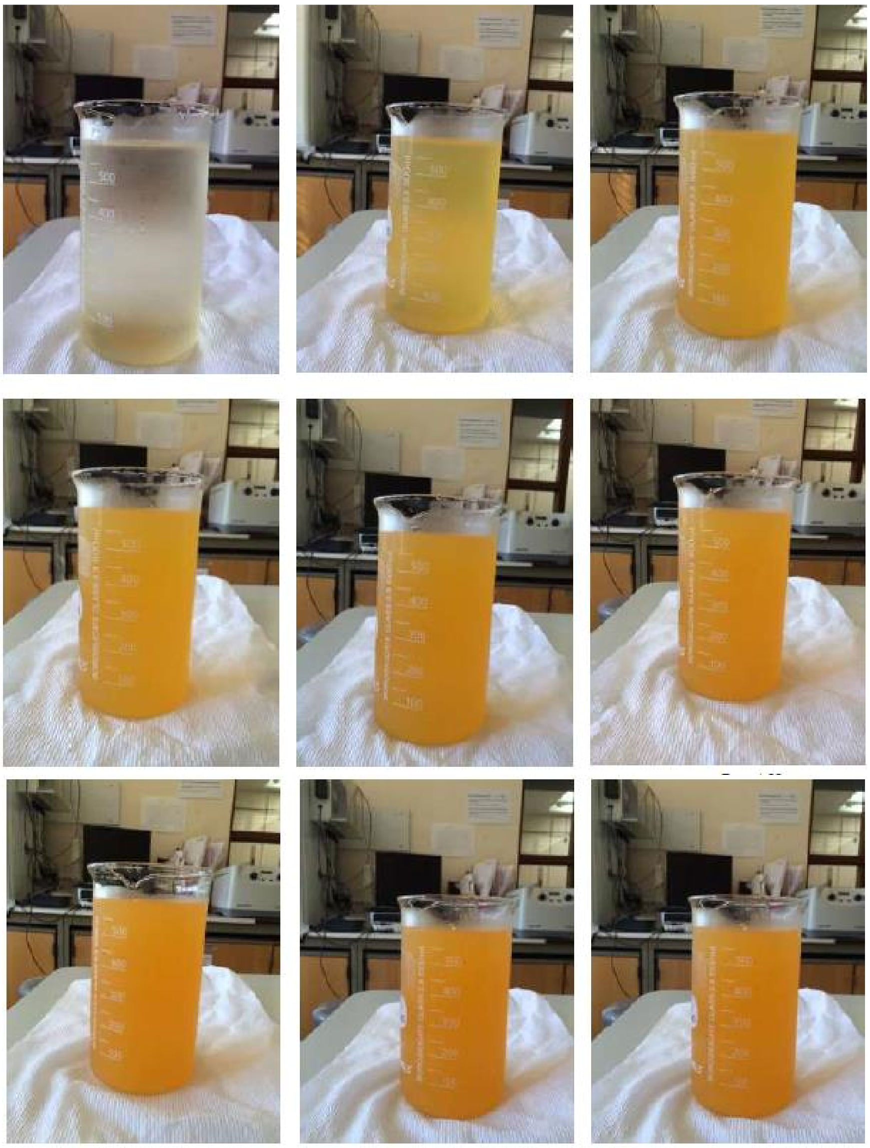


Figure 27. Time lapse photography (5 minute intervals) of oxidation and hydrolysis of ferrous sulphate solution, at 5°C.

Photo: A. Raftery (2016).

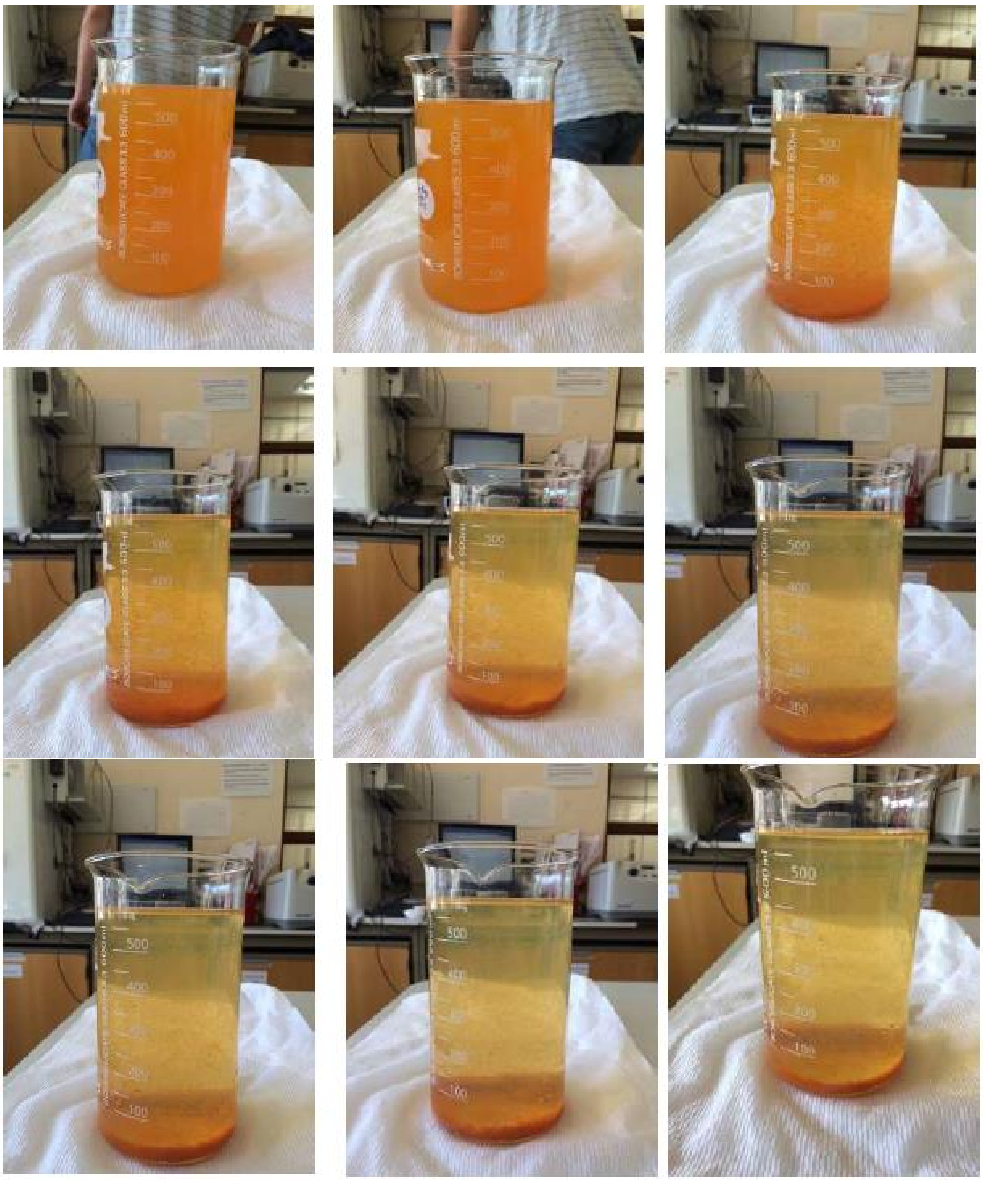


Figure 28. Time lapse photography (5 minute intervals) of oxidation and hydrolysis of ferrous sulphate solution, at 40°C.

Photo: A. Raftery (2016).

Conclusions

It was found that the heat exchange capacity of the closed loop heat exchanger was higher at times when the Caphouse mine water was pumping and flowing through the aeration pond, than at times when there was no throughflow. Advection of mine water thus increases the heat exchange capacity of the closed loop heat exchanger.

The heat exchange capacity of the closed loop "Energy Blade" was lower than the manufacturer's published value. It is thought that this was due to the low capacity of the *GeoCube*'s (thermal response test rig) circulation pump – it was inadequate to attain the 0.9 L/s recommended by the manufacturer for optimal heat exchange capacity.

The heat exchange capacity varied through time as follows:

Table 1. Variation in apparent closed loop Energy Blade heat exchange efficiency with time, as derived from four thermal response tests.

Date of test	Heat transfer coefficient (W/K) with mine water pumping	Heat transfer coefficient (W/K) without mine water pumping
8th-9th October 2015	c. 1130 - 1180	c. 920 - 970
20th-27th October 2015		Aeration lagoon desludged
23rd March 2016		1000-1010
27th-28th April 2016	c. 1000	c. 900
19th-20th January 2017	c. 790 -820	c. 740 - 780

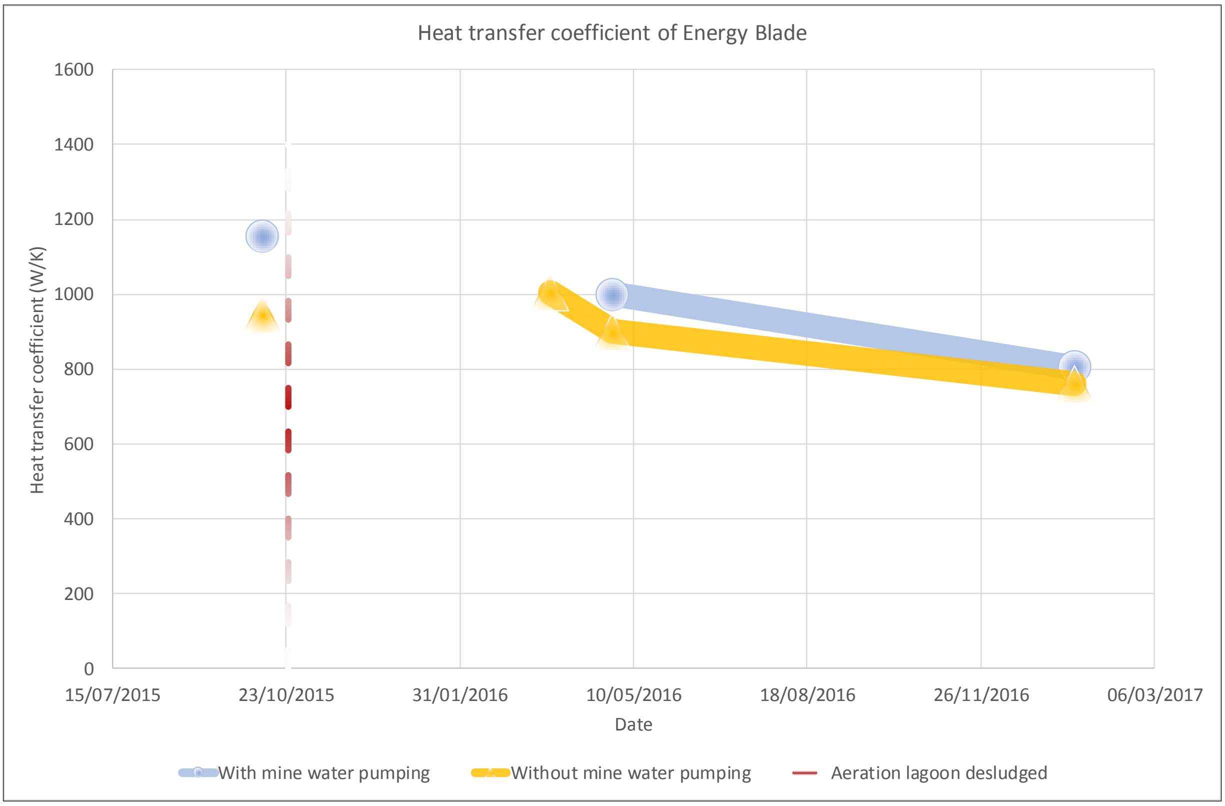


Figure 29. Graphical representation of data on apparent change in Energy Blade heat exchange efficiency with time

Source: University of Glasgow own elaboration

During the test period, the top aeration lagoon was reportedly desludged once, during 20th-27th October 2015. We can see that desludging the aeration lagoon tentatively resulted in an apparent small increase in heat transfer capacity, which then declined slowly with time. This may be related to ochre sludge building up around the Energy Blade's heat exchange surfaces and impeding convective heat transfer from those surfaces.

As regards the laboratory studies, we conclude that the main findings were

- for an increase of 10°C, Fe (II) oxidation rates (oxidation only) increase by 1.5 – 2.5 times across three separate solution chemistries.

- in a 30-minute particle-size (Zetamaster) experiment, solutions at 45 °C undergo the complete process of Fe (II) oxidation, hydrolysis, flocculation and precipitation, 20 minutes faster than a solution at 5 °C.
- in a solution of ferrous sulphate, batch experiments (oxidation, hydrolysis and precipitation) have shown that a 35 °C temperature increase leads to a 40 % increase in precipitate mass for a given time.
- solutions prepared with acidified ferric chloride (hydrolysis and precipitation only) showed a 75 % increase in precipitate mass under the same conditions.

Exploitation and impact of the research results

The study has provided a real-life demonstration of the application of a closed loop heat exchanger in a mine water treatment basin, with documented performance data.

The findings have been published in a peer reviewed journal:

- Banks, D., Athresh, A., Al-Habaibeh, A. & Burnside, N. (2017) Water from abandoned mines as a heat source: practical experiences of open- and closed-loop strategies, United Kingdom. Sustainable Water Resources Management. doi: 10.1007/s40899-017-0094-7

The laboratory findings are published in an MSc thesis:

- Raftery, A. (2016) An assessment of ferrous iron oxidation, hydrolysis and precipitation as a function of temperature. MSc Hydrogeology Thesis, University of Birmingham. 28/6/16.

The complete data files have been submitted to project management for open access via the LoCAL project website:

1) Four Excel files containing the analysed results of each of four thermal response tests on the closed loop "Energy Blade"
    - TRT Caphouse Oct 2015.xlsx
    - TRT Caphouse Mar 2016.xlsx
    - TRT Caphouse Apr 2016.xlsx
    - TRT Caphouse Jan 2017.xlsx
2) Single Excel file containing all data (barometrically corrected) for divers installed at Caphouse minewater treatment system - ***Caphouse diver data 2015-2017.xlsx***

The last named file provides a valuable resource for those intending to construct thermal models of any pond, reservoir or lagoon based heat exchange system.

WP3. Models for efficiency of energy extraction and distribution

Main objectives

WP3 main objective was socio-economic analysis of issues concerning heat recovery from mine waters. All activities were conducted to have influence on potential beneficiaries like local politicians, decision makers, developers and investors as well as private households owners. A set of gathered basic data catalogued and categorized played a role both as an informational and guide material summarizing different aspects of heat recovery from mine waters.

All tasks within WP 3 were logically connected and coherently oriented on the line from informing, helping to understand, parametrising and supporting with certain tools to make improvement in aspects of potential investments during mine closures period.

Specific objectives of WP3, as in Technical Annex:

- Using recent commercial performance data from large-scale groundwater cooling systems in the UK as a platform for developing a mine-water specific protocol and costings model for direct and indirect use of abandoned coal mine waters for space cooling
- Using established Technology Readiness Level (TRL) appraisal tools widely used in the EU to evaluate all the technical results arising from the other work packages, to establish how far up the TRL scale they have reached during the life of LoCAL
- Selection of the optimal solution as regards centralized and decentralized system of heat transfer the comparative analysis
- Identification of the optimum solution from the point of view of all the relevant criteria and factors affecting the viability and profitability of the pilot

All objectives were accomplished through realization of five Tasks described below.

Description of activities and discussion

In frame of Task 3.1 an analytical model (analytical tool for investors) has been developed that uses the collected data from other tasks, and allows to analyse the cost-effectiveness of thermal energy use from mine waters. The model focuses on the technical possibilities of using mine water for the thermal energy purpose, the financial aspects of the reality of the investment implementation and its profitability, as well as on the identification of economic and environmental reasons, which speak of the ultimate profitability of the investment.

The activities of Task 3.2 included: assessment of the TRL level for the LOCAL's projects in the three countries; workshop to assess route to markets; on-line survey to assess the knowledge and awareness of the technology within local councils, public, academic and industrial organizations and institutions as well as the development of a small-scale simulator to explain the technology and involve university students in the design and implementations.

In frame of Task 3.3 the thermodynamic analysis of the systems has been accomplished by the development of three spreadsheet analytical models. In addition to purely thermodynamic / heat transfer data, these spreadsheets also allow analysis of economic and energetic efficiency of various cooling solutions.

In frame of Task 3.4 an analytical model (analytical tool for investors) has been developed that uses the collected data from other tasks, and allows to analyze the cost-effectiveness of thermal energy use from mine waters.

In frame of Task 3.5 LoCAL Toolbox was designed for end-users interested in uptaking heat from minewaters. It's value was tested in real conditions and for technological purpose at the ARMADA pilot site.

Main results

All planned LoCAL Project WP3 main results have been reached as follows:

- M. 3.1. STEEP analysis results
- M. 3.2. Results of economical analysis
- D. 3.1.Methodology of analysis of technical circuits with CBA and DGC
- D. 3.2 Results of market analysis

- D. 3.3 Models for incorporating cooling into a delivery system
- D. 3.4. Toolbox assuring multiplication of the project results

Main results are specifically described below and divided on specific Tasks.

Conclusions

WP3 Models for efficiency of energy extraction and distribution was a complex pack of economical, business and social tasks. Every task was important to create a coherent knowledge about the heat uptake from mine waters as well its practical potential for implementation.

The analyzes carried out in Task 3.1 show that the use of mine water for thermal energy purposes may prove cost-effective from an economic point of view. At this stage of the work, it was diagnosed that the greatest importance for the profitability of investments is the size of the installation, and the actual amount of thermal energy generated by it. Aspects of commercialization were considered for long term and short term periods, with set of conditions allowing to unlock technical feasibility of technology implementation.

Task 3.3 has resulted in a comprehensive state-of-the-art review of arguably the three largest minewater-based heat pump systems, which incorporate cooling, active in the world today – Barredo, Heerlen and Springhill – and the different means by which heating and cooling are delivered to customers. As part of the project an analytical model (analytical tool for investors) has been developed that uses the collected data from other tasks, and allows to analyse the cost-effectiveness of thermal energy use from mine waters.

As a physical visualization of all elaborated within Project LoCAL tools a dedicated toolbox (http://local.gig.eu/index.php/toolbox) was prepared (within task 3.5). Toolbox was elaborated in form of web page, so it is easy to access world-wide with also impacts on easy dissemination of WP3 results.

Exploitation and impact of the research results

Results have been published within few peer-reviewed articles, which are listed within specific tasks description.

Task 3.1 Technical, legal and management STEEP/ cost-benefit analysis of various types of decentralised heat pump system, versus centralised plant room system

Task leader: GIG

Main objectives

There are several aspects of use of mine water as a source of thermal energy, such as: technical, ecological, economical, social, and legal. Therefore, in order to select the optimal solution as regards centralized and decentralized system of heat transfer the comparative analysis of the proposed solutions was conducted. In WP3 the possible solutions were analyzed with the use the following methods:

- STEEP analysis (social, technical, economical, ecological, political aspects)
- Analysis of dynamic generation cost (DGC)
- Analysis of socio-economic costs and benefits (CBA)

The first step of the analysis consisted of identification of all possible outer and inner factors as well as technical, ecological, economical, social, and legal aspects of planned solutions. This step was necessary in order to clarify the local conditions of construction and maintenance of the mine water heat recovery system.

The second step consisted of Dynamic Generation Cost Analysis with the use of DGC (Dynamic Generation Cost) index. The analysis was based on calculation of technical cost of obtaining the unity ecological effect in the given time horizon. The results of DGC analysis allowed for direct comparison of eco-efficiency of given variants in relation to the unity of heat. Therefore, the employment of DGC analysis allowed for the ranking of individual solutions as regards their eco-efficiency.

The third step consisted of use the variants of CBA (Cost-Benefit Analysis), which was adequately fitted to dimensions, complexity and cost of planned solutions. The CBA analysis supported the decision-making process by securing the proper relation of the costs and benefits.

The analyzes were prepared in the form of reports and computational models and became the basis for construction of the interactive tool for investors.

Description of activities and discussion

A revision of the existent models for economical analysis has been undertaken. Based in this review it was made an upgrade specific for the issues concerning heat uptake from mine waters. Results from this task can be practical used in form of interactive tool.

Main results

The STEEP Analysis

This section identifies the key social, technological, economic, environmental and political trends and drivers that are likely to shape potential of heat extracting from mine waters over the next 10 to 20 years. The analysis of each STEEP dimension ends with a broad assessment of the extent to which the trends and drivers can be influenced and affected by potential beneficiaries. Two variants of heat systems, centralized and decentralized have been analyzed. As a beginning a common matrix both for centralized and decentralized system was prepared. The analysis has been divided into several logic compounds, first is an identification of general factors concerning a phenomena of extracting heat from mine water. Than those general factors has been divided into groups indicating some common issues like ecological life style or knowledge about renewable energy sources. It has mainly the educational and informational purpose. After those two introducing elements the final STEEP analysis concerning centralized and de-centralized systems for heat uptake were conducted using a specialist scientific software MICMAC.

After analysis of several aspects of centralized and decentralized heat uptake systems it seems that for households settlement centralized system is more stable. It seems that in technical aspects easier system operation played one of the main role. Also as main advantage of central system was positive PR for city decision makers as well less intervention into environment, connected with promotion of low carbon economy.

In both cases social aspects was strongly addressed. The analysis for centralized heat uptake system was more stable and well calibrated than for decentralized on. It also is taken into account like advantage of central system. Of course there might be plenty of different cases, with will require additional analysis. As whole analysis gathered plenty of different factors, and was further utilised as a base for conducting more quantified economical analysis as well as risk analysis.

