Co-production of clean energy and metals – the CHPM concept

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CHPM2030 is an EU-funded H2020 project with the strategic objective to develop a novel technological solution that can help satisfy the needs for energy and strategic metals in a single interlinked process. In the CHPM technology vision, an enhanced geothermal system (EGS) will be established in a deep-seated (4 km or more) metal-bearing geological formation. By leaching metals from the mineralised rock body and recovering them at surface, the co-production of energy and metals will be possible and may even be optimised according to market demands.

Le projet CHPM2030 dérive du projet européen H2020 avec, comme objectif stratégique, le développement d'une solution technologique nouvelle qui puisse satisfaire les besoins en énergie et en métaux stratégiques à partir d'un procédé associé unique. Dans l'approche technologique CHPM, un système géothermal optimisé sera mis en place au sein d'une formation minéralisée située à grande profondeur (4 kilomètres ou plus profond encore). Par lessivage des métaux à partir du corps rocheux minéralisé et leur récupération en surface, la production combinée d'énergie et de métaux sera possible et pourra même être optimisée selon la demande du marché.

CHPM2030 es un proyecto financiado por el programa europeo H2020 con el objetivo estratégico de desarrollar una solución tecnológica y novedosa que pueda ayudar a satisfacer las necesidades energéticas y de metales estratégicos mediante un proceso interconectado. En la visión tecnológica de CHPM, será establecido un sistema de mejora geotérmica en un dispositivo metálico profundo (4 km o más), emplazado en una formación geológica. Por filtración desde el cuerpo rocoso mineralizado y posteriormente recuperado en superficie; la co-producción de energía y metales será posible y podría incluso ser optimizada de acuerdo con las exigencias del mercado.

Introduction

The European Commission actively promotes research and development on enhanced geothermal systems (EGS). The main problems related to these systems are improving the efficiency of the underground heat exchanger, increasing the economic lifetime of EGS plants and lowering capital and operative costs. With

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the recovery of metals from the geothermal fluid, the CHPM technology can contribute to the solving of these problems. The technology is worked out in the frame of the European Union's Horizon 2020 project 'CHPM2030 – Combined Heat, Power and Metal extraction from ultra-deep ore bodies'. The project started in January 2016 and runs for 42 months, but aims to initiate pilot plants by 2030.

In the envisioned technology, an engineered geothermal system is established within a metal-bearing geological formation at depths of 4 km or more, which will be manipulated in such a way that the co-production of energy and metals will be possible (*Figure 1*). Critical to this is the understanding of the natural networks of hydraulically conductive mineral veins that could function as heat-exchange surfaces and sources of metals. If metals can be leached from the orebodies in high concentrations, and over a prolonged period of time, then their recovery may substantially influence the economics of the engineered geothermal systems. Furthermore, leaching of metals from subsurface pathways in a controlled way has the potential to

improve fluid flow, and so increase system performance over time.

Identification of the geological setting

When planning the establishment of a CHPM system, first the applicability of the technology in the given area has to be examined. Working with the tools of geophysics, geology, geochemistry, hydrogeology, rock mechanics and geoenergetics, the boundary conditions for both energy and potential for metal recovery have to be defined.

In the early phase of the project, the four major European metallogenic provinces were reviewed, which correlate with the larger tectonic zones. The focus was on the EGS potential of the main ore deposit types within the provinces. The prospective zones or formations for the CHPM technology were assessed in each metallogenic province (Hartai *et al.*, 2016). The most appropriate settings are:

1. Magmatic-hydrothermal mineralisations associated with intrusive bodies, as the mechanical properties of the mostly granitic host rocks are appro-

priate for drilling and maintaining open fracture systems allowing fluid transport.

2. Basins in rift or subduction zones, where mineralised horizons form as a consequence of submarine volcanism and exhalation. Such mineralised formations may be relatively thin, but with large lateral extension.

3. Deep-rooted fault zones, with larger extension and elevated heat flow. Shallow level hydrothermal ore deposits in this environment often originate from remobilisation of metals of an earlier mineralisation. These deposits may indicate a deep-seated fertile rock body, which can have a potential for further leaching (Németh *et al.*, 2017).

