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Combined Heat, Power and Metal Extraction from Ultradeep Ore Bodies

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ABSTRACT

This paper describes the results of the CHPM2030 research project, which was running in the period 2016-2019. It was funded through the European Commission Horizon 2020 programme with the aim to develop a novel and potentially disruptive technology solution that can help satisfy the European needs for energy and strategic metals in a single interlinked process. The intention was to create a proof of concept of the technical and economic feasibility at laboratory scale for new routes to valorise critical metals from high-performance geothermal systems. An important part of the work consists of a series of laboratory experiments and orebody investigations as well as simulations to validate the methodological framework. The main components in the system are: (1) Underground heat exchanger, (2) Production wells, (3) Electrolytic metal recovery, (4) Geothermal binary power plant, (5) Heat production unit, (6) Gas diffusion electro-precipitation, (7) Salt gradient power generation and (8) Injection wells. Sub-models of the different components describe their behaviour and these have been combined in one overall mathematical model. It is used to study selected scenarios based on conditions in known geothermal reservoirs in Europe. Sensitivity analysis and results of optimization of combined metal extraction and power generation will be presented.

1. INTRODUCTION

The CHPM2030 project aims to develop a novel technological solution of Combined Heat, Power and Metal (CHPM) extraction from ultra-deep ore bodies, that will pave the way for pilot-scale systems to be operational by 2030. This technology will help increase the attractiveness of renewable geothermal energy and also reduce Europe's dependency on the import of metals and fossil fuels. In the envisioned technology (Figure 1), 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. Critical to this, is an 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 engineered geothermal systems (EGS). 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.

2. METHODOLOGY FRAMEWORK DEFINITION

Methodology framework definition provides a conceptual framework for the technology of energy production and the extraction of metals from ore deposits located at depths below the conventional mining, where the temperature is above 100°C. Working on the boundaries of geophysics, geochemistry, hydrogeology and geoenergetics our aim was to discover and examine the geological, tectonic, geochemical, and petrologic factors that define the boundary conditions of such novel EGS both in terms of energy and potential for metal recovery .

As the distribution of metallogenic provinces strongly correlates with the tectonic setting, four large metallogenic provinces can be identified within Europe: (1) Precambrian Fennoscandian Shield province, (2) Early Paleozoic Caledonian province, (3) Late Paleozoic Variscan province, (4) Mesozoic-Cenozoic Alpine province (Figure 2). The prospective zones or formations for the CHPM technology were assessed in each metallogenic province (Hartai et al. 2016).

Magmatic-hydrothermal mineralization associated with intrusive bodies was the most obvious choice as a genetic process producing potential targets. Mechanical properties of plutonic (mainly granitic) rocks can be considered as appropriate for drilling and maintaining a crack system allowing fluid transport: deep geothermal projects so far were based on such bodies mostly.

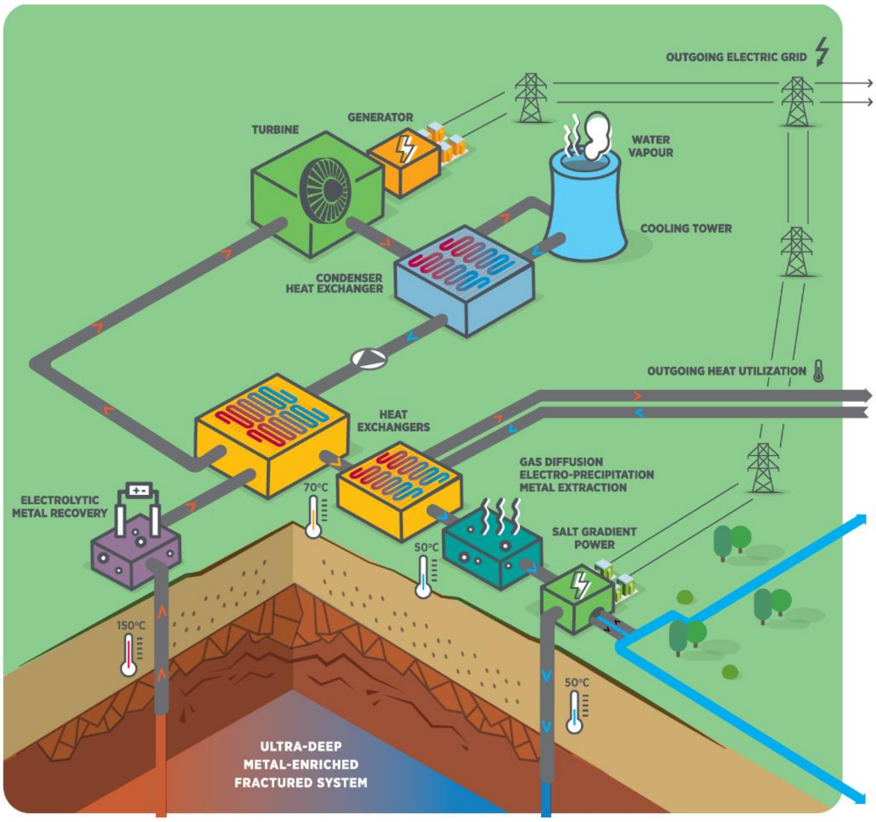


Figure 1: Schematic representation of the CHPM concept

Another metallogenetic environment of considerable potential is a subsiding basin in a rift or subduction zone, where mineralized horizons form as a consequence of submarine volcanism and exhalation. Such ore bodies may be relatively thin, but with large lateral extension. Most important deposit types are the volcanic massive sulphide (VMS) ores, the sediment-hosted (stratiform or stratabound) base metal deposits and the black shale horizons, where metal enrichments are bound to organic matter.