Analysis of dynamic generation cost (DGC)

Method of DGC (indicator of dynamic unit cost) was used for the financial comparison of the options (and pilot sites operational data) considered in the project with which the ratio of unit costs of the system can be estimated. The method of determining this indicator is based on the methods of discounting known and used for many years, but it introduces analysis of the forecast effects of the investments in tangible terms and it refers to discounted investment costs (including the costs of implementation and operation) to the discounted material effects.

As part of the project it has been developed an analytical model (analytical tool for investors) that uses the collected data from other tasks, and allows to analyse the cost-effectiveness of thermal energy use from mine waters. The model focuses on the technical possibilities of using mine water for the thermal energy purpose, the financial aspects of the reality of the investment implementation and its profitability, as well as on the identification of economic and environmental reasons, which speak of the ultimate profitability of the investment.

The method developed was used to calculate specific examples. The analysis was made for available solutions by Markham UK and Barredo (ES). Both installations are in different countries, so their analysis takes into account different regional conditions. In addition, both installations are designed on a different rock. Barredo installation generates several dozen times more annual energy, so both solutions can’t be compared with each other.

The DGC analysis was carried out for the available models, because at the stage of conducting analyzes only access to full investment and operating costs was available for these models. The analysis was carried out for a 25-year exploitation period. Includes all operating costs, investment and replacement expenses.

The results of the analysis for the Markham installation (0,101 euro/kW) show that it is an expensive way of thermal energy pumping. This is due to the fact that the installation works on a small scale. With such assumptions, it seems more profitable to remain with the current source of thermal energy. However, there is a high probability that with a large installation producing much more energy, the investment will prove profitable. Barredo installation generates more heat annually. The results of DGC analysis for the Barredo installation (0,04 euro/kW) shows that it pays to develop this technology on a higher scale. The installation has much higher investment and operating costs, but taking into account its much greater effects (more thermal energy). the investment becomes profitable. The operation of such an installation in the 25-year period seems to be much more profitable than traditional methods of acquiring thermal energy.

Analysis of socio-economic costs and benefits (CBA)

CBA has a quantitative nature, which means the necessity of bringing quality categories to countable values. The analysis of costs and benefits of all the benefits and losses are expressed in units of financial and taking into account their value changes over time (NPV- Net Present Value). The valuation of social costs and benefits used social discount rate (SDR). In the analysed project the main attention was focused on greenhouse gas emissions.

In order to fully grasp the context of the issue, one should take into account whether the implementation of the investment will generate environmental benefits or generate environmental costs, hence the cost-benefit analysis (CBA) was used to assess and compare investment projects, where the number of greenhouse gases emitted was used. The economic cost of greenhouse gas emissions is related to the increase or reduction of greenhouse gas emissions generated by the project. In addition, future emissions of greenhouse gases have been discounted social discount rate applicable to the whole project, which reflects his marginal impact.

The CBA analysis was carried out for the available models, because at the stage of conducting analyzes only access to full investment and operating costs was available for these models. The analysis was carried out for a 25-year exploitation period. Includes all operating costs, investment and replacement expenses, as well as economic benefits for the environment resulting from the use of greener sources of thermal energy.

The following table presents the results of the CBA analysis for the Markham installation.

Table 2. Results of the CBA analysis for the Markham installation

Results of Economic Analysis	
NPV	-18 348
ENPV	-14 106
B / C	0,772

Source: GIG own elaboration

The analysis of the above table shows that from the financial point of view, the creation of a small heat recovery facility is poorly viable from the business point of view (negative NPV indicator). Taking into account the environmental benefits in the analysis improves the economic result of the investment, however, further the investment is unprofitable in business (ENPV <0 and B / C <1).

Economic analysis for a much larger installation should be much more profitable financially. The following table presents the results of the CBA analysis for the Barredo installation, which generates more heat annually.

Table 3. Results of the CBA analysis for the Barredo installation

Results of Economic Analysis	
NPV	1 902 942
ENPV	2 324 868
B / C	3,316

Source: GIG own elaboration

The results of the financial analysis for the Barredo installation are very beneficial. The investment from the business point of view is fully profitable (NPV> 0). In addition, the inclusion of environmental benefits in analyze (lower emission of greenhouse gases) significantly improves the profitability of investments (ENPV> 0 and B / C> 1). The economic analysis for the Barredo installation shows that using minewater for thermal energy (for a sufficiently large installation) is profitable for financial and economic reasons.

Conclusions

The analyzes carried out in Task 3.1 show that the use of mine water for thermal energy purposes may prove cost-effective from an economic point of view. At this stage of the work, it was diagnosed that the greatest importance for the profitability of investments is the size of the installation, and the actual amount of thermal energy generated by it.

The experience gathered in this task has allowed to build a general model for carrying out financial and economic analyzes for installations for recovering heat from mine waters. As part of subsequent tasks, a tool was created to model any installations, as well as to compare them with the current source of thermal energy.

Exploitation and impact of the research results

Interactive tool for investors gives a technical and economic value for potential beneficiaries interested in investments on hydrothermal energy. Results are available from LoCAL web page.

Results from this task were also disseminated within scientific article:

- Cichy L., Głodniok M. (2016) Risk analysis in the investment planning phase, concerning use of mine water for heating family houses, Energy Policy Journal, vol. 19, 117-136, ISSN 1429-6675

Task 3.2 Pathways to market

Task leader UoG

Main objectives

It was planned to use established Technology Readiness Level (TRL) appraisal tools widely used in the EU (e.g. http://ec.europa.eu/enterprise/sectors/ict/files/kets/ex_of_practice_ket_final_report_en.pdf) to evaluate all the technical results arising from the other work packages, to establish how far up the TRL scale they have reached during the life of LoCAL. All LoCAL outputs felled above TRL 5, and some reached TRL 8 ("…Actual Technology completed and qualified through test and demonstration …"). For those outputs falling below TRL 8, an analysis were performed of the remaining steps to reach 8, and for those at TRL8, the industrial partners in LoCAL participated in a focused workshop on final delivery to market (TRL 9).

Description of activities and discussion

The activities included the following:

1. Assessment of the TRL level for the LOCAL's projects in the three countries.
2. Workshop to assess route to markets.
3. On-line survey to assess the knowledge and awareness of the technology within local councils, public, academic and industrial organizations and institutions.

4. The development of a small-scale simulator to explain the technology and involve university students in the design and implementations.

Main results

This task has analysed the possibilities of market implementations. Such analysis intends to bring research and scientific results of LoCAL projects closer to market. We have used established Technology Readiness Level (TRL) appraisal tools, widely used in the EU, to evaluate all the technical results arising from the project, to establish how far up the TRL scale they have reached during the life of LoCAL. As anticipated, all LoCAL outputs have ranked above TRL 5. For systems at TRL8, the industrial partners have participated in a focused workshop on final delivery to market (TRL 9). To support generic development, an on-line survey was developed for companies, students/academics, local councils and the public to capture their knowledge and understanding of the technology to develop a comprehensive commercialisation plan to TRL9. Hence, the industrial partners will then be empowered to take forward the advancement of all outputs to TRL 9.

A Workshop for pathway to commercialization on Challenges and Opportunities of using water from Flooded Coal Mines for Heating and Cooling applications was organized at Nottingham Trent University (NTU), presided by Prof. Amin Al-Habaibeh. The workshop has included participants from a wide range of sectors including Nottingham City Council, Alkane Energy Ltd, The Coal Authority, Clean Rivers Trust, Gannet Ltd, UK Community Works CIC (Community Works) and energy researchers.

Professor Al-Habaibeh defined the topics of this workshop that needed to be discussed which are:

1. What are the challenges towards commercialisation to enable the technology to be widely implemented? (with respect to local council, energy companies, installers, users, environment, planning permission, etc.)
2. What are the commercial benefits that can be obtained from using mine water for heating/cooling?

Figure 30. The workshop: Pathways to Commercialisation of energy from flooded coal mines, organised at NTU.

Source: Prof. Amin Al-Habaibeh, Nottingham Trent University (NTU) archive

An online survey was carried out. The survey had 4 different questionnaire targeting 4 different audiences (energy companies, local councils, consumers and students/academics). In total 28 companies responded, 16 local councils, 85 students/academics and 40 representatives of the general public. The objective was to see if further and wider improvement of the awareness of the technology is needed to enhance the pathway to commercialisation on the long term. The results found indicate that more efforts are needed to educate students/academics and the public about the technology to enhance the commercialisation on the long term (see Figure 31 and Figure 32). However, the results show that most of local councils and energy companies are aware of the technology. From the survey (Figure 33) it is clear that the majority of the energy-related companies are aware of the possibility of using the mine water as an energy resource. Majority of the local councils who influence the general decision making were also aware of the technology of using mine water as an energy resource. However, the survey showed that the general public which includes customers and researchers/students were not aware of the principles of the technology of using mine water as an energy resource (Figure 33). This is bit concerning, as without the awareness about the principles of the technology, it would be difficult for the companies to convince customers to go for this technology without a clear long term strategy.

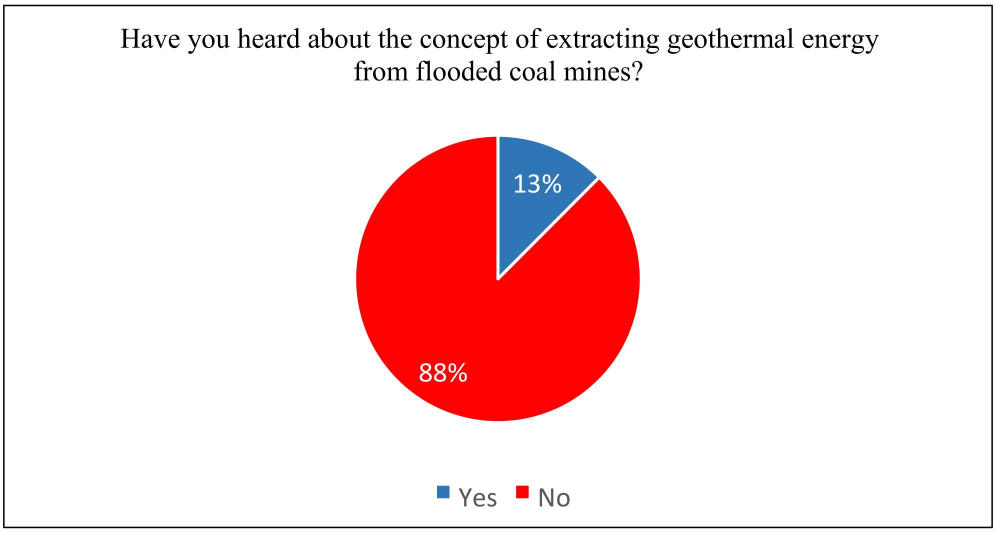


Figure 31. Survey regarding the Technology awareness among the general public

Source: NTU own elaboration

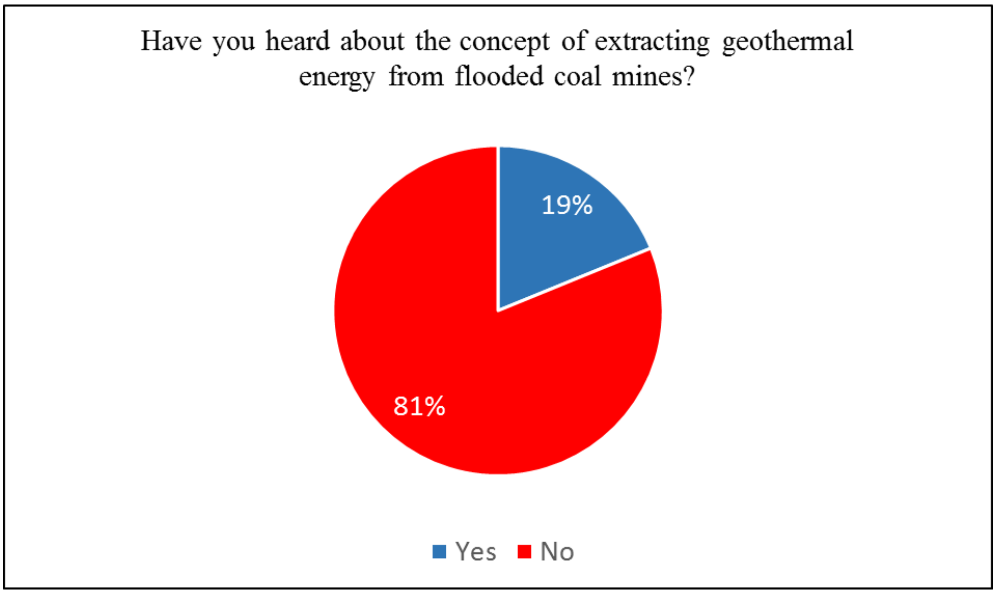


Figure 32. Survey regarding the Technology awareness among students and academics

Source: NTU own elaboration

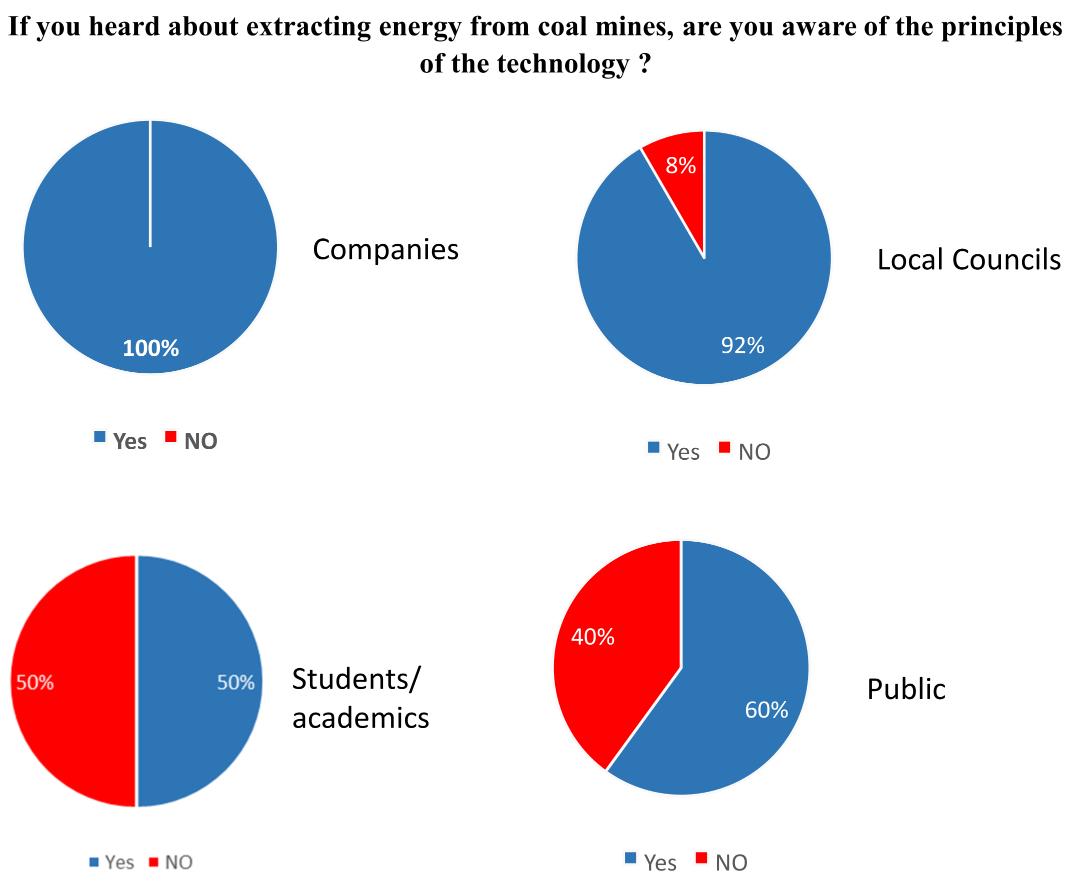


Figure 33. Awareness of the technology among the respondents who have heard about extracting energy from flooded coal mines

Source: NTU own elaboration

The results have been presented within Deliverable 3.2 (see Annex 13 to the report).

Conclusions

It is clear from our workshop, LoCAL work packages and the on line survey that pathway to commercialisation could be considered for long term and short term aspect:

Short term: The technology could be feasible commercially for the short term if some conditions are available:

1. Infrastructure bore hole is available.

2. Water already pumped (for other reasons)

3. Government organisations can absorb the cost of infrastructure.

4. One main user of energy (e.g. hospital, university, shopping mole), where discussion and discussions can be simplified.

5. Water level is high (low energy for pumping).

The above conditions will allow shorter payback period and enhance the commercialisation process.

Long Term: On the long term, the following measures should be taken:

1. Integrate the technology with education and public media.

2. More public engagement programmes are needed.

3. Educate energy installers companies and provide training courses on how the technology works and how much it should cost.

4. Some legal issues should be resolved regarding the technology, particularly in relation to district heating.

5. The need to be able to change suppliers or ensure reasonable cost (cheaper than current technologies).

Exploitation and impact of the research results

In relation to this task, the following publications have been delivered:

- Al-Habaibeh, A., 2018. How the legacy of dirty coal could create a clean energy future, *The Conversation*.
  The paper has achieved high public impact with more than 12,500 public reads and was republished in *EconoTimes* and *IMechE*.
- Al-Habaibeh, A., Meyerowitz B., Duolan, and Athresh A., 2015. The design and development of an innovative simulator for an open loop system for extracting energy from flooded coal mines. Energy Procedia, 75, pp. 1470-1476. ISSN 1876-6102
  The paper integrated basic knowledge with teaching and learning and technology presentation to students and public audience.
- Al-Habaibeh, A., Shakmak, B. and Fanshawe, S., 2017. The development of an experimental test rig to evaluate the performance of a new technology for stratified hot water storage - the Water Snake. Energy Procedia, 142, pp. 3644-3653. ISSN 1876-6102
  The paper explore thermal storage technology as part of enhancing the efficiency.

Task 3.3 Models for incorporating cooling into a delivery system

Task leader: UoG

Main objectives

Stated objective (proposal): "We will use recent commercial performance data from large-scale groundwater cooling systems in the UK (cf Birks et al. 2013) as a platform for developing a mine-water specific protocol and costings model for direct (i.e. with only a heat exchanger) and indirect (i.e. incorporating also a heat-pump) use of abandoned coal mine waters for space cooling. For the case of flooded underground workings we will examine the practical implications of use of mine water as an inter-seasonal thermal energy store, with heat rejected in summer being available for exploitation for space heating during winter. We will also undertake a complete energy analysis of such a system, with the aim of identifying the threshold conditions (in terms of local ambient air temperature and mine water temperature and available flow rate) at which it becomes economically preferable to incorporate a heat-pump into a cooling delivery system. GIG will perform the task concerning Polish site using the data from Poland, whereas university of Oviedo will perform the task for Asturias (Spain)"

Description of activities and discussion

The outputs of the project have been completed as follows:

- A report, comprising two parts:
  - Part 1 examines various modes by which a cooling component can be incorporated into mine water heating schemes (passive vs active cooling, reversible heat pumps, district cooling networks, manipulation of mine reservoirs as thermal energy stores).
  - Part 2 documents three examples of mine water schemes which have implemented a component of groundwater cooling in practice: Barredo (Asturias, Spain), Springhill (Nova Scotia, Canada) and Heerlen (Netherlands)
- Three Excel based spreadsheet models, which assess the thermal and economic performance of various options for incorporating cooling into a mine water (or other groundwater-based) system:

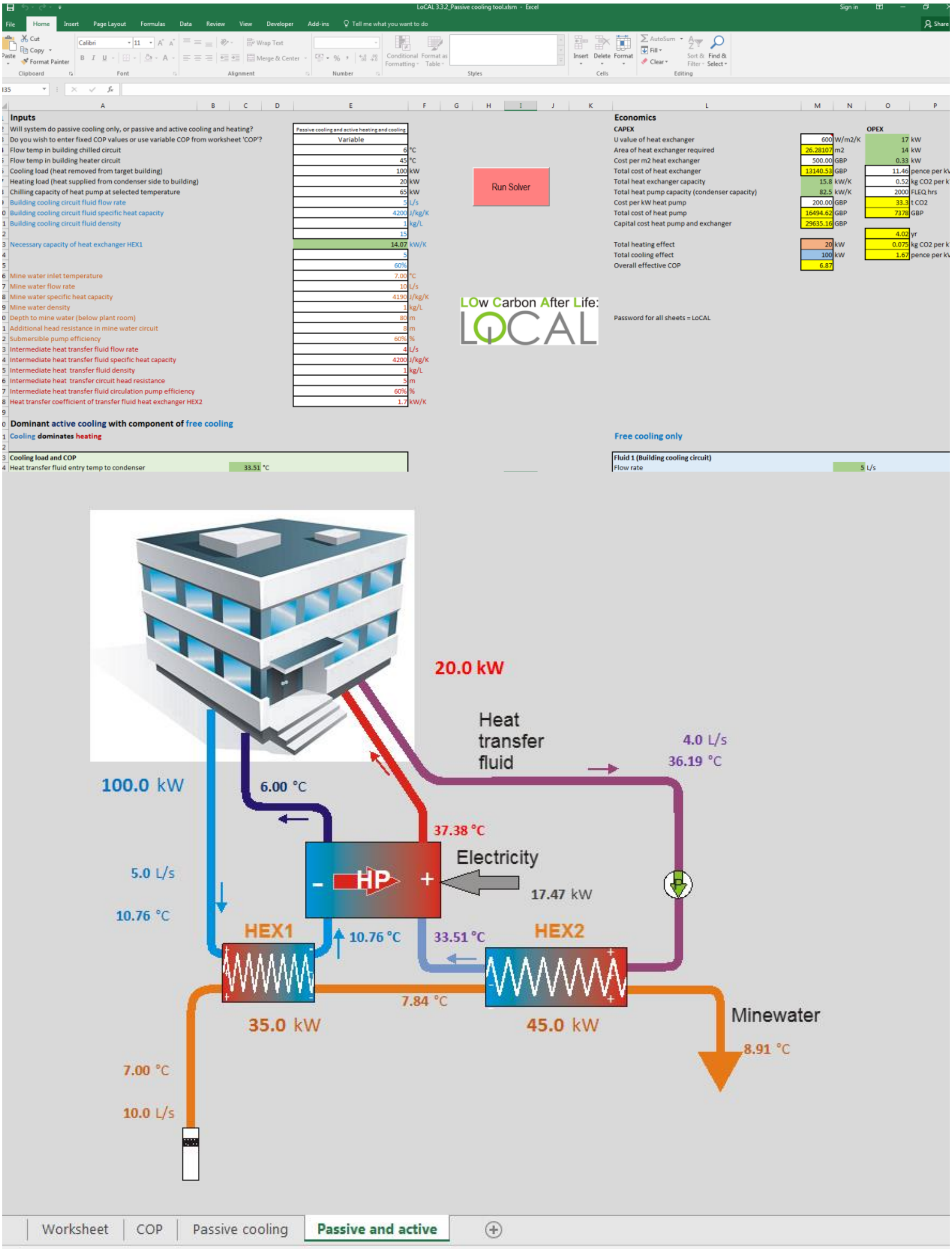
i. **Model 1.** LoCAL 3.3.1_Active heating or cooling tool.xlsm. This model simulates the incorporation of cooling into active (heat pump-driven) systems. The model simulates both heating-dominated or cooling-dominated systems.

ii. **Model 2.** LoCAL 3.3.2_Passive cooling tool.xlsm. This tool simulates both straightforward passive cooling performed by mine water, and the incorporation of an element of passive cooling into an active cooling / heating system.
iii. **Model 3.** LoCAL 3.3.3_Discrete heating and cooling arrays.xlsm. This model simulates the use of "chillers" and heat pumps performing cooling and heating simultaneously in a system.