Metal mobilisation

Leaching tests were carried out at the British Geological Survey and at the University of Szeged. The rock and ore samples for the tests were collected by the project partners and represent the four study sites: the Cornubian Ore Field (SW England), the Banatitic Magmatic and Metallogenic Belt (Romania), Norrbotten and Skellefte mining districts (Sweden) and the Iberian Pyrite Belt (Portugal). The collection was completed by different ore types from Hungary.

A key aspect of the CHPM2030 concept is that metals can be transported in solution in rock bodies and extracted at the surface. The extraction process is more efficient with higher dissolved metal concentrations, but too large a dissolved load may lead to problems of precipitation within production boreholes or surface infrastructure. Thus, the potential for recovering more metals should be balanced against increased maintenance operations. Environmental aspects also have to be considered when additives to the geothermal fluids are used as 'mild' leaching agents. The leaching experiments conducted within the project were aimed at testing a range of possible additives in terms of their leaching behaviour in several different types of mineralised rocks.

The rock types contained different ore minerals, though all were dominated by sulphide mineralisations. These were exposed to and reacted with a range of leaching solutions that included deionised water, tap water, dilute brine (0.6 M sodium chloride), de-ionised water with 20 bar Pco_2, 0.1 M ethylenediaminetetraacetic acid (EDTA),
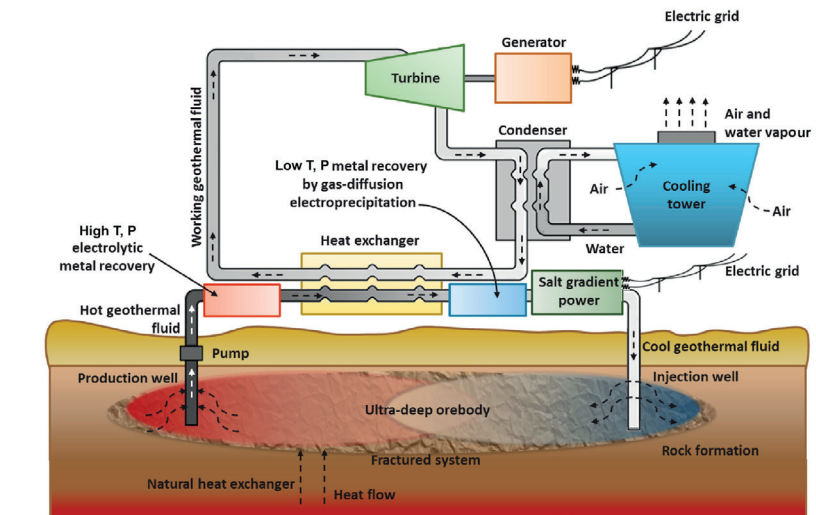

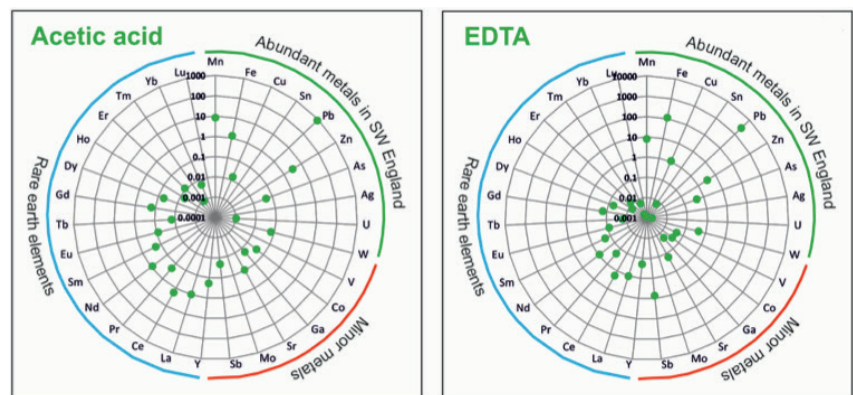Figure 1: Schematic overview of the envisioned CHPM facility. © CHPM2030 Team.

Figure 2: Amounts of metals released after 4 weeks of reaction at 70 °C. The centre of each plot represents 0 ppm, and the outer part of the plot 1,000 ppm (left) and 10,000 ppm (right) for dilute acetic acid or dilute EDTA solution (Kilpatrick et al., 2017).