Main results

The report (57 pages) was completed by the end of 2016 (and was sent out for review on 7th January 2017). The final version (v. F1.1) of the report, together with the 3 models, was issued on 15th March 2017. The results have been presented within Deliverable 3.3 (see Annex 14 to the report).

Collaboration and input to the report was gratefully received from HUNOSA (Spain) and from Mr Brian Herteis of Cumberland Municipality, Nova Scotia (responsible for the Springhill mine water system). The contact with Mr Herteis raises a potential future collaboration with Cumberland Municipality as a Canadian partner and a collaborative paper on their mine water systems.



Inputs

Will system do passive cooling only, or passive and active cooling and heating?	Passive cooling and active heating and cooling	
Do you wish to enter fixed COP values or use variable COP from worksheet 'COP'?	Variable	
Flow temp in building chilled circuit	6	°C
Flow temp in building heater circuit	45	°C
Cooling load (heat removed from target building)	100	kW
Heating load (heat supplied from condenser side to building)	20	kW
Chilling capacity of heat pump at selected temperature	65	kW
Building cooling circuit fluid flow rate	5	L/s
Building cooling circuit fluid specific heat capacity	4200	J/kg/K
Building cooling circuit fluid density	1	kg/L
	15	
Necessary capacity of heat exchanger HEX1	14.07	kW/K
	5	
	60%	
Mine water inlet temperature	7.00	°C
Mine water flow rate	10	L/s
Mine water specific heat capacity	4190	J/kg/K
Mine water density	1	kg/L
Depth to mine water (below plant room)	80	m
Additional head resistance in mine water circuit	8	m
Submersible pump efficiency	60%	%
Intermediate heat transfer fluid flow rate	4	L/s
Intermediate heat transfer fluid specific heat capacity	4200	J/kg/K
Intermediate heat transfer fluid density	1	kg/L
Intermediate heat transfer circuit head resistance	5	m
Intermediate heat transfer fluid circulation pump efficiency	60%	%
Heat transfer coefficient of transfer fluid heat exchanger HEX2	1.7	kW/K

Dominant active cooling with component of free cooling

Cooling **dominates** heating

Cooling load and COP

Heat transfer fluid entry temp to condenser 33.51 °C

Economics

CAPEX			OPEX	
U value of heat exchanger	600	W/m2/K	17	kW
Area of heat exchanger required	26.28107	m2	14	kW
Cost per m2 heat exchanger	500.00	GBP	0.33	kW
Total cost of heat exchanger	13140.53	GBP	11.46	pence per k
Total heat exchanger capacity	15.8	kW/K	0.52	kg CO2 per k
Total heat pump capacity (condenser capacity)	82.5	kW/K	2000	FLEQ hrs
Cost per kW heat pump	200.00	GBP	33.3	t CO2
Total cost of heat pump	16494.62	GBP	7378	GBP
Capital cost heat pump and exchanger	29635.16	GBP		
			4.02	yr
Total heating effect	20	kW	0.075	kg CO2 per k
Total cooling effect	100	kW	1.67	pence per k
Overall effective COP	6.87			

Password for all sheets = LoCAL

Free cooling only

Fluid 1 (Building cooling circuit)

Flow rate 5 L/s

Figure 34. Screenshots from Excel Model *LoCAL 3.3.2_Passive cooling tool.xlsm.*

Source: UoG own elaboration

Conclusions

Task 3.3 has resulted in a comprehensive state-of-the-art review of arguably the three largest minewater-based heat pump systems, which incorporate cooling, active in the world today – Barredo, Heerlen and Springhill – and the different means by which heating and cooling are delivered to customers. The Task has also developed three analytical spreadsheet-based models of heating and cooling delivery by various configurations of heat pumps and heat exchangers. Such models are not previously readily available to heat pump system designers.

Exploitation and impact of the research results

The Task 3.3 report has been made available to the public via *ResearchGate* as is assigned doi: 10.13140/RG.2.2.27377.48486. As of 18/7/17 it has achieved 70 reads.

The three spreadsheet based models are also all freely available in the public domain via *ResearchGate* and the Toolbox facility at the LoCAL website (http://www.local.gig.eu/index.php/toolbox).

Task 3.4 Ownership, management and financial models; accessibility to subsidies with different ownership models and responsibility for contamination / licensing aspects with different ownership models

Task leader: GIG

Main objectives

Within Task 3.4 one of the main issues was to identify optimum solution from the point of view of all the relevant criteria and factors affecting the viability and profitability of the pilot.

The implementation of solutions which are the subject of pilot requires interference to the existing ownership and formal legal conditions involving additional participants in the project, both during construction of the pilot installation and its maintenance (including consumers of thermal energy).

A specific and very important aspect of LoCaL project was to determine the appropriate legal and formal regulations protecting the interests of all stakeholders. To achieve this task it was conducted:

- formal and legal analysis in aspect of water ownership in each country,
- analysis of law concerning environmental aspects of minewater discharge,
- elaboration of models concerning legal, financial and responsibility aspects,
- analysis of possibilities of implementing different ownership models.

According to the current state of knowledge regarding land ownership and infrastructure conditions at the liquidated mines are a common obstacle to market activities involving stakeholders from both the public and private sectors.

The result of the task will be to develop an appropriate model of constructing the subjective character of the project, which will allow for optimal relationships and dependencies - legal, ensuring the implementation of the project with the available sources of funding and maintenance of the new infrastructure.

Description of activities and discussion

On the basis of the obtained information and materials, work began on the calculation algorithm, which ultimately was used to perform both the socio-economic costs and benefits analysis of such investments (results from CBA as GDC and analysis). Information obtained at the stage of desk research, as well as on the basis of materials provided by the project partners in the form of data and macroeconomic parameters (including data on investment and operating costs) and technological developments in the field of operating parameters from an industrial scale (industrial plant), were used. On this basis GIG team developed a catalogue of indicators for each of the individual modules (environmental, economic, ecological, legal, technological, etc.) used during analysis.

For purpose of effective realization of Task 3.4 it has been created tool that works in two steps and allows the first step to be conducted on the basis of the number of questions (interview with a potential investor), show the recovery of heat from mine water is at all possible in the region. User tools were prepared in a simple manner (based on the "traffic light") whether the investment is feasible and indicate which items can hinder or completely prevent the construction of the installation.

Main results

Based on the experience gathered as part of Task 3.1, an analytical tool was developed to analyze the cost-effectiveness and financial viability of using mine water to obtain thermal energy. As part of the work in this task, the greatest amount of work was absorbed by finding all technical, formal, legal and financial aspects, which affect the results of analyses and include them in an universal analytical tool. Analysis were consulted with partners and then refined with information coming from feedback.

For further use in interactive tool algorithms including interrelation between different types of ownership and technical aspects were prepared (Figure 35).

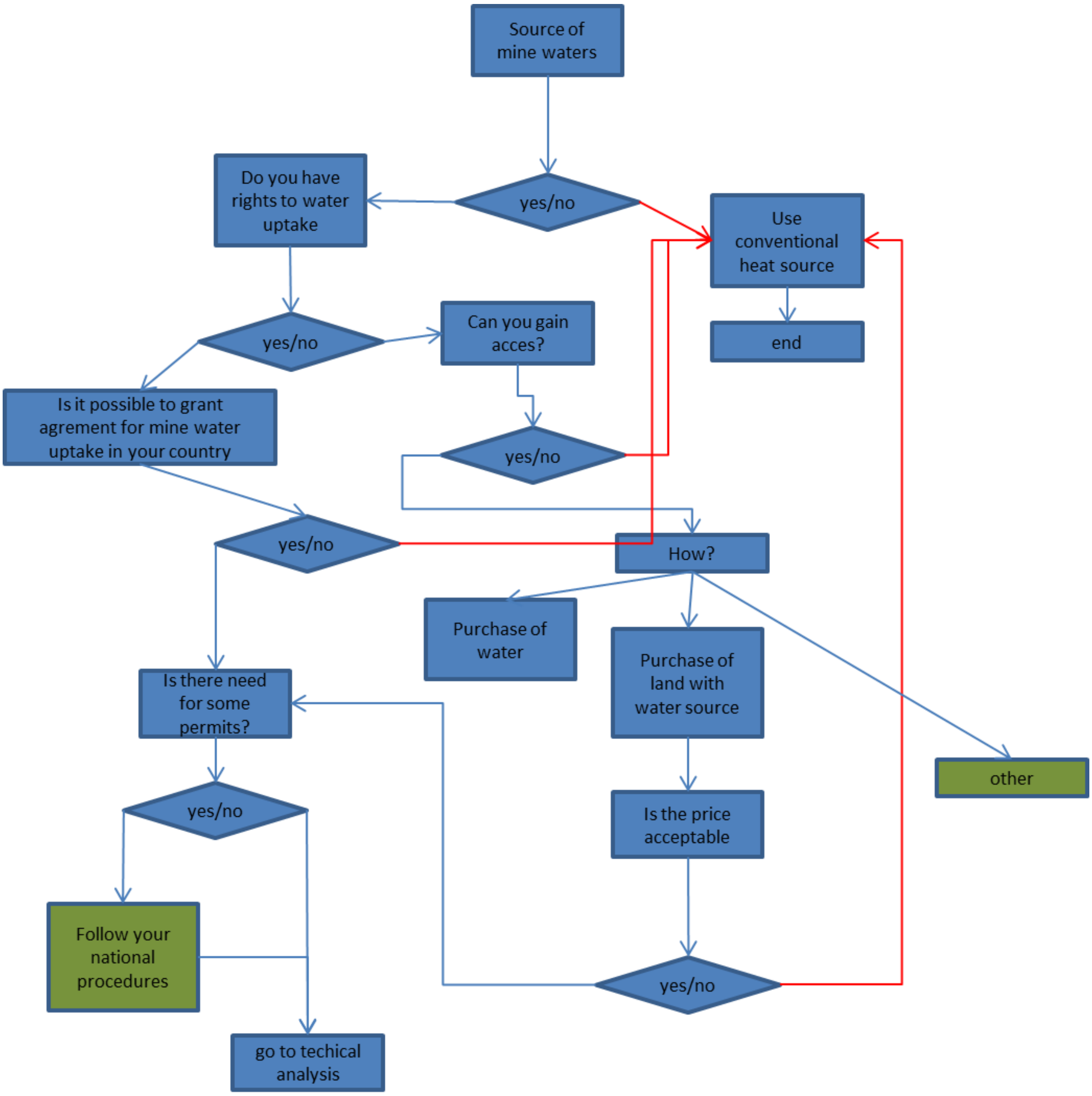


Figure 35. An example of algorithm prepared for implementation into interactive tool for investors

Source: GIG own elaboration

For preparation of tool for investors results from task 3.1 and analytical work in task 3.4 were utilised.

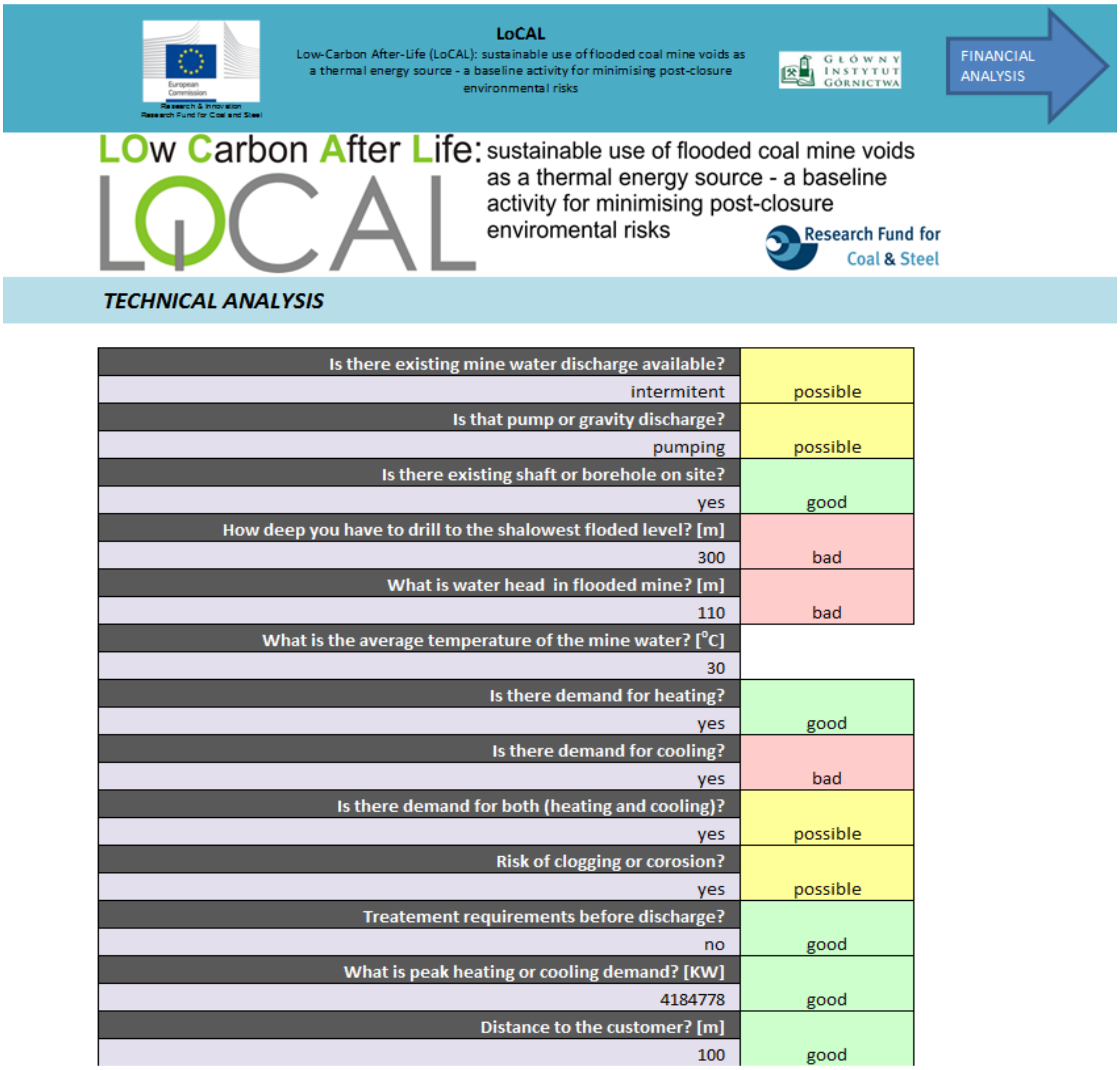
An analytical model (analytical tool for investors) has been developed. This tool uses the methodology elaborated in tasks 3.1. and collected data from and 3.4, and allows to analyse the cost-effectiveness of thermal energy use from mine waters. The model focuses on the technical possibilities of using mine water for the thermal energy purpose, the financial aspects of the investment implementation and its profitability and the identification of economic and environmental reasons, which speak of the ultimate profitability of the investment.

With the combination of all obtained information regarding the possibility of carrying out investments in the heat energy acquisition from the mine water, user has the possibility to make the final decision. By the use of this tool the user gets full information regarding the profitability of the investment, compared to the current (conventional) source of thermal energy.

The user on the basis of environmental benefits analysis can assess whether the investment actually brings environmental benefits and, for example, despite the unfavourable financial results is indicated for its realization for reasons of no financial benefit. But in order to get a complete view of information to make investment user should analyze the results of indicators for economic net present value (ENPV) and benefit / cost indicator (results of CBA - costs and benefits analysis). In the figure below the results presented by the tool for the economic analysis were presented.

With the combination of all obtained information regarding the possibility of carrying out investments in the heat energy acquisition from the mine water, user has the possibility to make the final decision. By the use of this tool the user gets full information regarding the profitability of the investment, or to remain at the current (conventional) source of thermal energy.

An exemplary analysis made with the developed tool is presented below.



LoCAL
Low-Carbon After-Life (LoCAL): sustainable use of flooded coal mine voids as a thermal energy source - a baseline activity for minimising post-closure environmental risks

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

LOCAL

TECHNICAL ANALYSIS

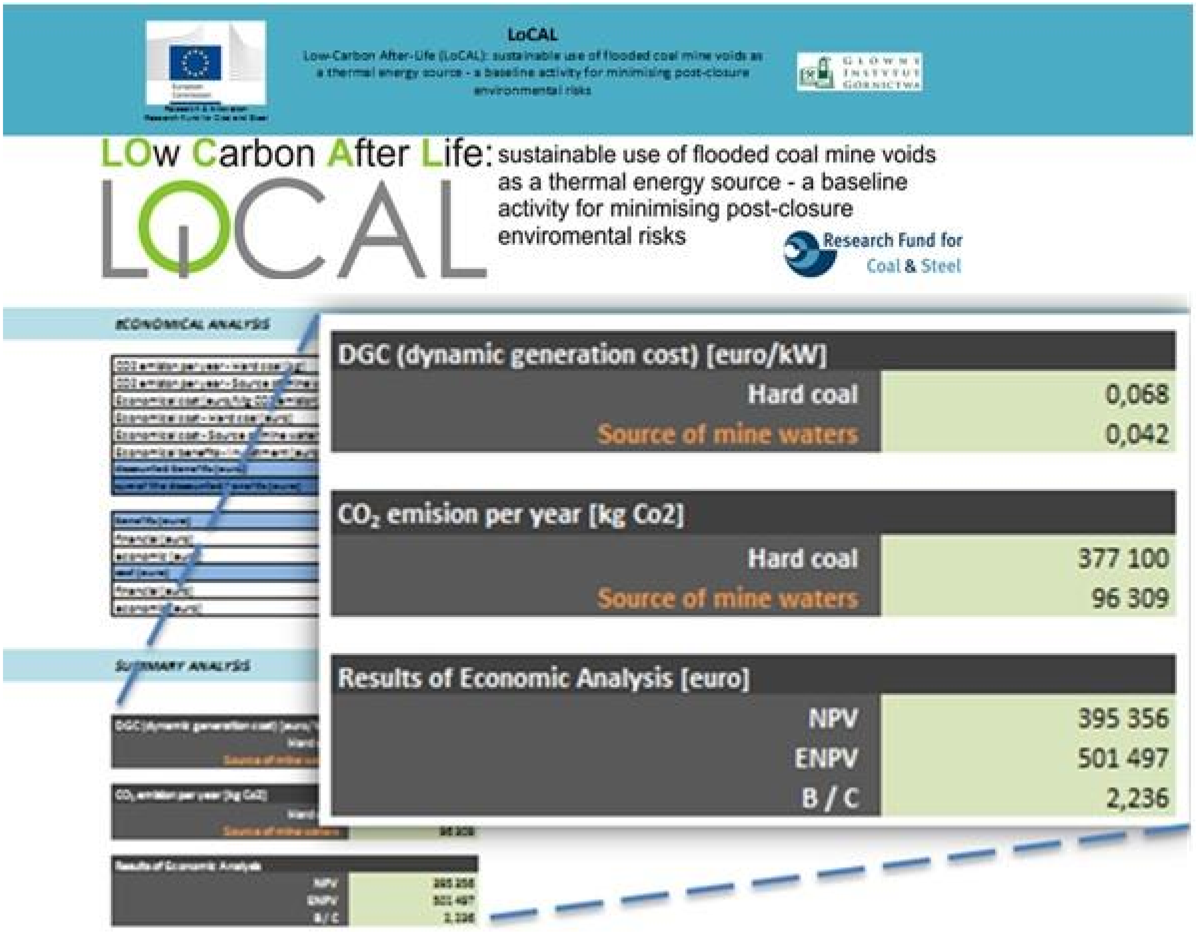
Is there existing mine water discharge available? intermitent	possible
Is that pump or gravity discharge? pumping	possible
Is there existing shaft or borehole on site? yes	good
How deep you have to drill to the shalowest floded level? [m] 300	bad
What is water head in flooded mine? [m] 110	bad
What is the average temperature of the mine water? [°C] 30	
Is there demand for heating? yes	good
Is there demand for cooling? yes	bad
Is there demand for both (heating and cooling)? yes	possible
Risk of clogging or corosion? yes	possible
Treatement requirements before discharge? no	good
What is peak heating or cooling demand? [KW] 4184778	good
Distance to the customer? [m] 100	good

Figure 36. Example result from the tool for investors (with traffic light methodology)

Source: GIG own elaboration

The above example shows that the tool using "traffic lights" shows the reasons for which the investment can be profitable or can’t be profitable for financial reasons. The next stage of the analysis in the developed tool is the analysis of financial profitability in relation to another alternative energy source.

When performing the analysis, the user obtains information about the DGC indicator value during the analysis period (15, 20 or 25 years). The results can be compared with an alternative source of thermal energy. The tool also allows you to calculate the payback period of the investment and present it in the figure. The user obtains information about the greenhouse gas emissions that will occur depending on the choice of a particular source of thermal energy. In the final part, the user obtains economic indicators (ENPV and B/C) that ultimately allow making a decision regarding the profitability of the investment. A complete analysis can be made for both the centralized and decentralized systems. The following figure shows the analysis performed for a centralized system for a specific installation example (Figure 37).



LoCAL

Low-Carbon After-Life (LoCAL): sustainable use of flooded coal mine voids as a thermal energy source - a baseline activity for minimising post-closure environmental risks

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

ECONOMICAL ANALYSIS

SUMMARY ANALYSIS

DGC (dynamic generation cost) [euro/kW]	
Hard coal	0,068
Source of mine waters	0,042

CO_2 emision per year [kg Co2]	
Hard coal	377 100
Source of mine waters	96 309

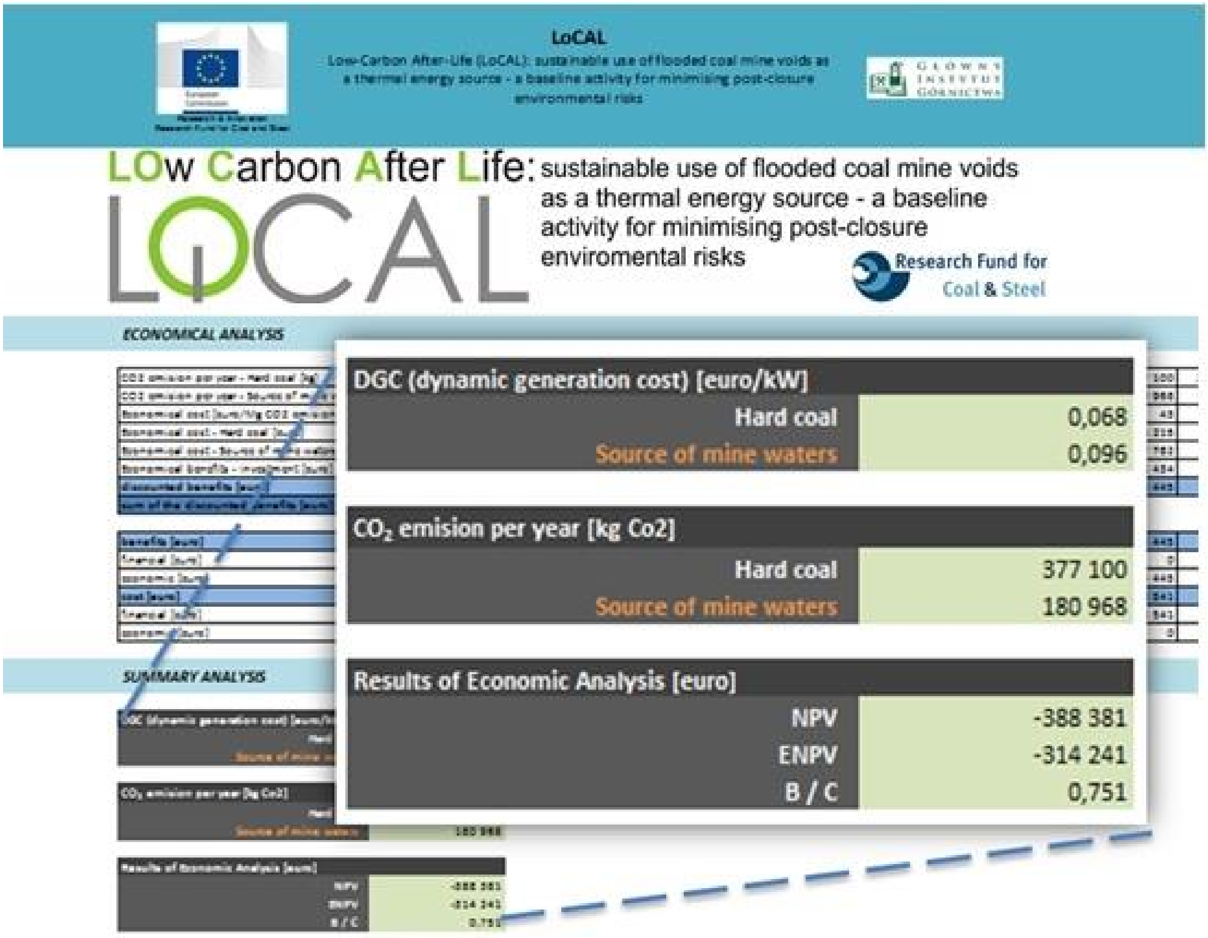
Results of Economic Analysis [euro]	
NPV	395 356
ENPV	501 497
B / C	2,236

Figure 37. Results of analysis for a centralized system for a specific installation example

Source: GIG own elaboration

The analysis for the centralized heat supply system (source of mine waters) was made with reference to the alternative source (hard coal). The basic financial indicators show that commissioning the installation using mine water is more cost-effective than the existing system. Greenhouse gas emission indicators are also much better than the energy source used so far. Recent results show that in economic terms, the installation is very profitable (positive ENPV and B / C ratio> 1).

The following figure shows the analysis performed for a decentralized system for a specific installation example (Figure 38).



LoCAL

Low-Carbon After-Life (LoCAL): sustainable use of flooded coal mine voids as a thermal energy source - a baseline activity for minimising post-closure environmental risks

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

LOCAL

Research Fund for Coal & Steel

ECONOMICAL ANALYSIS

SUMMARY ANALYSIS

DGC (dynamic generation cost) [euro/kW]	
Hard coal	0,068
Source of mine waters	0,096

CO_2 emision per year [kg Co2]	
Hard coal	377 100
Source of mine waters	180 968

Results of Economic Analysis [euro]	
NPV	-388 381
ENPV	-314 241
B / C	0,751

Figure 38. Results of analysis for a decentralized system for a specific installation example

Source: GIG own elaboration

The analysis for the decentralized heat supply system (source from mine waters) was made for an alternative source (hard coal). The basic indicators show that financial performance of the installation is unprofitable. However, greenhouse gas emission indicators are much more favorable than the energy source used so far. Nevertheless, the last economic indicators show that the installation is still unprofitable for the investor in relation to the 15-year analysis period.

In summary, for each of the systems, the analysis of financial and economic profitability will have different results. A centralized system is characterized by a much higher profitability and a faster payback period.

The tool and other results of works within task 3.1. and 3.4 are presented within Deliverable 3.1 (see Annex 12 to the report).

Conclusions

As part of the project an analytical model (analytical tool for investors) has been developed that uses the collected data from other tasks, and allows to analyse the cost-effectiveness of thermal energy use from mine waters. The model focuses on the technical possibilities of using mine water for the thermal energy purpose, the financial aspects of the reality of the investment implementation and its profitability, as well as on the identification of economic and environmental reasons, which speak of the ultimate profitability of the investment.

Exploitation and impact of the research results

Task 3.4 main results was preparation of survey questionnaire for potential investors which further became a one of main part of interactive tool for investors (available at: http://www.local.gig.eu/index.php/businessman). Also elaborated algorithms were utilized as an engine for above mentioned tool. Summarizing, the Task 3.4 conducted actions lead to develop an appropriate model of constructing the subjective character of the project, which will allow for optimal relationships and dependencies - legal, ensuring the implementation of the project with the available sources of funding and maintenance of the new infrastructure. All results were also presented at the dedicated workshop during LoCAL Final Conference, which was held at GIG premise in Katowice on 1st of June 2017.

Task 3.5 Toolbox assuring multiplication of the project results

Task leader: GIG

Main objectives

All LoCAL tools and algorithms (elaborated within Tasks 1.1, 1.2, 2.1, 2.2, 3.2, 3.3) were combined as a one toolbox gathering all utilities for mine waters heat extraction.

Elaborated tools were characterized and categorized within Toolbox, with full description and manuals. Such approach will allow to multiplication solutions for preliminary studies at sites that gives opportunity to heat extraction from mine waters.

Description of activities and discussion

LoCAL Project Toolbox is a web page space containing all tools elaborated within LoCAL project, which are categorized in three categories: Science, Engineering and Economy.

LoCAL Project Toolbox, is a web page space containing all utilities elaborated within LoCAL project. All tools are categorized in three categories: Science, Engineering and Economy. So represent three switches, were user can find specific tool description, button for its download and button for manual download.

For analytical purposes three possible paths of Toolbox use has been prepared. Every path is focused on different goal, and shows simple roadmap how to use different tool in specific cases. Suggested paths are addressed to science, business, and official representatives.

Figure 39. Toolbox start page

Source: http://local.gig.eu/index.php/toolbox

Toolbox is free and available at the internet address http://local.gig.eu/index.php/toolbox. Additional guide for toolbox use is presented in Annex 15 to the report.

Main results

Main result of Task 3.5 is elaboration of toolbox which allows to utilize LoCAL project results in "user friendly way". LoCAL Toolbox was designed for end-users interested in uptaking heat from minewaters. It's value was tested in real conditions and for technological purpose at the ARMADA pilot site. Especially for end-users three suggested paths of use were prepared:

Toolbox use – suggested pathways

For analytical purposes three possible paths of Toolbox use has been prepared. Every path is focused on different goal, and shows simple roadmap how to use different tool in specific cases. Suggested paths are addressed to science, business, and official representatives, below main subpages of Toolbox and way of its use were described:

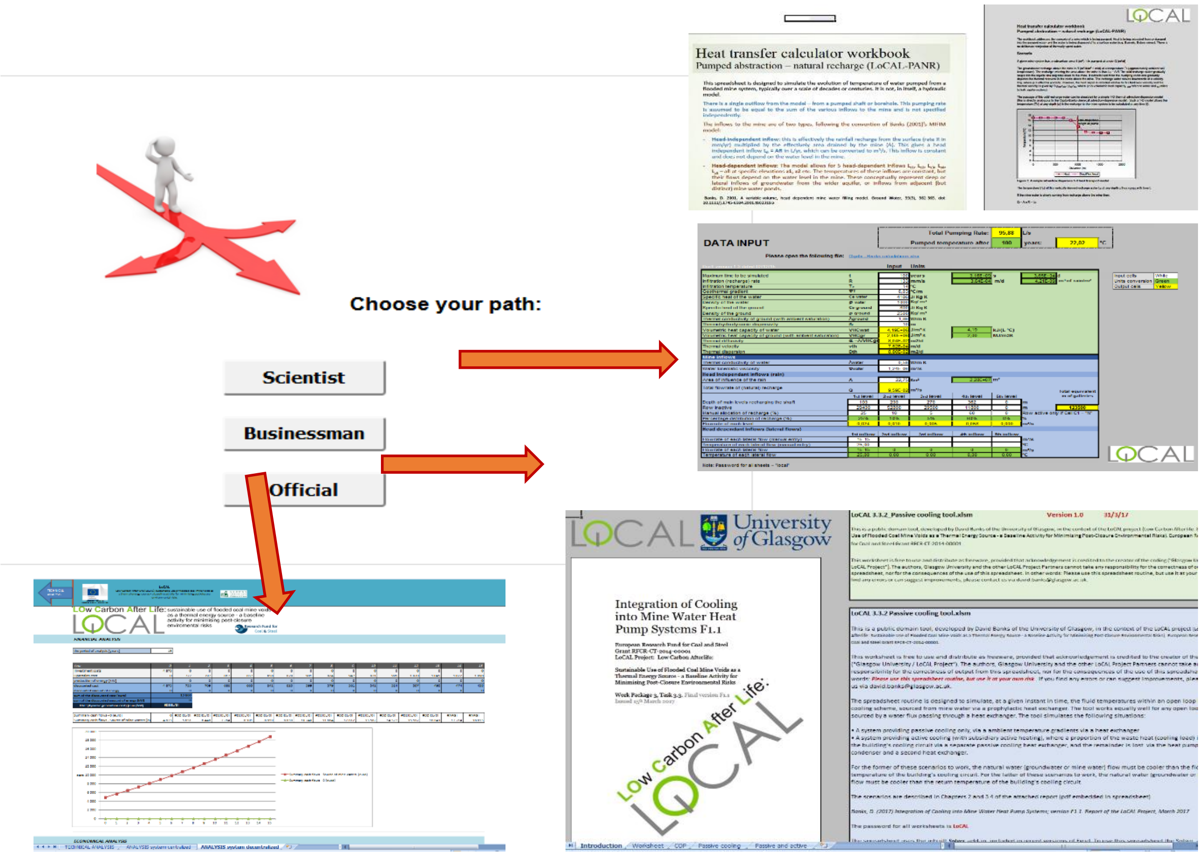


Figure 40. Possible paths selection and pictures of tools proposed as a starting point for each path

Source: GIG own elaboration, http://local.gig.eu/index.php/toolbox

User needs to click on proper button, and then moves to the subpage with description and roadmap for selected path. The possibility of choosing each of the paths is presented in a pictorial way, with instructions.

Scientist's path: Path suggested for scientist allows to make full use of elaborated tools. As a first step we suggest to use PNAR and PAAR tool, to understand and model heat transfer phenomena. If someone wants to go further in analysis can make use of engineering tool for heating/cooling process. For estimation of potential costs , economic tool will be useful.

Businessman's path: Path suggested for business starts from interactive tool for investors (economy) and allows for fast indication of potential value coming from heat extraction from mine waters. Second step of analysis allows to go deeper in technical aspects of cooling and heating process .

Official's path: Suggested path for officials focuses mainly on socio-economic aspects from interactive tool for investors with specific use of CBA analysis that allows to indicate environmental and social aspects of heat extraction from mine water.

Summarizing LoCAL Project Toolbox is a web page space containing all utilities elaborated within LoCAL project. All tools are categorized in three categories: Science, Engineering and Economy. For analytical purposes three possible paths of Toolbox use has been prepared. Every path is focused on different goal, and shows simple roadmap how to use different tool in specific cases. Suggested paths are addressed to science, business, and official representatives.

Conclusions

Elaborated Project LoCAL toolbox (http://local.gig.eu/index.php/toolbox) contains all tools that were elaborated within the project. Use of html techniques made toolbox easy to access and wide spread set of practical knowledge that now is available for every person interested in heat extraction from nine waters. Making elaborated tools interactive with web page access makes them easy to use from every platform with net connection.

Exploitation and impact of the research results

Possibility of future use of LoCAL Toolbox was widely spread among mine companies at branch meetings and workshops as well as at the dedicated toolbox workshop at LoCAL Final Conference.

WP4. Pilot Implementations

Main objectives

Work Package 4 involved the implementation of pilot plants in the UK, Spain and Poland. As well as having individual objectives and deliverables of their own, each pilot essentially acted as a 'testbed' to provide information to help inform various tasks in other work packages.

Main objectives of this work-package have been as follows:

- to find out how the COP of a large-scale system differs with water level at different heights below the ground surface attending to a flooding process,
- to quantify the mixing process and the affection to the efficiency (COP) in a large-scale system the reinjection of used mine water,
- to find out how the COP of a large-scale system differs by the use of different heat exchanger and the economic impact of WP2, advanced methods for preventing corrosion and incrustation affecting heat transfer,
- to support with real data models for efficiency of energy extraction and distribution analyzed on WP3.

Description of activities and discussion

Pilot implementations at sites in the UK, Spain and Poland have been realized.

In frame of Task 4.1 LoCAL project pilot applications in UK have been implemented in: Markham Colliery, Bolsover, Derbyshire and Caphouse Colliery, Overton, near Wakefield, Yorkshire.

In frame of Task 4.2 Spanish pilot implementation have been performed at Barredo shaft in Mieres, Asturias. In the initial plan only two installations (Hospital and University) were meant to develop this task. But in 2016 another installation was built and it started to operate in May 2016 so the results of this installation were of course very useful to fulfill the objectives of this task. This project was in the FAEN (Asturian Energy Foundation) building very close to Barredo Shaft.

In frame of Task 4.3 pilot application in Poland have been performed. Pilot site is located in Bytom on post mining area where polish project partner - Armada Development, continues its activity of land reclamation as golf course club and housing development. The proximity of mine water discharge from abandoned but still dewatered Szombierki mine was the reason for using renewable energy as the main source for heating at the planned residential area

Main results

Task 4.1 Markham: The monitoring and telemetry system developed at this site has enabled detailed data gathering on performance. The use of the plant has also been extended to include heating of a 1.5MWe gas reciprocating engine. Low grade heating is required when the engine is on standby for serving calls from the grid for support generation. Previously this was done with an integral 11KW electric heater but the heat pump system now serves this duty at significantly reduced cost.

Task 4.1 Caphouse: Operation of both the open loop and closed loop (energy blade) systems have been carried on Telemetry was installed to provide detailed real time monitoring of the system and electronic data gathering. The dosing equipment has been installed to inject sodium dithionate into the raw minewater feed prior to the heat exchangers. The dosing process has been automated based on monitoring of minewater quality parameters. Data have been gathered on the performance of the dosing process in inhibiting the build-up of ochre in the heat exchangers and pipework.

The main results of the **Task 4.2** can be summarized as follows:

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 once and it was completely clean.
In FAEN installation the result is the same, it is in operation since May 2016 and there is no need to clean the heat exchanger. It is different in the University Installation where there is a need 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.
The great amount of water available in Barredo Shaft helps to control the COP in each installation, so there is no important reduction in the COP during the normal operation when the heat exchanger is dirt with iron.

As a result of **Task 4.3** the designed and implemented heating system in Armada Bytom powered by the heat of mine water works properly, and gives satisfying result. During the low daily temperatures it gives significant cost savings for heating purposes. With the COP of 3 it can be indicated that by the cost of 1 kW of electrical energy 3 kW of heat energy can be obtained.

Conclusions

LoCAL project pilot applications in UK have been implemented in: 1) Markham Colliery, Bolsover, Derbyshire and 2) Caphouse Colliery, Overton, near Wakefield, Yorkshire. The closed loop system at Markham is based on reinjection of mine water into the same shaft after heat recovery. At Caphouse both open loop and closed loop systems are in operation.

The main conclusions from Spanish pilot installation are as follows:

- 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 once and it was completely clean.
- In FAEN installation the result is the same, it is in operation since May 2016 and there is no need to clean the heat exchanger. It is different in the University Installation where there is a need 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.
- The great amount of water available in Barredo Shaft helps to control the COP in each installation, so there is no important reduction in the COP during the normal operation when the heat exchanger is dirt with iron.

The designed and implemented heating system at Armada site in Bytom powered by the heat of mine water works properly, and gives satisfying result. During the low daily temperatures it gives significant cost savings for heating purposes. With the COP of 3 it can be indicated that by the cost of 1 kW of electrical energy 3 kW of heat energy can be obtained. Gathered measurements data from the system indicates also a potential for its optimization. Implemented and tested system is fully multipliable, and will be hopefully implemented by Armada in the future for new house estates promoting the low carbon economy based on flooded coal mines.

Exploitation and impact of the research results

Results of works are presented within specific Tasks descriptions.

Task 4.1 Pilot implementation at Markham site (UK)

Task leader: Alkane

Main objectives

Main objective of the task was to develop pilot plants at two different sites having different hydro-geological conditions, in order to:

- find out how the COP of a system differs with a water level at different heights below the ground surface attending to a flooding process.
- quantify the mixing process and the effect on the efficiency (COP) in a system with the reinjection of used mine water,

Description of activities and discussion

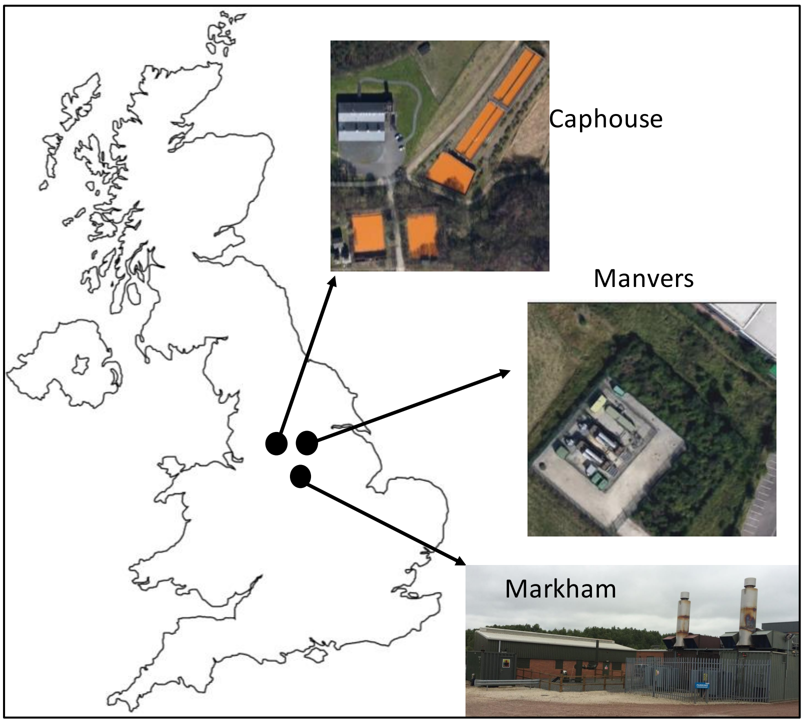


Figure 41. Pilot plant locations

Source: Alkane own elaboration

Markham:

The pilot GSHP plant installed in Markham kept the Markham offices warm throughout the winters of 2014-2017. According to Markham site the work undertaken within task 2.1 in 2016 included the collection and elaboration of data obtained from a functioning GSHP pilot plant. The specification of GSHP system is described below.