0.1 M acetic acid, 0.1 M sodium dodecyl sulfate (SDS), 0.1 M ammonia (NH_3), 0.1 M hydrogen peroxide (H_2O_2), 0.1 M hydrochloric acid (HCL) with 0.03 M nitric acid (HNO_3), and 0.01 M hydrochloric acid with 0.003 M nitric acid.

Three types of experimental equipment were used for the leaching tests at the premises of the British Geological Survey. A rotating mixing assembly holding up to twenty 250 ml HDPE bottles filled with approximately 200 ml of leaching solution and 5 g of granulated ore. This equipment was maintained at 70 °C inside an oven and used to test the reactions of the ore samples with a wide variety of different leaching solutions.

1. Titanium or PTFE-lined stainless-steel autoclaves, which held approximately 330 ml of leaching solution and 8.8 g of granulated ore. These were stirred periodically, rather than continuously, and ran at 100 °C, 150

°C and 200 °C and at 20 MPa pressure.

2. Titanium-lined Dickson-type rocking autoclaves, which held 200 ml of leaching solution and 5 g of granulated ore. These were run at 200 °C and 20 MPa pressure.

The elevated temperatures and pressures of the latter two types of experiments make them more representative of in-situ conditions within an ultra-deep metal enrichment. Most experiments ran successfully for approximately 4 weeks. Analytical data were obtained from samples of solution and solids extracted at the end of the experiments, though certain experiments were subsampled more regularly to provide time-series data.

The mixture of mineral acids was the most effective solution used for liberating a range of metals; however, solutions containing organic compounds (EDTA, acetic

acid, SDS) also proved effective (*Figure 2*).

EDTA and SDS (like mineral acids) led to higher concentrations of dissolved aluminium and silica, whereas acetic acid did not. This could be an advantage, as lower concentrations of aluminium and silica would tend to disfavour clay formation - clays could potentially occlude fluid flow if they formed within flow zones. Oxidation reactions were critical in breaking down sulphide minerals, and experiments with more oxygen appeared to result in more dissolution. Where $Fe3+$ ions stay in solution, their formation (e.g. from chalcopyrite or pyrite dissolution) appears to be key in enhancing the rates of dissolution of other sulphide minerals – largely because $Fe3+$ can act as a very effective oxidising agent and catalyse sulphide oxidation reactions.

Sulphide oxidation produced acidity, and whilst this might benefit metal mobility, it may lead to corrosion issues for well linings and surface infrastructure. Reaction of this acidity with carbonate or aluminosilicate minerals was observed, as evidenced by dissolution features such as etch pits. Such reaction of gangue minerals in fractures or minerals in the wallrock has the potential to buffer fluid pH to more neutral values, though reaction types will be site-specific (Kilpatrick *et al.*, 2017).

Experiments on the use of carbon nanomaterials for metal mobilisation were performed at VITO. This included the modification of selected materials for improved metal sorption selectivity/capacity under different temperature and pressure conditions (i.e. towards targeted recovery of individual metals). One of the findings was that functionalisation of the carbon nanoparticles changed the nature of the sorption performance. In some cases this resulted in lower overall sorption, but metal sorption occurred over a broader pH range, which might facilitate metal capture over a wider range of natural environments (Mullens *et al.*, 2018).

Recovery of metals from the geothermal fluid

Metal recovery experiments were carried out at two sets of conditions: by high pressure, high temperature electrolysis and at lower pressure and temperature, with gas-diffusion electroprecipitation and electrocrystallisation.

High pressure, high temperature electrolysis

Experiments on high pressure, high temperature electrolysis were conducted at KU Leuven. During the metal recovery process, the first step is the exploration of the technical feasibility of extraction of the leached metals from the solution phase using electrodeposition at high pressure and high temperature conditions of the brines emerging from the geothermal wellhead. Metal ions present in the leachate can be reduced onto a substrate by passing current to drive the electrode to a potential lower than the reduction potential of the metal. Additionally, the high pressure also prevents silica from precipitating further in the reactor, which can potentially interfere with the metal electrodeposition. Based on potential-pH diagrams developed at elevated temperatures and pressures for several metals of interest (Cu, Ag, Ni, Sn, Pb and Zn), Cu was chosen as the primary metal of interest.