The GSHP pilot plant of size 20 kW thermal output is used to heat the control centre and the maintenance depot of Alkane Energy and the site requires heating 24×7. The office building uses three different kinds of emitter systems to heat the buildings, they include wet radiator units, fan coil units and under floor heating systems, see Figure 42.

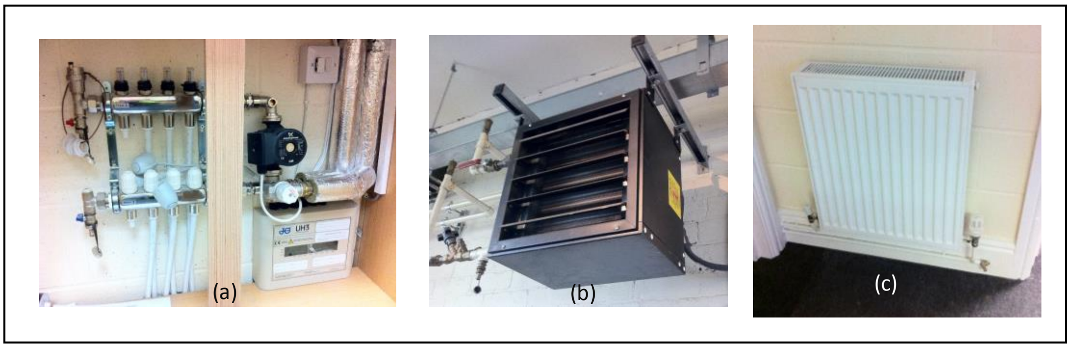


Figure 42. The Emitter systems used to dissipate the heat

Photos: Alkane archive

The system is designed to extract warm water from the abandoned mine shaft and inject a slightly colder spent water back into the same shaft, and the heat pump is used to upgrade the low grade heat of mine water into a higher grade heat and utilise this high grade heat to heat the office buildings of the Alkane Energy at Markham. Within the project duration, the GSHP was extended to pre-warm one of the standby gas engine as well.

The system consists of a commercial 20 kW Danfoss heat pump, two counter flow shell and tube type heat exchangers of 12.5 kW capacity each, a 300 litre buffer tank, mesh filter and pipes connecting all the units are fitted in a 20 feet modified container. The container also houses the control panel for the borehole pump. A 11 kW borehole pump is installed at a depth of 170m and return diffuser at a depth of 153m below the ground level. Initially the borehole pump was installed at a depth of 235m below the ground level and the diffuser was at a 250m depth. As a safety mechanism, the methane in the mineshaft is monitored and would trip the system if the methane level crosses 1.75 %. System components are shown in the figures below.

Figure 43. Mine water flow and return pipe.

Photos: Alkane archive

Figure 44. (a) Filter. (b) Heat exchanger.

Photos: Alkane archive

Figure 45. (a) Heat pump. (b) Buffer tank.

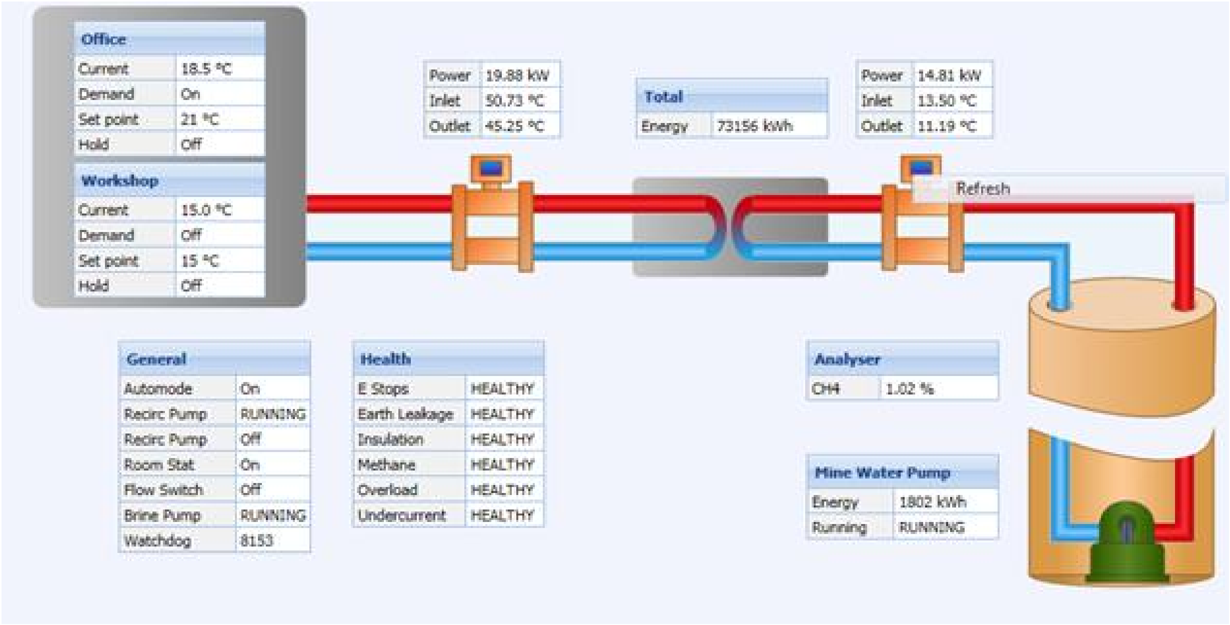
Photos: Alkane archive

Instrumentation and monitoring system at Markham site.

The energy meters are installed to measure the electricity consumption of heat pump and borehole pump. KAMSTRUP Multical 602 heat meters are used to monitor both mine water and the heat pump hot water parameters. The heat meter measures the flow rate in m^3/hr, ΔT of the water in degree C, instantaneous power in kW and cumulative energy in MWh. The KAMSTRUP Multical 602 consists of an integrated flow and temperature sensors and an integrator to calculate the energy based on the flow and temperature values. The entire monitoring system is connected to a telemetry system; all the devices send the data in Modbus protocol to a redlion unit.

Figure 46. Data monitoring and acquisition unit.

Photos: Alkane archive



Office	
Current	18.5 °C
Demand	On
Set point	21 °C
Hold	Off

Workshop	
Current	15.0 °C
Demand	Off
Set point	15 °C
Hold	Off

Power	19.88 kW
Inlet	50.73 °C
Outlet	45.25 °C

Total	
Energy	73156 kWh

Power	14.81 kW
Inlet	13.50 °C
Outlet	11.19 °C

General	
Automode	On
Recirc Pump	RUNNING
Recirc Pump	Off
Room Stat	On
Flow Switch	Off
Brine Pump	RUNNING
Watchdog	8153

Health	
E Stops	HEALTHY
Earth Leakage	HEALTHY
Insulation	HEALTHY
Methane	HEALTHY
Overload	HEALTHY
Undercurrent	HEALTHY

Analyser	
CH4	1.02 %

Mine Water Pump	
Energy	1802 kWh
Running	RUNNING

Figure 47. Remote monitoring screen.

Photos: Alkane archive

Using the GSHP to heat the engines at Markham site.

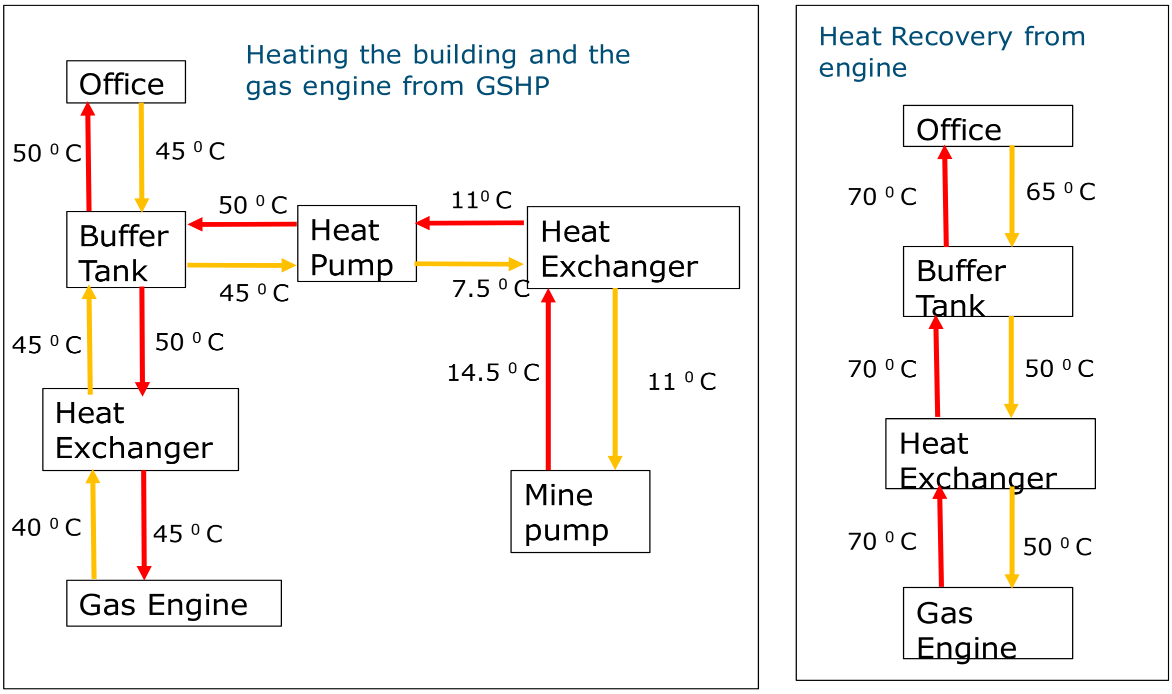


Figure 48. Schematic of the GSHP engine heating.

Source: Alkane own elaboration

There are two natural gas engine generators at Markham that are used to generate electricity, as when there is a demand for electricity from National Grid, UK. This kind of generation is known as STOR (Short Term Operating Reserve) (National Grid 2016). The engines can be pressed into service within a short space of time, in order to do that, the engines are pre warmed in the standby mode. An Electric heater was providing the heating. Recently the GSHP has been extended to provide heating for one of the engine as well. The other benefit is that when the engine is running, the heat from the engine is recovered and stored in the buffer tank and used for space heating, negating the use of GSHP. Using the GSHP by coupling it with a conventional system, increases the overall efficiency. This coupling of GSHP with the engine was not a part of the initial research work and was added later and no experimental work has been carried out, as the engine is run mainly in the evenings of the winter months of November to February, when the demand for the energy is the greatest and there is less day light hours and very little energy is generated by solar.

The Figure 49 shows the location of the engine, GSHP plant and the mineshaft. Figure 50 shows the thermographic image of the engine in standby mode and the amount of heated that is being chucked out through the engine exhaust when the engines are in operation.

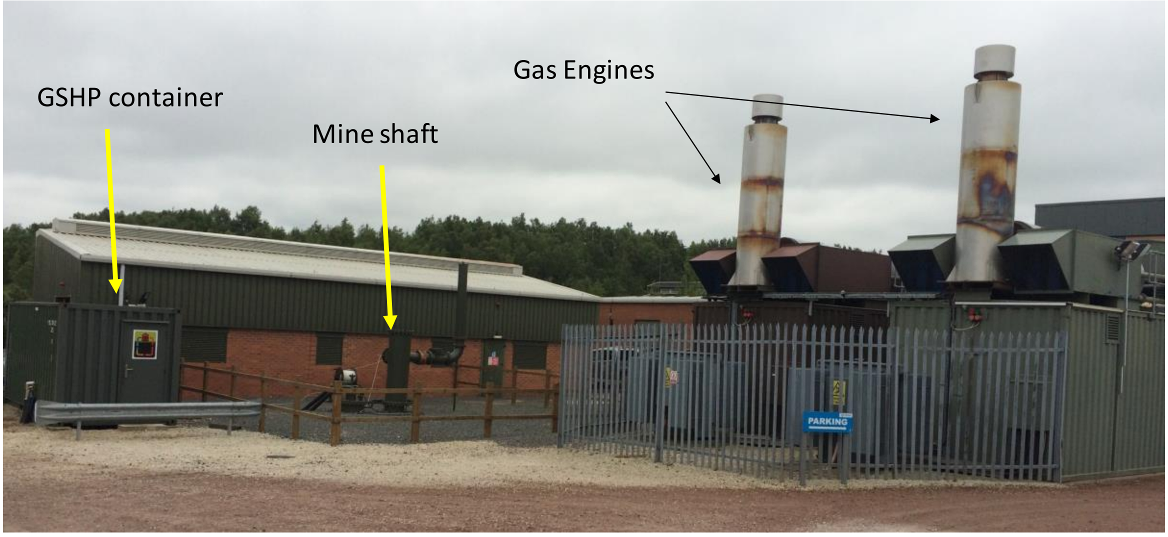
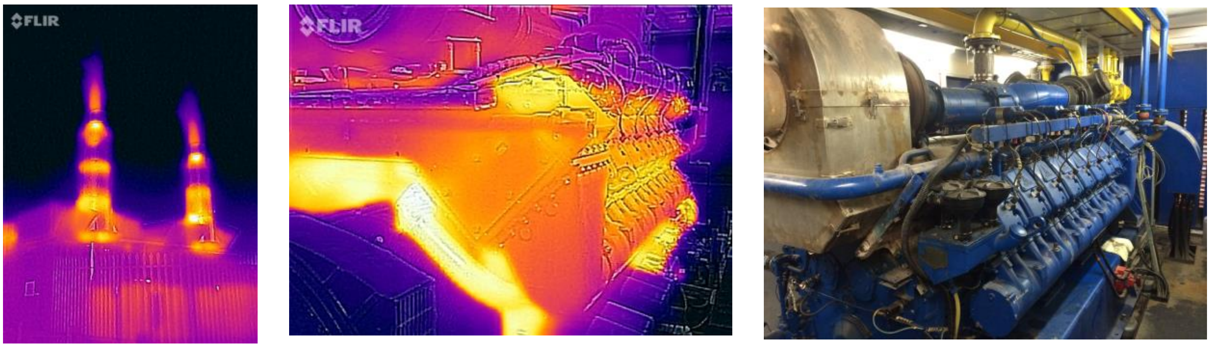


Figure 49. The standby gas generators at Alkane Energy, Markham.

Photos: Alkane archive



(a) (b) (c)

Figure 50. (a) The thermal image of the engine in operation mode. (b) The thermal image of the engine in standby mode. (c) Normal image of the engine.

Photos: Alkane archive

Maintenance issues due to ochre at Markham site.

Results and detailed information about the process and solutions to prevent the clogging of pumps and pipe lines due to ochre in an open loop GSHP system are provided in description of *Task 2.1 Closed-loop strategies for oxidised, ochre-precipitating mine waters in treatment system*.

Caphouse:

The GSHP pilot installation at Caphouse works from March 2015. In 2016 the works related to gathering the data from both functioning systems (open loop and closed loop) were undertaken. Detailed installation about GSHP at Caphouse are provided below.

The GSHP system at Caphouse consists of a single 10.5 kW commercial Vaillant heat pump, two sets of prophylactic shell and tube type heat exchangers. However, only one heat exchanger is used for operation and the other one is always kept on standby. A mesh filter is also used to provide initial filtration before the heat pump. The filter unit also includes two separate filter baskets that can be easily swapped by turning the knob, to allow for maintenance, similar to the heat exchangers. A 300 litres buffer tank is used to allow stable operation of the heat pump during fluctuation in heating demands. The heat from the system is used for heating the old Inman shaft building that is currently used as an exhibition space at the museum. In order to keep the mining museum galleries dry, water needs to be pumped daily, at a flow rate of circa 30 l/s. During the winter months, water is pumped 24 hours a day and in summer months, the water is pumped for circa 15 hours a day. A small amount of mine water is tapped from the main pumping header line and used in the pilot plant and later injected back to mine water treatment lagoon.

The system for pumping water from the coal mine includes two parallel systems (header pipes) one or both could be operating at any specific time. To allow the extraction of water by either pipe, a novel design allows the heating system to circulate water from either pipe based on their pressure, and at the same time preventing the loss of pressure due to water leakage to the low pressure/empty one. If both systems are pressurised, this will create a functional flow based on the lowest pressure assuming both are above the threshold value of the valves.

Data Acquisition and Monitoring of the system at Caphouse.

As part of the work undertaken the main parameters to determine the performance of the system are energy consumption and heat transfer rates between mine water and the brine were monitored. These parameters are determined by measuring the fluid input and output temperatures and instantaneous flow rates. Two Multical 602 Kamstraup heat meters are used to monitor both mine water and heat pump output parameters. The heat meter measures the flow rate in m^3/h, ΔT of water in degree C, instantaneous power in kW and cumulative energy in MWh. The Multical 602 Kamstraup heat meter consists of an integrated flow and temperature sensors and an integrator to calculate the energy based on the flow and temperature values (Figure 51-b).The entire monitoring system is coupled to telemetry and the data is continuously collected (Figure 51-c). The electricity consumption is measured using an 'Autometer 100m' energy meter(Figure 51-a).

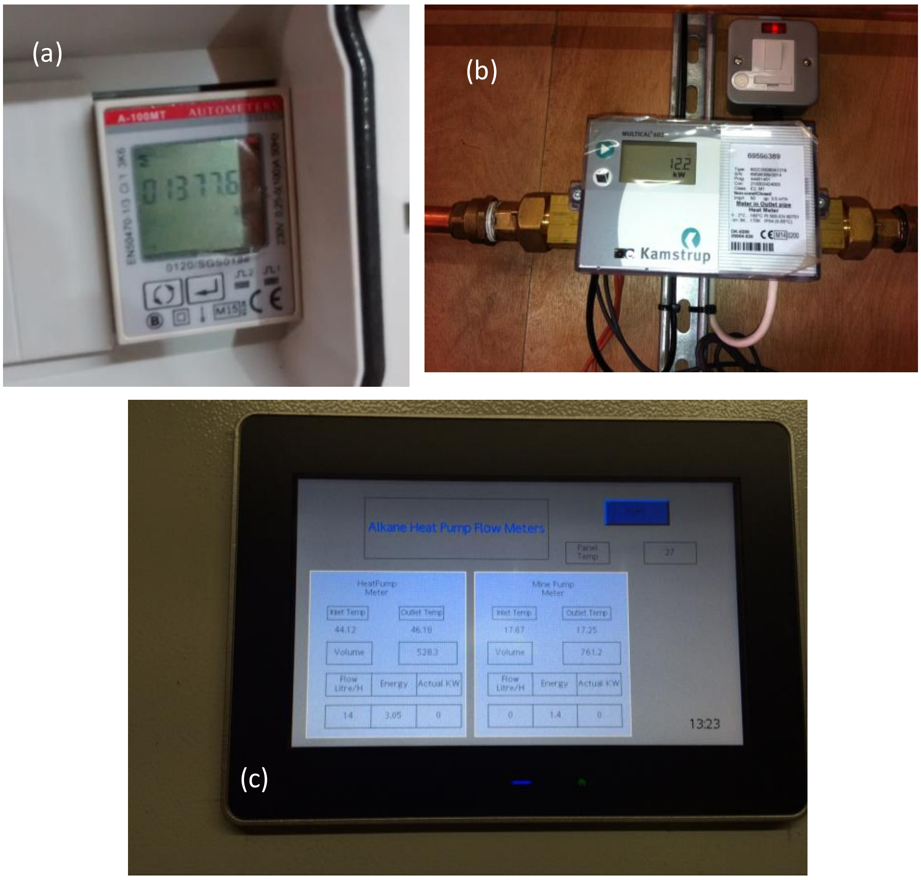


Figure 51. (a) Energy meter. (b) Heat meter. (c) Data acquisition unit.

Photos: Alkane archive

Maintenance issues due to ochre at Caphouse site.

Due to the nature of mine water at Caphouse, and their oxygenation in the pumping shaft the ochre precipitation was noticed. Detailed information about the process and used solutions are provided in description of *Task 2.1 Closed-loop strategies for oxidised, ochre-precipitating mine waters in treatment system*.

Manvers:

Despite the efforts the supplemental agreement needed to drill a new borehole from the Coal Authority could not be obtained due to a commercially damaging condition placed on Alkane Energy, where the existing Coal Mine Methane extraction license needed surrendering. Alkane Energy's main business is extracting methane and generating electricity and it has not been feasible for Alkane to surrender the Methane Extraction license. Additional conditions, to decommission and seal the existing shaft was also placed. This additional cost of sealing and decommissioning was not accounted in the initial proposal and it causes a huge financial burden. However, the entire exercise of applying for various permits has been worthwhile and has provided valuable knowledge which provides information for other Tasks within the LoCAL project.

Main results

Markham site results:

At Markham, the water is being extracted and discharged back into the same shaft. The main advantage of this setup being smaller land area and lesser capital cost (almost half) instead of having two boreholes to pump from one and discharge into the other. From Figure 52, the overall COP is rising as the water level rises and since the water is predicted to rise further, the overall COP is expected to get better than the current value.

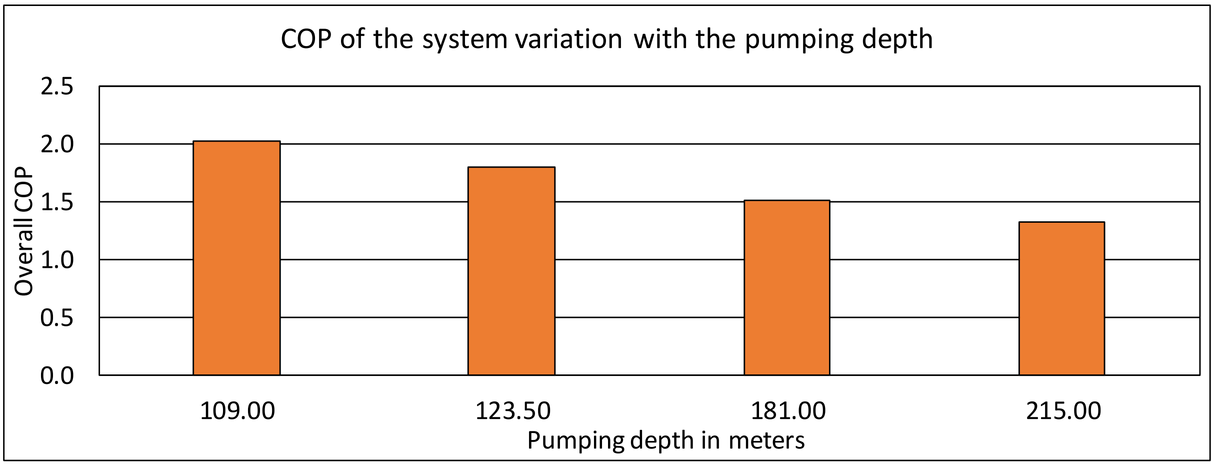


Figure 52. Improvement in the overall COP due to the rising mine water levels

Source: Alkane own elaboration

Coal Authority UK, is responsible for operating the mine water pumping stations in UK to prevent the mine water from discharging into surface water bodies like lakes and rivers and contaminating them. In order minimise the pumping cost the pumps are supposed to achieve an ideal pumping efficiency of 5 kW/Ml/m (The energy required in kWh to lift a mega litre of water from a depth of 5 meters).

The pumping efficiency at Markham is on a higher side, see Figure 53, even though the power consumption is steadily reducing with the rise in mine water levels. This is because the borehole pump being used is oversized for the current heat load.

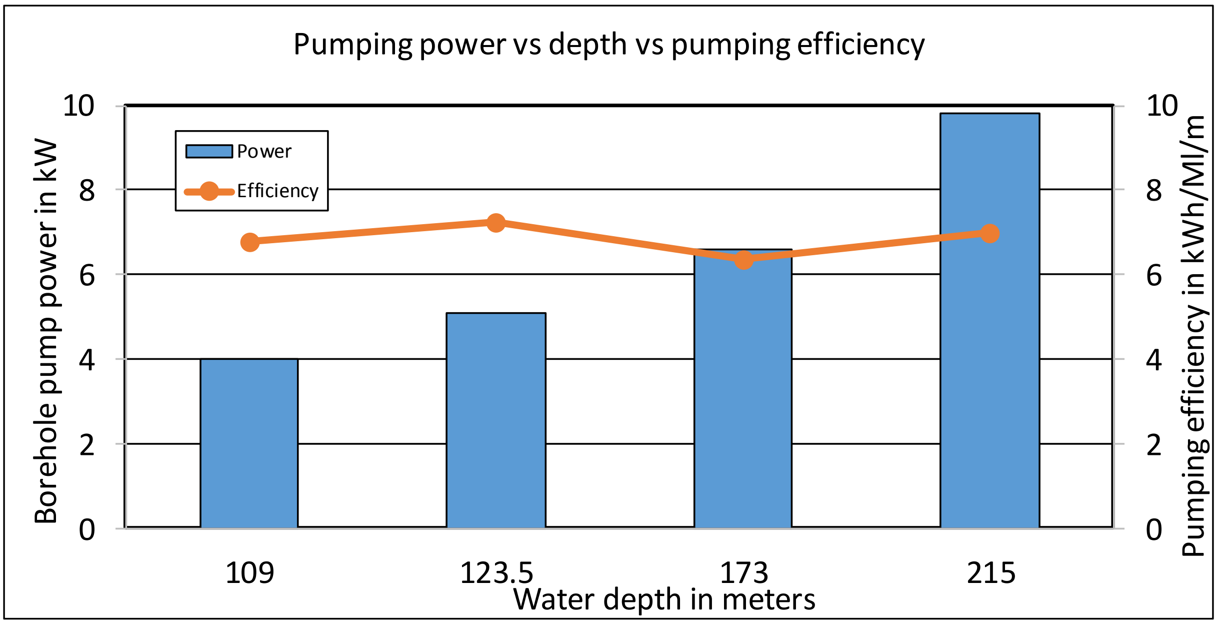


Figure 53. Pumping efficiency graph

Source: Alkane own elaboration

Apprehensions regarding the decrease in the inlet water temperature when a single shaft is used for both extraction and discharge of mine water has been allayed to rest at Markham site. The water temperature has remained relatively stable as seen in Figure 54.

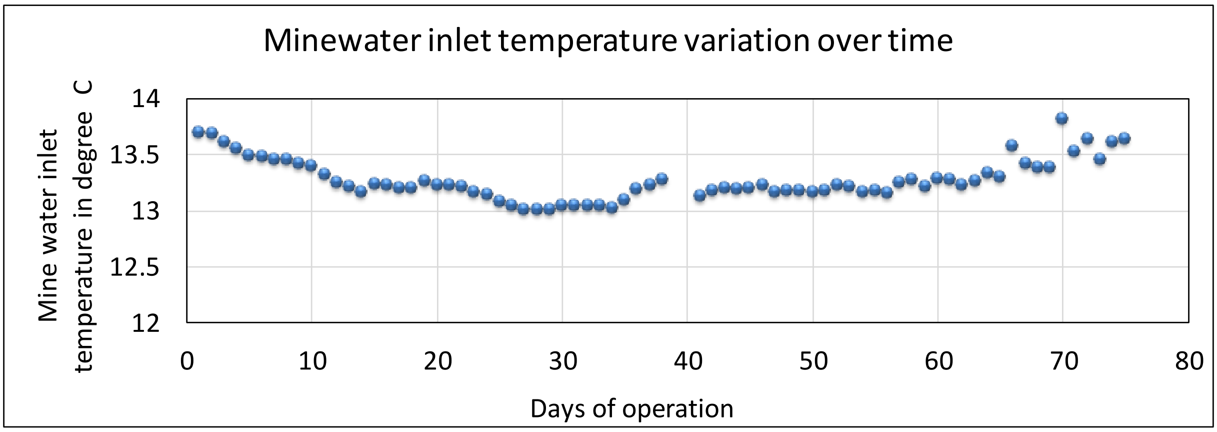


Figure 54. The mine water inlet temperature variation over time

Source: Alkane own elaboration

Maintenance issues due to ochre at Markham site are described in Task 2.1 Closed-loop strategies for oxidised, ochre-precipitating mine waters in treatment system.

Caphouse site results:

At Caphouse since the water is already pumped to the surface no additional energy is needed to pump the water and the COP of the system is almost equal to the COP of the GSHP. The temperature of the mine water has been fairly constant at circa 14 degree C (Figure 55, Figure 56) shows the average daily COP of the GSHP and it has been stable with the value being more than 4 for most of the time.

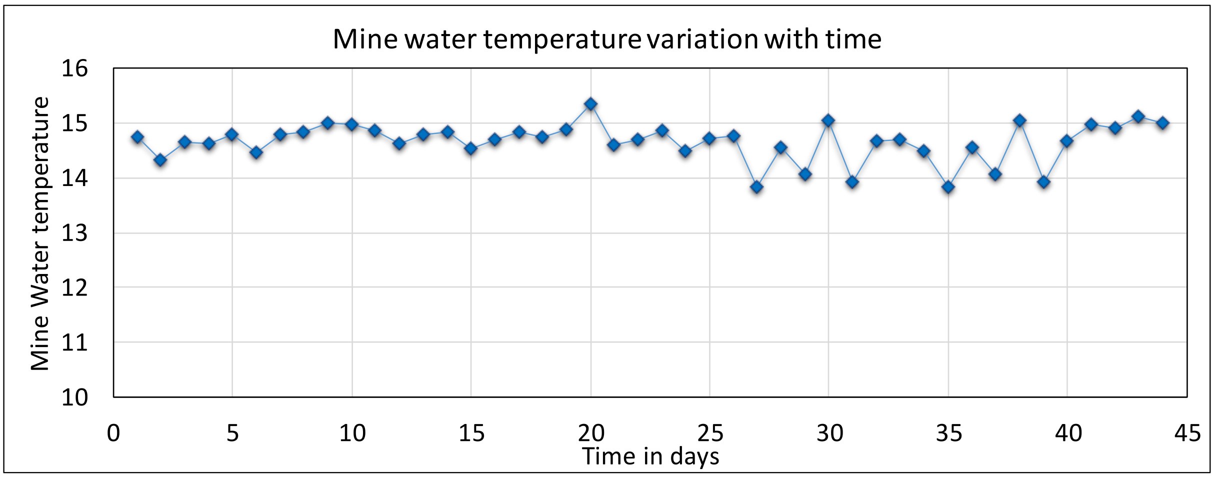


Figure 55. Mine water inlet temperature variation over time.

Source: Alkane own elaboration

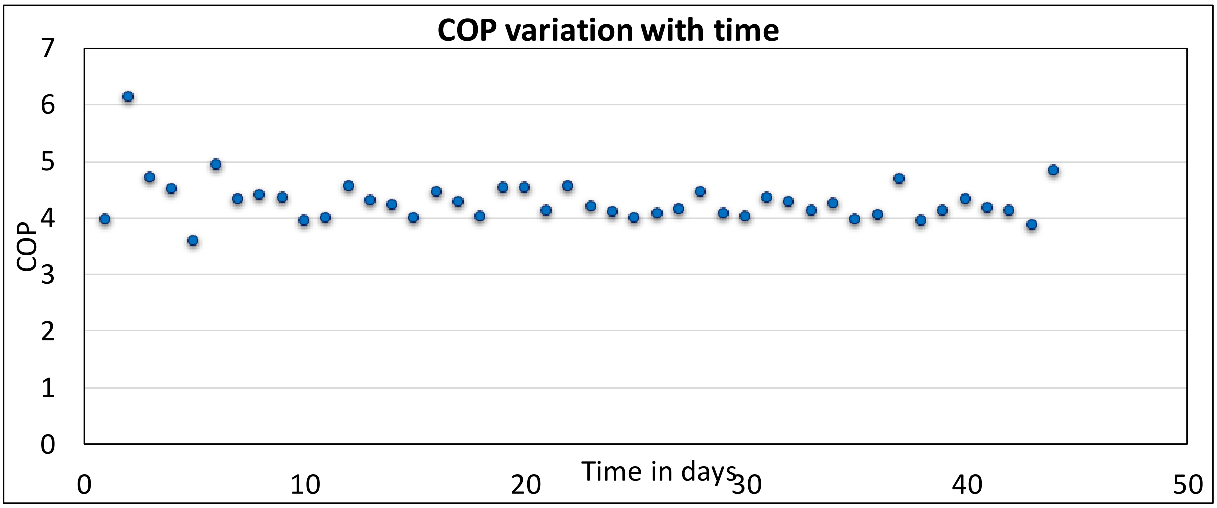


Figure 56. Performance of the GSHP at Caphouse.

Source: Alkane own elaboration

Maintenance issues due to ochre at Caphouse site are described *Task 2.1 Closed-loop strategies for oxidised, ochre-precipitating mine waters in treatment system* description.

More detailed description of works within Task 4.1 is presented in Annex 25.

Conclusions

Markham:

The monitoring and telemetry system developed at this site has enabled detailed data gathering on performance. The use of the plant has also been extended to include heating of a 1.5MWe gas reciprocating engine. Low grade heating is required when the engine is on standby for serving calls from the grid for support generation. Previously this was done with an integral 11KW electric heater but the heat pump system now serves this duty at significantly reduced cost. A further development beyond LoCAL will be to implement heat recovery and storage from when the engine is running to add to the heat resource available for the site.

Caphouse:

Operation of both the open loop and closed loop (energy blade) systems have been carried on Telemetry was installed to provide detailed real time monitoring of the system and electronic data gathering. The dosing equipment has been installed to inject sodium dithionate into the raw minewater feed prior to the heat exchangers. The dosing process has been automated based on monitoring of minewater quality parameters. Data have been gathered on the performance of the dosing process in inhibiting the build-up of ochre in the heat exchangers and pipework. Pilot implementation at Caphouse was not planned at the project start, however it have replaced the application at Manvers initially planned in Technical Annex.

Manvers:

The experiences at Manvers have illustrated the many and complex issues which need to be resolved to develop a mine water heat project using boreholes.

Exploitation and impact of the research results

Results have been published in scientific papers:

Athresh, A.P., Al-Habaibeh, A. and Parker, K., 2016. The design and evaluation of an open loop ground source heat pump operating in an ochre-rich coal mine water environment. *International Journal of Coal Geology.*
Athresh, A.P., Al-Habaibeh, A. and Parker, K., 2015. Innovative Approach for Heating of Buildings Using Water from a Flooded Coal Mine Through an Open Loop Based Single Shaft GSHP System. *Energy Procedia,* 75, pp. 1221-1228.
Al-Habaibeh, A., Meyerowitz, B. and Athresh, A., 2015. The Design and Development of an Innovative Simulator for an Open Loop System for Extracting Energy from Flooded Coal Mines. *Energy Procedia*, 75, pp. 1470-1476.
Burnside, N.M., Banks, D., Boyce, A.J & Athresh, A. 2016. Hydrochemistry and stable isotopes as tools for understanding the sustainability of minewater geothermal energy production from a 'standing column' heat pump system: Markham Colliery, Bolsover, Derbyshire, UK. *International Journal of Coal Geology*
Athresh, A.P., Al-Habaibeh, A. and Parker, K., 2017. An innovative and integrated approach for using energy from the flooded coal mines for pre-warming of a gas engine in standby mode using GSHP. *Energy Procedia, 10*5, pp. 2531-2538
Banks, D., Athresh, A.P., Al-Habaibeh, A. and Burnside, N., 2018. Water from abandoned mines as a heat source: practical experiences of open- and closed-loop strategies, United Kingdom. *Sustainable Water Resources Management.* (doi:10.1007/s40899-017-0094-7)
Athresh, A.P., Al-Habaibeh, A. and Parker, K., The performance and analysis of a single shaft open loop GSHP system. Applied Energy

Task 4.2 Pilot implementation at pilot site in Asturias (ES)

Task leader: HUNOSA

Main objectives

The main objectives of WP4 are the following:

- To find out how the COP of a large scale system differs with water level at different heights below the ground surface attending to a flooding process
- To quantify the mixing process and the affection to the efficiency (COP) in a large scale system the reinjection of used mine water.
- To find out how the COP of a large scale system differs by the use of different heat exchangers and the economic impact of the WP2, advance methods for preventing corrosion and incrustation affecting heat transfer.
- To support with real data models for efficiency of energy extraction and distribution analyzed on WP3

Description of activities and discussion

The main objective of this task and also the main problem in dealing with mine water in HUNOSA mines is the iron and calcium from this water and the precipitation of these substances along the different elements of the installations

Figure 57. Filter full of iron

Source: HUNOSA archive

To minimize this problems HUNOSA follows different strategies:

To reduce the length of 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 Mieres Hospital. The distance 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. In the figure the pipes in red carry mine water and the rest of the pipes only carry clean water so the iron and calcium only precipitate in 20m of pipes.

Figure 58. Heat exchanger in Barredo Shaft (left)

Source: HUNOSA archive

- Use tubular heat exchangers instead of plate exchangers. In tubular exchangers the water circulates so quickly and creates turbulent flow that avoids solids precipitation. 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 two next figures it is shown an example for the efficiency and dirt accumulation comparison in tube and plate heat exchangers. 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 causing economical loses. When plate exchangers are used they must be cleaned frequently, this is what happens in the installation than HUNOSA uses to give geothermal energy to the University Investigation Center. As it was said previously the initial idea was to remove the iron precipitation three times per year.

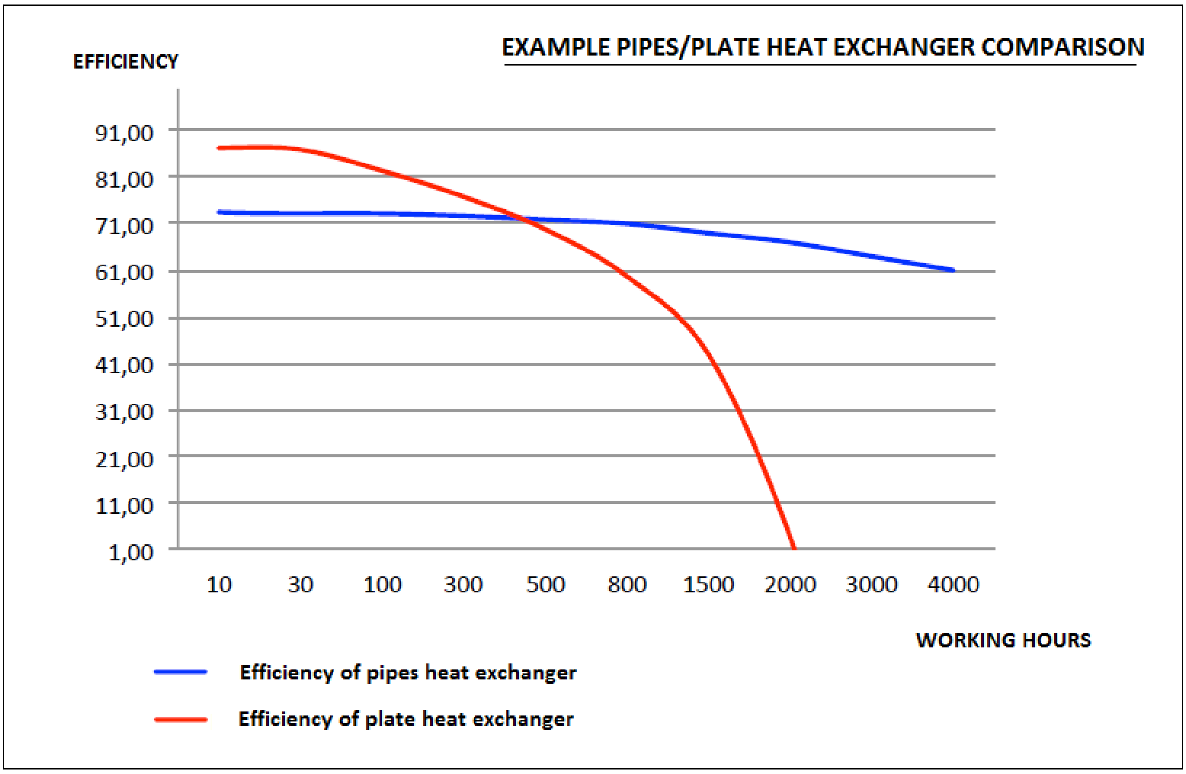


Figure 59. Efficiency of heat exchanger in time

Source: HUNOSA own elaboration

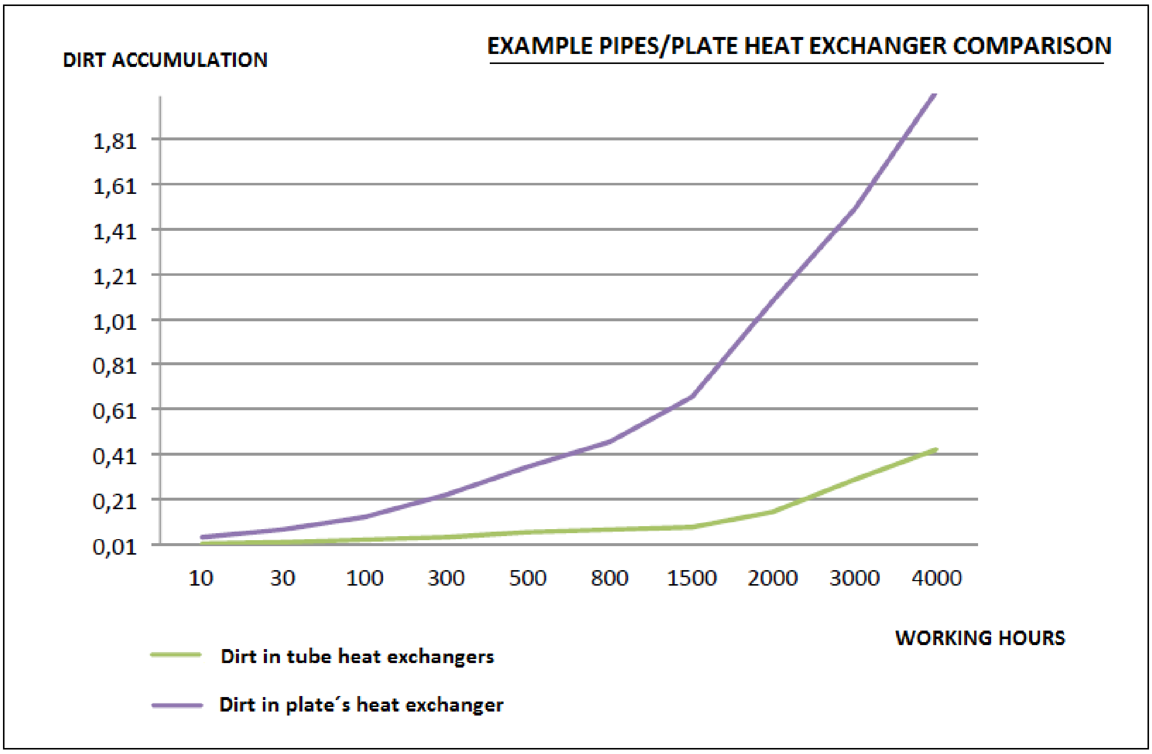


Figure 60. Dirt accumulation in heat exchangers

Source: HUNOSA own elaboration

To reduce the possibility of the oxygen reaching 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 just at the water level inside the shaft.