In the reactor, mesoporous platinum deposits on a Pt disk were achieved with pore size ranging between 5 nm and 10 nm. The electrodes showed a rapid and stable potential response. Additionally, the stability of the electrode with temperature was confirmed. Cyclic voltammograms indicated that the electroreduction of Cu^{2+} ions and subsequent electrooxidation of Cu in aqueous medium at pressures of 5 MPa behaved similarly as that at atmospheric pressure. However, SEM images indicate that the electrodeposits at elevated pressures are denser and closely packed. As expected, at temperatures greater than 100 °C and elevated pressures, the cyclic voltammograms exhibited currents that were at least 10 times higher than those obtained at room temperatures. Additionally, the deposit morphology at 100 °C does not exhibit the crystalline-type deposit observed at room

temperature, instead displaying a layered deposit which was rather scattered and porous (Fransaer *et al.*, 2018).

Gas-diffusion electroprecipitation and electrocrystallisation

Experiments on gas-diffusion electroprecipitation and electrocrystallisation (GDEx) were carried out by VITO in a flow-by three-chamber electrochemical cell. Platinum was used as a counter anode, and a gas-diffusion electrode was used as the working cathode (*Figure 3*).

It was observed that temperature affects the performance of the system, and since the brine treated by the GDEx technology can be within 20-60°C, this parameter was evaluated in the system, first using simulated brines. The most important effects of temperature within this range concerned the formation of different products, variations on the system resistance, processing time, level of current, and process efficiency. The long-term performance under these conditions was also assessed. Based on the relevant brine compositions obtained from the literature study, experiments with simulated Li Al brines were conducted, as well as with real brines containing these metals (i.e., Romanian geothermal brines). The formation of mixed metal hydroxides was obtained, which have ample commercial relevance. Recovery of Li and Al was demonstrated using the GDEx process. However, a more in-depth analysis is needed to evaluate the process and how the varied parameters can affect it. The feasibility of employing microbial-electrochemical systems (i.e., bioanodes coupled to GDEx cathodes) was also tested, proving that
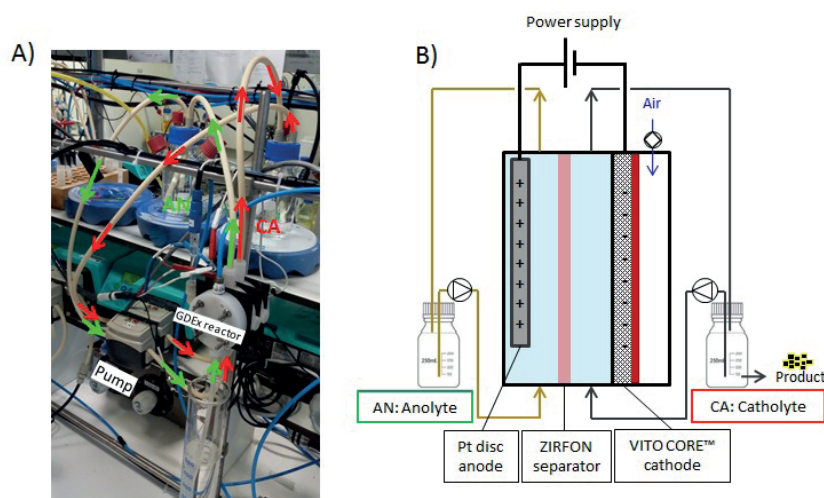

Figure 3: Schematic diagram of the gas-diffusion electroprecipitation and electrocrystallisation (GDEx) technology for metal recovery from geothermal brine:. (A) setup used for experiments and (B) schematic diagram of the experimental setup (Dominquez-Benetton et al.*, 2018).*

Figure 4: Semi-pilot setup for salt gradient power generation by reverse electrodialysis (SGP-RE) experiments (Photo: Joost Helsen)

the GDEx system could be operated with lower or negligible power consumption, or could even be used for the co-generation of electricity. Overall, the GDEx process is two- to three-fold more economical than classical mineral processing at the metal concentrations of geothermal brines and its upscalability is feasible (Dominquez-Benetton *et al.*, 2018).

Salt gradient power generation

The CHPM project concept involves the feasibility assessment of extracting surplus electrical energy from the geothermal brine. Chemical energy is stored in the brine in the form of dissolved salts. This energy can be tapped using a process called 'reverse electrodialysis'. Reverse electrodialysis (RE) has been tested at a pilot scale for river water, sea water and concentrated brine applications. Extracting salt gradient power (SGP) from geothermal brines is a new concept, launched in this project. A specific lab-scale setup to test a single cell pair SGP-RE system was designed and built for investigating the applicability of the process (*Figure 4*). Four steps were taken to elucidate the most important factors influencing the performance: (1) examination of the performance of three commercially available membrane pairs, (2) effect of increased temperature, (3) effect of multivalent ions and (4) combined effect of multivalent ions and increased temperature.