To 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.

The main elements to develop this task are the heat exchangers:

1. In the installation for the hospital there is a huge tube heat exchanger of 4MW.
2. In the installation for the Investigation Center of University there is two plate heat exchangers of almost 400kW one of them for cooling and the other for heating. Right now the installation is working in heating mode between November and April.
3. In the installation for the FAEN building there is a small tube heat exchanger of 100kW

To check which the best type of heat exchanger is, information related to the operation parameters of the three installations have been gathered. But before extract any conclusions is important to understand how the installations manage the energy supply to each building. The objective is always to keep the heating pump working in the optimal conditions that is keeping the COP as high as possible.

In our system the amount of water available is very much of what is needed to operate the installation, so it is very easy to control the temperatures opening and closing one simple valve. This valve allows more or less mine water to flow towards the heat exchanger to maintain the optimal temperature in the other side of the heat exchanger. Of course more water to give heating is necessary when it is colder.

But what happens when the heat exchanger is dirt with iron precipitates. In this case the heat transmission through the heat exchanger is lower so to keep the temperature in the heating pump the control system increases the flow of mine water to try to supply the same required energy. Due to this operating control our installation can cope easily with iron problems. Only when there is too much precipitation inside de heat exchangers the cleaning is required.

Therefore there are two ways to follow the iron effect in the system, to study the amount of water required by the system (more iron more water to supply the same energy to the system) and to study the temperature of the cold side of the heating pumps (more iron less temperature in the cold side of the heating pump). This was the main part of task 4.2.

The tubular heat exchangers were design just for the chemical conditions of the mine water, they were quite expensive, for example the cost of the heat exchanger was 227.000€ while the equivalent one with plate technology would cost 127.000€. But with this exchanger the COP develops by the whole installation is 7.8. With this value the savings in energy gets 88% related to gas for heating and refrigeration tower for cooling, the economic savings gets 57% and the reduction of CO2 gets 60%. So we can conclude that the innovation of this projects is the demonstration that with mine water geothermal projects to supply acclimatization are completely feasible sometimes cheaper than conventional energies and that is easily to cope with iron and calcium problems.

Main results

The results clearly show that the tubular exchangers do not need cleaning in less than one year while the plate heat exchanger must be cleaned twice per year.

The following table shows for example the energy extracted from the mine water for FAEN building. This energy (fourth column) is similar along 2016 so this means that the tube heat exchanger kept clean along the year.

Table 4. Heat extracted from mine water for FAEN building

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

Source: HUNOSA own elaboration

The following figure shows an example of results using temperatures as indicator of dirtiness. Two situations are represented after and before one of the cleanings of the plate exchanger. The COP of the heating pump is almost the same (the reference value is 4) because the system can adapt itself to avoid low COP values as was said before. The temperature of the water entering in the evaporator before the cleaning is 8,7ºC. After cleaning it increased until 16,3ºC. In both cases the flow of mine water is the same but as the heat exchanger is not able to transmit the needed heat, the system cools down. The heating pump reduces its own load (74% to be able to maintain the COP value) this causes that the system is working more time to give the same energy.

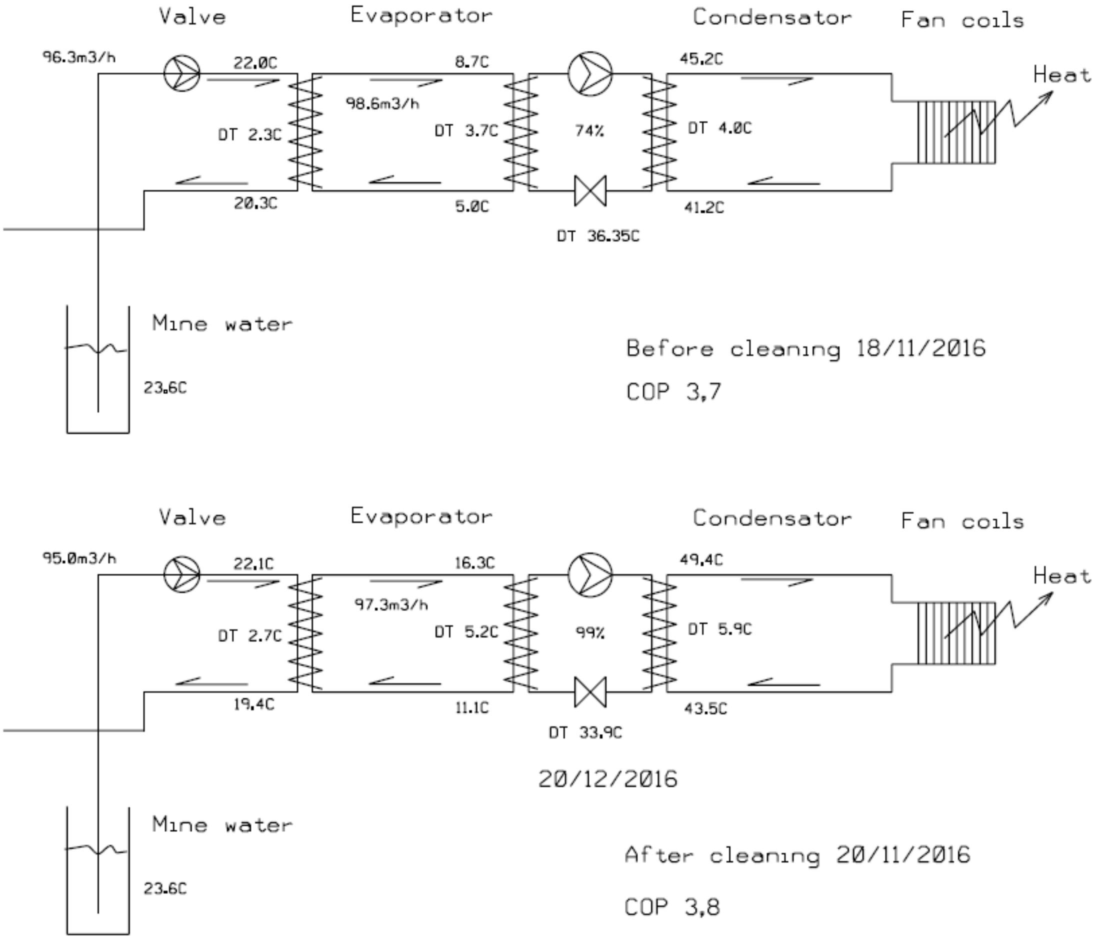


Figure 61. After/Before cleaning

Source: HUNOSA own elaboration

Conclusions

The main conclusions of the task can be summarized in the following lines:

- 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 once and it was completely clean.
- In FAEN installation the result is the same, it is in operation since May 2016 and there is no need to clean the heat exchanger. It is different in the University Installation where there is a need 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.
- From the economical point of view this conclusions give the following results:
  1.- Comparison between heat exchangers in case of University.
  Cost of the plate heat exchanger in Investigation Centre: 6.200 €
  Cost of one equivalent tube heat exchanger (550kW): 21.000€
  Current use of the installation; 50% (only in winter)
  490€/cost of cleaning
  Twice per year the heat exchanger is cleaned: 980€/cost of cleaning per year
  Difference: 14800/980 = 15,1 years to recover the difference.
  2.- Comparison between heat exchangers in FAEN Building.
  Cost of one equivalent plate heat exchanger: 1.600 €
  Cost of tube heat exchanger (90kW): 8.000€

Current use of the installation; 100% (all year)
490€/cost of cleaning
Four times per year the heat exchanger should be cleaned: 1960€/ cost of cleaning per year
Difference: 6400/1960 = 3 years to recover the difference.
The result is the same, when the installation is done to work all year the best option is to use a tube heat exchanger.

The great amount of water available in Barredo Shaft helps to control the COP in each installation, so there is no important reduction in the COP during the normal operation when the heat exchanger is dirt with iron.

In task 1.2 it was indicated the idea of using mixing process to change this temperature. In Barredo Shaft the aim was focus in the reduction of water temperature that goes to the heat exchanger (when the installation is giving cooling). The initial idea was to use the cooler water of Mariana Adit to mix with Barredo Water. But the amount of water available in summer is only 2l/s. The old galleries of Mariana Mine were studied to look for a place to store water to use during the cooling supply. But only an option to store the water outside in a tank of 30m3 was possible. With this amount of water only would be possible to increase the COP in 0.1 and the cost of the installation was too much to be recovery with the economic benefit of having a COP only a little higher.

All the achievements made in this task are converted in some criteria to design future installations:

1. If the installation is going to operate all year is better to use tubular heat exchangers design with very high Reynolds number to create a turbulent flow inside the pipes, so iron problems are avoid and the transmission of heat is raised.
2. With mine water temperature up to 23ºC it is possible to get COP of almost 7 and better conditions than conventional energies can be developed for the client. Right now new refrigeration fluids for the heating pumps allow to raise the temperature of the water up to 80ºC with COP of 3.6 so we are now developing new projects for conventional heating installations in domestic buildings.
3. If there is enough water it is very easy to control the efficiency of geothermal systems of low enthalpy with heating pumps.

Exploitation and impact of the research results

The three installations in Barredo site have demonstrated the viability of these kind of projects, for example, for the Hospital Project the total investment was 1,1M€ and the economic result we get is 200.000€/year. So HUNOSA have decided to build two more installations (two district heating) for public and domestic clients at the same time. This is possible due to new heating pumps that produce water up to 80ºC so it is possible to supply heating to buildings with conventional heating installations.

One district heating will be built in Mieres with Barredo mine water to supply energy to the big building of the university, one primary school, one secondary school and three domestic buildings. The other will be built in Langreo with water from Fondon Shaft ant it will supply energy to several domestic buildings, one sport center with one swimming pool, one hotel with spa, one geriatric and health centers. Of course the results gathered during Local investigation are helping to design the new projects for example the use of tube heat exchanger is assured.

These results can be used for other type of geothermal project the main difference is the water temperature that gives different COP, apart from the COP other parameter that determine the feasibility of one project is the relation between the distance of the client to the source of water and the energy consumption, for example in the hospital the distance is 2 km and the building needs more than 7GWh of energy every year.

The whole results including economic results were presented during LoCAL Final Conference that took place in on 1st June 2017 in Katowice, Poland. In HUNOSA web (www.hunosa.es) some information of these projects can be found.

Task 4.3 Pilot implementation at pilot site in Bytom (PL)

Task leader: Armada

Main objectives

Pilot site is located in Bytom on post mining area where polish project partner - Armada Development, continues its activity of land reclamation as golf course club and housing development. The proximity of mine water discharge from abandoned but still dewatered Szombierki mine was the reason for using renewable energy as the main source for heating at the planned residential area. All main objectives regarding, pilot project, installation and testing were fulfilled. Also economic analysis were conducted to proof effectiveness of planned installation.

Description of activities and discussion

Technical Project of the pilot site infrastructure with all necessary site compounds (buffer tank and pipeline) was prepared for Armada company by a consultant: Firma Inżynierska "PROJEKT PL" mgr inż. Łukasz Plaza.

Work in construction of pilot site undertaken during the project lifetime undertaken by Armada consisted of: inquiry for construction project of pilot site in Bytom (01.2015), final version of construction project (04.2015), application for a building permit from local government (05.2015), obtaining of preliminary permission from Central Mine Dewatering Department (CZOK - owner of mine water) for uptake of heat from mine waters & getting acceptation from CZOK of construction project for pilot site (06.2015), obtaining of building permit from local government (06.2015), start of construction of pilot site. Construction works included: installation of pumps with equipment, electrical installation, central heating installation, installation of the container at the pumps (10.2015).

During the project activities in relation to pilot installation in Armada the main problem occurred when the permission for use of water generally resulted in delay of construction works. In June 2015 it was possible to obtain the preliminary permission from Central Mine Dewatering Department (CZOK - owner of mine water) for uptake of heat from mine water with the note that final legal and financial terms for future water use will be designed. Armada Development got also from CZOK an acceptation of construction project for pilot site. After a lengthy period of seeking to resolve mine water ownership and access the matter was resolved in February 2016, when finally Armada received permission for use the water for free. Collection and transfer pipeline was installed and the 9KW compacted heat pump system was constructed during the second half of 2016. Final installation of the heating systems in the buildings utilizing fan coil units was carried out in early 2017 with the system being operational in spring 2017.

Armada works resulted in construction of the container (building for installation of pumps with equipment) and connection of CZOK pipeline with buffer tank. Effects are presented on photos below.

Figure 62. Excavation for a pipeline (connection between buffer tank and container).

photos: Armada Development archive

Figure 63. Pilot installation of heat pump at Armada Development premise.

photos: Armada Development archive

Figure 64. Final look over installation container

photos: Drone photo by GIG

Whole system is fully operational, and was tested in low ambient temperature conditions. The results were satisfying, by reaching the proper indoor house temperature.

Main results

Option of implementation an open-loop heat pump solution, with prophylactic heat exchangers transferring heat from the mine water flux to the heat pumps, together with appropriate pipework was the best technical solution in ARMADA pilot site. The technical implementation and technical solution for the pilot site resulted from preliminary analysis and were a basis for conducting feasibility study for implementation of such solutions. The pilot site was also equipped with monitoring instrumentation to provide information about the mine water temperature evolution, process efficiency and heat loads delivered. Based on analysis of the pilot site, a report summarizing the results of system implementation and recommendations for future expansion has been prepared.

Installation at Armada site have been equipped with measuring devices for testing its efficiency. Main parameters that have been measured are: circuit temperature, energy consumed from grid and heat energy introduced into heating system. Below a block scheme shows the localization of measuring devices at pilot installation.

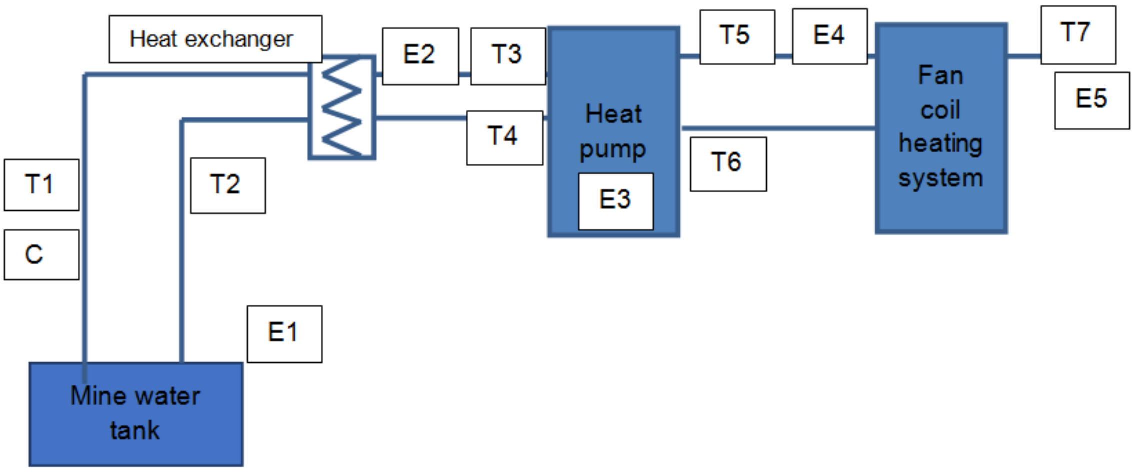


Figure 65. Block scheme of pilot installation with localization of measuring devices.

Source: ARMADA Development own elaboration.

Description of devices:

T1 - -T7: temperature measuring devices

E1 – E5: energy measuring devices

C: conductivity measuring device

As shown on Figure 65, mine water is taken from mine water tank, then it circulates through heat exchanger: it is the first circuit. Second circuit runs on glycol and runs into the heat pump where heat condensates both with grid energy uptake. Then system heat goes on the third circuit that is located in building rooms and powers the system of fan coils with the heat. Such system allows for efficient heat uptake from mine waters with avoiding the risk of internal heat pump installation damage caused by mine water reactive properties. As the COP of this system is calculated on value 3, it shows that it is possible to uptake 2 times more heat than cost of electricity.

The results show that there is a little thermal difference between mine water temperature at the inlet and outlet from heat exchanger. The difference is ca 1 Celsius degree so it shows how little heat is extracted and how big thermal potential stands behind such heat source. The temperature at the heating system is about 20 degrees higher than the temperature at the output from heat pump heat exchanger (Table 5). Such difference proves that via correctly designed system good household heating conditions can be reached. To use a scientific background for such phenomena it need to be said that whole geological structure, and mine water works as a one huge heat exchanger (rock/water) underground. Despite all technological issues it is necessary to do as much as possible in order to avoid this natural resource being wasted.

Table 5. Average temperatures from heating system

Temperature at various points of the installation	Output from the heat exchanger to the mine water reservoir	Input from the heat exchanger from the mine water reservoir	Input from the heat exchanger from the heat pump	Output from the heat exchanger to the heat pump	Output from the heat pump to the buffer (heating system)	Input from the heat pump from the buffer (heating system)
average temperature	23,04	24,19	15,01	18,77	32,72	27,96

Source: GIG own analysis

Figure 66. Plot showing daily averaged energy taken from the grid vs daily averaged energy transferred into the system correlated with average daily temperatures of the ambient air measured by nearby meteorological station at Katowice airport.Figure 66 shows an important correlation between daily temperature and the operation parameters of the heating system. It can be noticed that during the days with relatively low temperature the systems works very efficient. During such days electric energy consumption raises to 20-30 kWh, and the heat energy of the system raises to 70-80 kWh. This situation changes when the daily temperature raises, then the need for system heating goes down and the system distributes very little amount of heat with lower effectiveness.

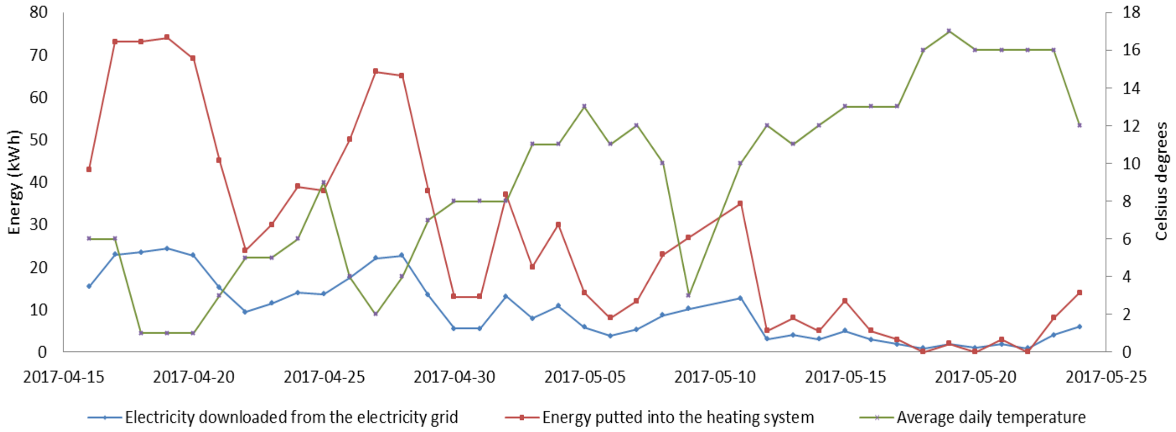


Figure 66. Plot showing daily averaged energy taken from the grid vs daily averaged energy transferred into the system correlated with average daily temperatures of the ambient air measured by nearby meteorological station at Katowice airport.

Similarly like in the previous plot, the correlation between energy taken and energy produced is compiled with heat pump COP (*coefficient of performance*). During the days with low ambient temperatures, the COP values are about 3 which shows good operating parameters of the system. COP value decreases when the heating system works on minimal electric energy consumption.

On the basis of data gathered from the preparation and operational phase of Armada pilot investment it was possible to estimate the regime parameters of this installation. Also having a wide set of operational data it is easy to indicate in with conditions the installation works the most efficiently (Figure 67).

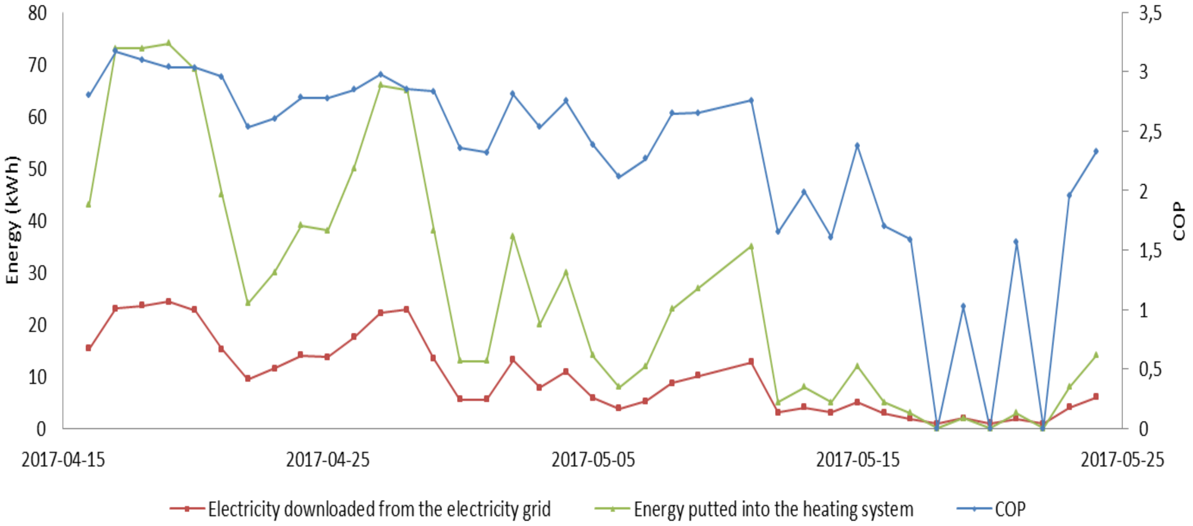


Figure 67. Plot showing energy taken from the grid vs energy transferred into the system correlated with resulting system COP

GIG own elaboration, based on data from Armada Development

Figure 68 shows the ambient temperatures, for which the pilot installation reaches the highest COP values (marked with blue circle). When daily temperature is up to 10 Celsius degrees (red line), then the heat pump works the most efficient way. At the plot it can be seen that the COP oscillates by the value of 3 in ranges of 0-10 degrees. Such temperatures were noticed during the operation phase of pilot installation. Therefore such result proves that the implemented pilot installation works properly during the heating demand period of the year. On a contrary, with ambient temperatures above 10 degrees C the system COP breaks down.

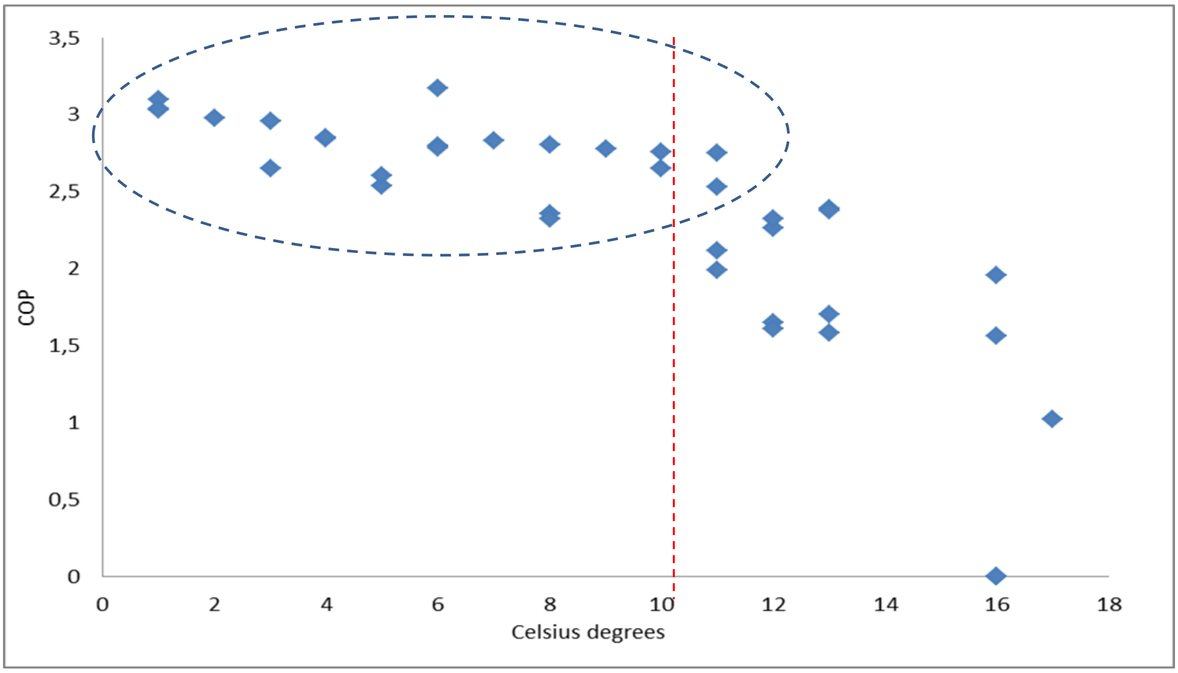


Figure 68. System COP values at Armada installation in Bytom vs ambient temperature

Source: GIG own elaboration

Conclusions

The designed and implemented heating system at Armada site in Bytom powered by the heat of mine water works properly, and gives satisfying result. During the low daily temperatures it gives significant cost savings for heating purposes. With the COP of 3 it can be indicated that by the cost of 1 kW of electrical energy 3 kW of heat energy can be obtained. Gathered measurements data from the system indicates also a potential for its optimization. Implemented and tested system is fully multipliable, and will be hopefully implemented by Armada in the future for new house estates promoting the low carbon economy based on flooded coal mines.

Exploitation and impact of the research results

Apart from described above pilot implementation at ARMADA site, company due to the proximity of the pipeline with mine water considering the possibility of using heat from the mine water to heat buildings (CO) and water (CWU) in planned multi-family buildings in future housing estates. The planned multi-family housing estate will consist of 29 multi-family buildings, where 685 flats will be built, with a total usable area of 36,479 m^2.

The source of heat from mine water is considered as an alternative solution for heating of water and living spaces. Originally estimated source of heat was from gas. Operating costs of heating the building and heating are on average between 2.94 PLN/m^2 (1,43 EUR/m^2) and 5.24 PLN / m^2 / month (1,24 EUR/m^2/month). It should be noted that the savings per month is PLN 107 248,26 (25 474,64 EUR) for heating and PLN 191 149,96 (45 403,79 EUR) for water heating per month, assuming that all flats are built and used.

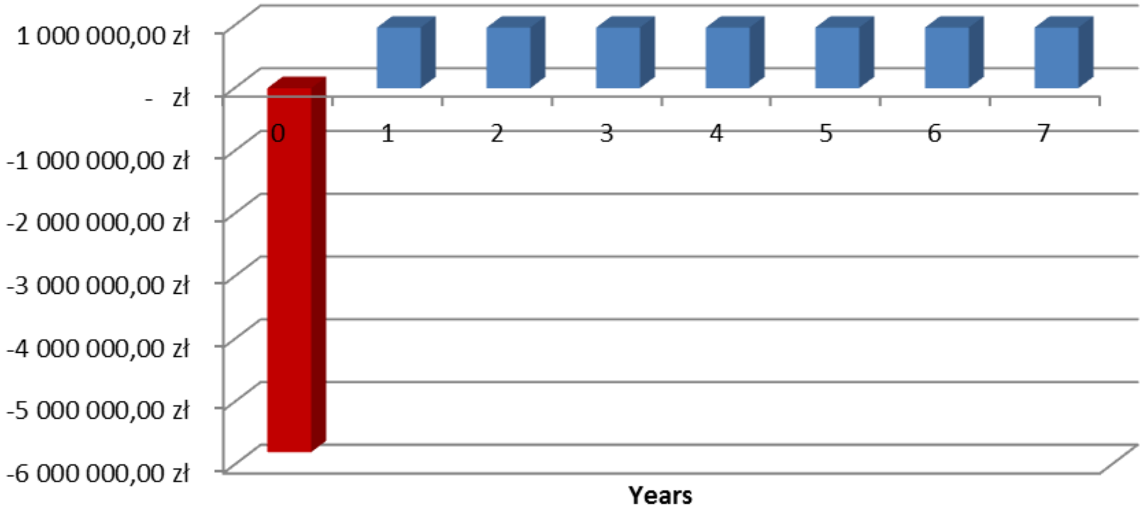


Figure 69. Plot for expenditures return with assumption for heating costs 2,94 PLN/m^2

Source: Armada Development own estimation

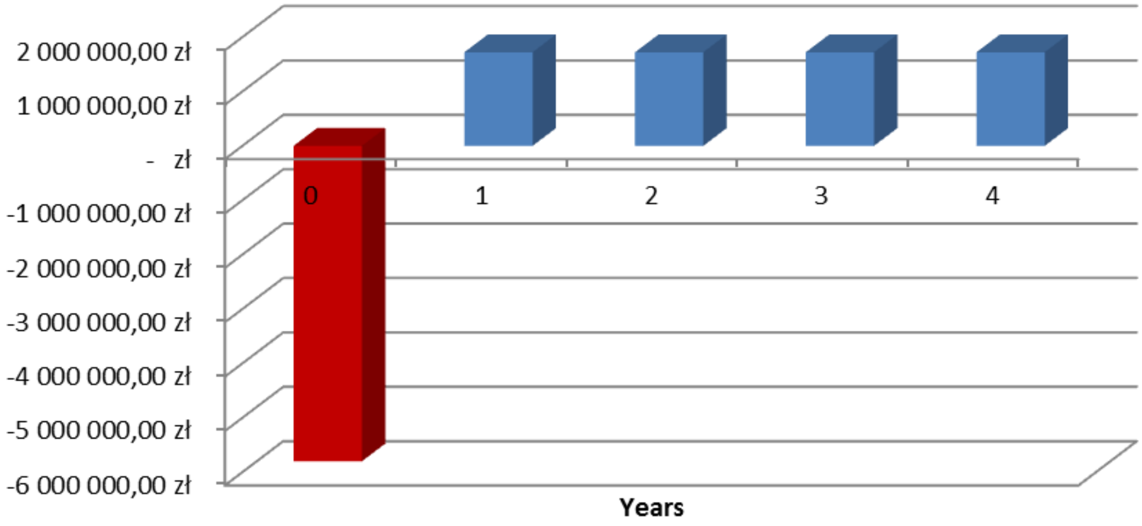


Figure 70. Plot for expenditures return with assumption for heating costs 5,24 PLN/m^2

Source: Armada Development own estimation

Assuming that we still have to pay the electricity costs for the heat pump operation, the savings are reduced to between PLN 965 234,34 (229 271,81 EUR) and PLN 1 720 349,64 (408 634,11 EUR) per year, and the cost of building a local boiler house serving the planned 685 apartments at the level of 5 800 000 PLN(1 377 627,20 EUR) the simple repayment period is between 4 and 7 (Figure 69 and Figure 70). This result means that investment costs will return in a very short time, i.e. between 4 and 7 years.

Bytom experiences and lesson learned have been presented on IMWA 2017 Conference:

- Janson E., Gzyl G., Głodniok M., Markowska M.: Use of Geothermal Heat of Mine Waters in Upper Silesian Coal Basin, Southern Poland – Possibilities and Impediments (2017) [in:] C.Wolkersdorfer, L. Sartz, M. Sillanpää i A. Häkkinen (eds.): Mine Water & Circular Economy, vol I, s. 415-422; IMWA conference materials, Lappeenranta, Finland 2017

WP5. Coordination & dissemination

Main objectives

The main aim of this WP was to ensure supervision and management by the coordinator. For the proper implementation of project tasks, communication between project partners and the permanent flow of information should be assured.

Description of activities and discussion

The necessary activities to ensure proper communication among project Partners and adequate coordination within the WPs and tasks have been undertaken. The administrative work on the project as well as oversight of the on-going actions during the whole project duration have been successfully conducted. Six coordination meetings took place, enabling coordinator and all partners to monitor the compliance of works undertaken with planned activities. The project website has been regularly updated, newsletters have been prepared. All project results have been disseminated. No relevant problems have been found in relation to tasks within WP5.

Main results

The main project results are reports submitted to the Commission, minutes from the coordination meetings and workshop as well as project web-site, presenting all project results.

Conclusions

The management and coordination activities were necessary to achieve the main project objectives. The dissemination of project results assured the interest from mining industry and management authorities.

Exploitation and impact of the research results

Not applicable - WP5 was focused on managing, administrative and organizational aspects. Any products in the forms of publication and patents have not been planned.

Task 5.1 Project management

Task leader: GIG

Main objectives

The main aim of this WP was to ensure:

- supervision and management by the coordinator,
- administration of the project,
- communication between project partners and Commission,
- organization of semi-annual coordination meetings.

Description of activities and discussion

GIG as a coordinator was responsible for project management and monitoring of work flow and control of achieved results. The day-to-day project management was carried out. Communication was via e-mail, telephone and teleconferencing.

To ensure the proper implementation of the LoCAL project and appropriate cooperation between beneficiaries two semi-annual meetings held place within reporting period:

- Kick-off Meeting was held on 3rd-4th of September, 2014 in Central Mining Institute, Katowice (PL). During the meeting the following issues were discussed, determined and accepted by Partners: rules of project implementation and cooperation among Partners, structure of project WPs and tasks and Introduction to the planned work flow, development and application of the pilot installation, assessment and management concepts concerning implementation of particular tasks.
- The 2nd meeting was held on 27th-28th of February, 2015 in Universidad De Oviedo in Spain. During the meeting the work progress of the current tasks and reporting summary according to first annual report were presented. The timetable of further works was scheduled. It was also established that the results of the project will be disseminated within *International Journal of Coal Geology and Mine water and the Environment*. Moreover, during the meeting the study visit on HUNOSA SA geothermal installations in Mieres took place.
- The 3rd meeting was held on 9th-10th of September, 2015 in Wakefield (UK). During the meeting the progress of current tasks was discussed. Moreover, the way of scientific and broad public dissemination have been established. During the meeting, there was a visit at

pilot plant in Markham, as well as visit at pilot plant and mine water treatment facilities in Caphouse.

- The 4th semi-annual meeting was held on 6th–7th of April, 2016 in Central Mining Institute in Katowice (Poland). During the meeting the work progress of the current tasks and reporting summary according to mid-term report were presented. The timetable of further works was scheduled. On second day of the meeting, besides of workshop itself, the visit on pilot site in Bytom (managed by Armada Development S.A.) took place.
- The 5th semi-annual meeting took place on 7th – 8th of September 2016 in University of Glasgow (UK). First day was scheduled mostly for a workshop on Task 1.2: concerning the results of isotope analysis in UK, Spain and Poland and results of monitoring in Spain, Poland and UK, and joint work on the interpretation of monitoring results in all countries. During second day, coordination meeting was organized, focused on finalization of deliverables due till the end of 2016.

Figure 71. Photos from coordination meeting in Katowice (left) and field visit on pilot site in Bytom & on Armada premise (right)

Photos: Małgorzata Markowska, Agnieszka Gieroszka, archive of GIG team

- Final (6th) project partners' coordination meeting took place at Central Mining Institute in Katowice on 31st of May 2017, the day before project final conference. The main aspect of the meeting was concerning finalization of project deliverables and schedule for good preparation of final report.

Figure 72. Photos from final coordination meeting in Katowice (left) and final conference (right)

Photos: Małgorzata Markowska, Sylwia Jarosławska - Sobór, archive of GIG team

Main results

Within Task 5.1 minutes from the coordination meetings and internal workshops were prepared as a main results of this task - Deliverable D5.6 (see Annex 22),

Conclusions

To achieve the main project objectives it was necessary to ensure permanent cooperation and information flow within project partnership. Organization of the project meetings and internal workshops was crucial for the successful completion of the LoCAL project.

Exploitation and impact of the research results

Not applicable

Task 5.2 Reporting

Task leader: GIG

Main objectives

According to requirements given by the European Commission the technical and financial reports have to be submitted. Within this task project coordinator in cooperation with project partners was responsible for preparation of the annual, mid-term, final reports in order to summarize all project achievements obtained during the project lifetime.

Description of activities and discussion

Within Task 5.2 reports required by the European Commission were prepared. The model of report preparation was developed and implemented within LoCAL project to improve efficiency process of report construction. Each Task leader was responsible for preparation of the input under the supervision of WP leader who finally transferred the integrated WP input to project coordinator. Consequently, project coordinator merged the document to the final form and submitted the reports to the Commission.

The first annual report of LoCAL project has been submitted to the Commission in March 2015, presented during the TGC1 meeting in Katowice (PL) in May 2015 and accepted by Commission.

Mid-term report has been prepared and submitted in March 2016, presented during TGC1 meeting in Aachen (DE) in May 2016 and accepted by Commission.

2nd Annual report has been prepared in March 2017 and presented during TGC1 meeting in Athens, (GR). Revised report has been prepared in July 2017 and accepted by Commission in September 2017.

Draft final report has been prepared.

Main results

The main results of this task are as follows:

- First Annual Report
- Mid-term Report
- Annual Report
- Draft Final Report

All reports are available on the CIRCABC platform.

Conclusions

In process of reports preparation the constant and smooth communication between project partners was necessary to achieve effective reporting process. The mentioned above model of report preparation allowed to improve the process of report development.

Exploitation and impact of the research results

Not applicable

Task 5.3 Dissemination

Task leader: GIG

Main objectives

The main objective was to ensure appropriate dissemination and promotion of achieved results within the project. The undertaken activities are intended to facilitate access to information about the LoCAL project.

Description of activities and discussion

Within the project duration the following activities were carried out:

- creation of the project website (local.gig.eu) (Deliverable D5.1, see Annex 21),
- preparation of newsletters informing about specific pilot actions (see Annex 23)
- organization of the Final Conference in Central Mining Institute (Katowice, Poland) on 1st of June, 2017. (Annex 24). Within the Conference thematic workshop to promote

the final project results – *Toolbox assuring multiplication of project results* has been organized (milestone 5.2).

- publishing project results on project web-site.
- scientific dissemination.

Main project results were published on project website.

Project results were presented during two IMWA conferences:

- ”IMWA 2016 – Mining Meets Water – Conflicts and Solutions” which took place in Leipzig, Germany (July 11–15, 2016). LoCAL project was promoted during the plenary session (presentation title: *Low Carbon After-Life – overview and first results of project LoCAL*).
- "IMWA 2017 - Mine Water & Circular Economy" which took place in Rauha, Laapeenranta, Finland (June 25-30, 2017). LoCAL project was promoted during the plenary session (presentation title: *Use of Geothermal Heat of Mine Waters in Upper Silesian Coal Basin, Southern Poland – Possibilities and Impediments*).

Main results

The main results of this task are Minutes from final Conference (Annex 24), including information about the workshop in order to promote the final project results – *Toolbox assuring multiplication of project results*, and a project website (Annex 21).

Many scientific scientific articles presenting LoCAL results and activities were published – list of + list of publications is presented in *Chapter 2 – Project Overview* of the report.

Newsletters about project overall idea, planned activities and pilot actions have been prepared - in two languages – Polish and English (Annex 23).

Information about project’s activities and newsletters can be found on project website **(http://www.local.gig.eu).**

Conclusions

The project results were successfully disseminated and promoted during the dedicated workshop as well as final Conference. Moreover, information about the project achievements were distributed during the IMWA conferences: ”IMWA 2016 – Mining Meets Water – Conflicts and Solutions” and "IMWA 2017 - Mine Water & Circular Economy”

Exploitation and impact of the research results

Not applicable

3. LIST OF ACRONYMS AND ABBREVIATIONS

CBA	Cost Benefit Analysis
CGHG	cost of greenhouse gas
COP	Co-efficiency of performance
CZOK	Centralny Zakład Odwadniania Kopalń (Central Mine Dewatering Department)
D	deliverable
DGC	Dynamic Generation Cost Analysis
EPA	Environmental Protection Agency
FAEN	Fundación Asturiana de la Energía
GRAM code	Groundwater rebound in abandoned mine code
GSHP	Ground source heat pump
GSHE	Ground source heat exchange
M	milestone
m	month due
MICMAC	Impact Matrix Cross-Reference Multiplication Applied to a Classification
MTE	Metallic Trace Elements
NPV	Net Present Value
PAAR	Pumped Abstraction with Artificial Recharge
PANR	Pumped Abstraction with Natural Recharge
R&D	Research and development
RFCS	Research Fund for Coal and Steel
SDR	Social discount rate
SRK	Spółka Restrukturyzacji Kopalń (Polish Mines Restructuring Company)
STEEP	Social, technical, economical, ecological, political aspects analysis
SWRM	Journal of Sustainable Water Resources Management
TRL	Technology Readiness Level
TRT	Thermal Response Test
USCB	Upper Silesian Coal Basin
VGHG	value of greenhouse gas
WFD	Water Framework Directive

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The LoCAL project aimed at facilitating wider use of thermal energy from mine water for both heating and cooling purposes. In order to achieve that, LoCAL project have developed new technical tools and have tested them on pilot implementations in 3 countries. In particular, the project have provided bespoke tools for investigating flow and heat transfer in flooded mine workings. New tools for quantifying and modelling heat transfer in networks of flooded mine workings have been also developed .

Another aspect of LoCAL project was to overcome the hydrochemical barriers to effective heat transfer from raw and treated mine waters. Ochre clogging is a well-known phenomenon which affects a lot of mine water heating and cooling systems.

LoCAL project not only covered technical and engineering issues, but also provided economic and management models for efficient energy extraction and distribution. Technical, legal, managerial and cost-benefit analyses of various types of decentralised and centralised heat pump systems have been carried out.

Project activities were simultaneously undertaken in mining areas of UK, Spain and Poland by research organizations in partnership with industrial enterprises. University of Glasgow in partnership with Alkane Energy Ltd. have implemented pilot applications in UK: Caphouse Colliery, Overton, near Wakefield, Yorkshire and Markham Colliery, Bolsover, Derbyshire. In Spain University of Oviedo and industrial partner HUNOSA have performed pilot implementation at Barredo shaft in Mieres, Asturias, while in Poland Central Mining Institute in partnership with Armada Development have performed pilot application in former Szombierki mine at Bytom, Upper Silesian Coal Basin.

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