The experiments at increased temperature showed a very clear benefit of using geothermal brines at 60 °C or even higher.

The power density at high temperatures increased 10 times compared to the tests at room temperature, even though the cell potential was less than expected due to deteriorating permselectivity at high temperatures (Helsen *et al.*, 2018).

System dynamics

The consortium identified the main technological elements of the CHPM system at a rather early stage of the project and then began to conceptualise the system's behaviour and identify a set of design parameters for plant operation. The seven distinct technological elements of the proposed CHPM plant are as follows (*Figure 5*):

1. Underground heat exchange, metal mobilisation
2. Production wells
3. Electrolytic metal recovery
4. Heat exchanger
5. Gas diffusion electrocrystallisation
6. Salt gradient power generation
7. Injection wells

The critical technical conditions that must be met for the technology to be operational are the design parameters. The availability of these parameters is problematic, especially for those technology components that are in the early laboratory testing phase. Even if lab-scale systems run under well-constrained conditions, it does not necessarily mean that these exact conditions will exist during the full-scale operation, or that the full range of these parameters will be known.

Design parameters provide useful information on the operability of the single CHPM technology building blocks; by comparing them one can retrieve the first hints on a crucial question of the CHPM innovation undertaking, namely the compatibility of these elements. The CHPM2030 project promises a technology to be framed together from engineered concepts that have never before been connected into a system. The identification of the parameters and the integration of the technological components into one operable CHPM system will be worked out by the end of the project.

Ongoing and further activities

Recent activities by the consortium are focused on establishing the mathematical models of the single technology elements. These technology components are at different TRLs (Technology Readiness Levels): some of them are at lab scale, while others
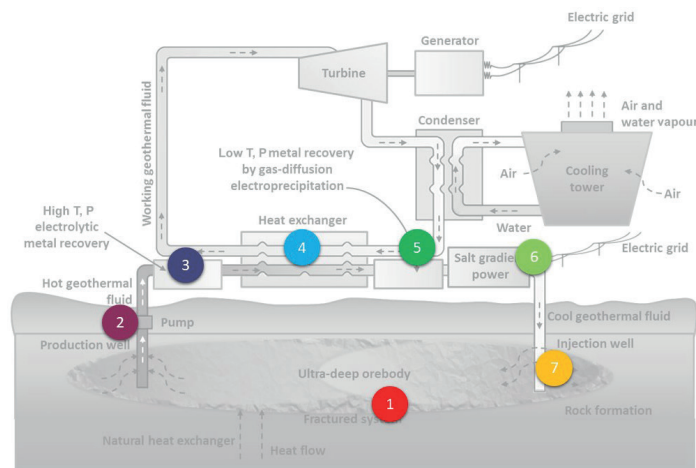

Figure 5: Components of the CHPM technology loop (Madarász et al.*, 2017).*

are capable of being upscaled. After the harmonisation of the components data, they will be connected to create the dynamic system model for various operational scenarios and potential pilot site operations.

The integrated assessment of the sustainability of the technology is also ongoing and will provide results by the end of the project. The framework for the complex assessment and the methodology for the economic feasibility assessment have been worked out. Several factors of the environmental impact have been studied (see Szanyi *et al.*, 2019). The ethical and the policy aspects of the application of the technology are under investigation.

The CHPM technology, as a whole, is still at low TRL and needs forward-looking efforts. Due to the disruptive nature of some of the innovative elements of the project and the parallel development of lab-scale technologies, it is inevitable that some knowledge gaps can be filled only after the closure of the project. Two time horizons have been identified: 2030 for pilot-scale operation and 2050 for full-scale operation. The forward-looking efforts are being undertaken in three interlinked areas: 1) mapping convergent technology areas, 2) studying pilot areas and 3) developing research roadmaps. The two roadmaps (2030 for early application, 2050 for break-

through research) will be provided by the end of the project, June 2019, and describe how to get to the desired future destination through emerging issues from the technology baseline of today.

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