A third possibility lies in the deep-rooted fault zones, mainly those of extensional nature and elevated heat flow. Shallow level hydrothermal ore deposits in this environment often originate from remobilisation of metals of an earlier mineralization. Occurrence of these deposits may indicate the presence of a deep-seated fertile rock body, which can have a potential for further leaching (Németh et al. 2017).

3. SAMPLE COLLECTION AND LEACHING TESTS

The consortium collected samples from potential study sites: the Cornubian Ore Field (SW England), the Banatitic Magmatic and Metallogenic Belt (Romania), the three mining districts of Sweden (Bergslagen, Skellefte and Northern Norrbotten) and the Iberian Pyrite Belt (Portugal); and were completed by further samples from different ore types in Hungary. Altogether, 26 samples were studied. The samples were analysed by X-ray diffraction, X-ray fluorescence spectrometry, polarisation microscopy and electron microprobe and EDX measurements.

In the frames of the CHPM project, ore is a material from which metallic components of economic value can be extracted, and ore deposit is any permeable rock body from which this extraction is technologically possible via hot aqueous solution. Therefore, the term ‘ore body’ does not cover the same objects as for the traditional mining. Ore minerals are not necessarily the ones containing a specific metal in the highest concentration, but the ones most likely to decompose or dissolve under physical conditions on the required temperature level of the Earth’s crust, releasing the metal to the solvent. On the other hand, the solution has to reach the surface and be processed for the extraction and separation of the metals, simultaneously with extraction of the heat. In a preliminary assessment, the following chemical elements were considered as useful and possible to process: Cu, Zn, Pb, Fe, As, Sb, Cd, Ag, Au, Mn, Co, Cr, Ni, U, Mo. The study was focused on sulphide mineralization carrying these metals (Szanyi et al. 2016).

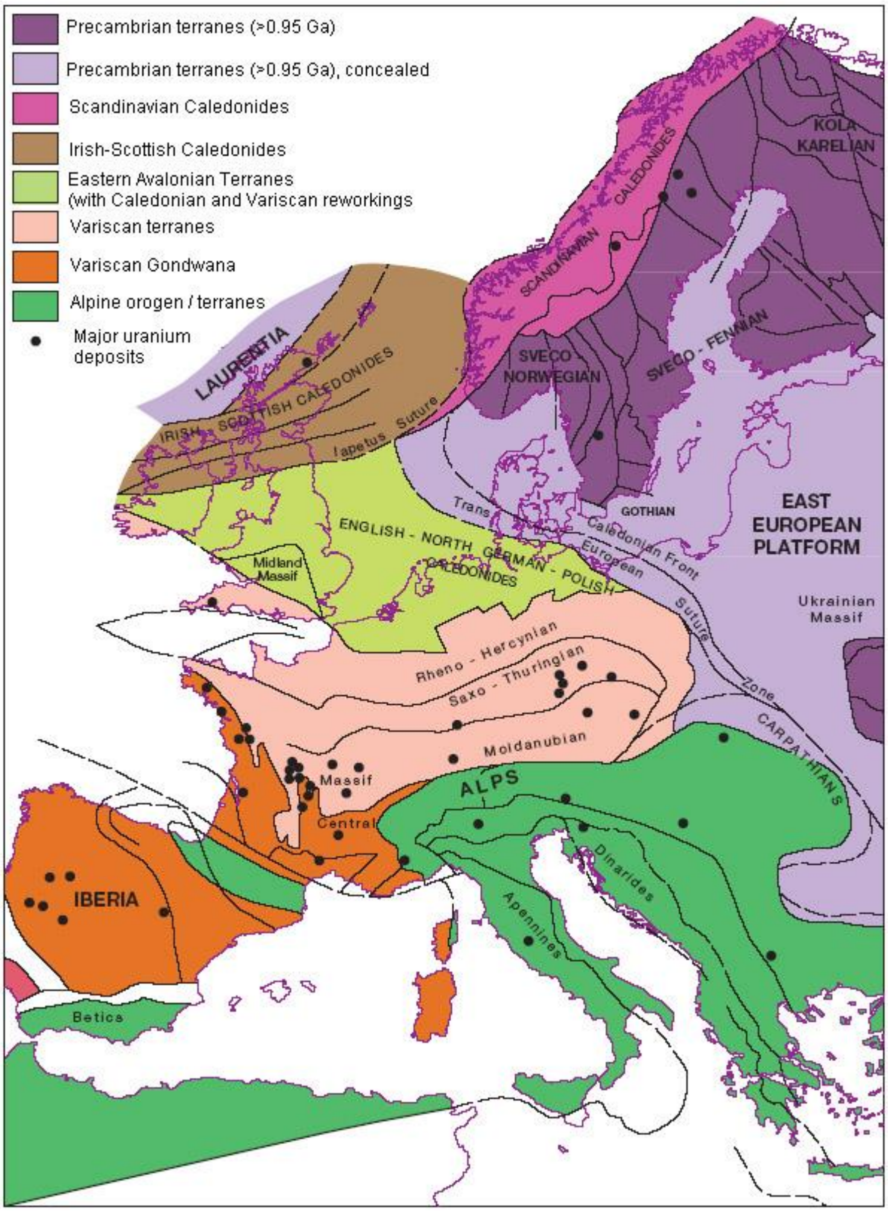


Figure 2: Major tectonic units of Europe (Plant et al. 2005).

When dealing with compositional data, not only the most abundant rock forming and ore minerals, but accessories are also important. Accessories, alteration products not linked directly to the ore formation but enriched in a larger rock volume may represent a quantity of similar magnitude as the ore minerals themselves. Some of the samples can be regarded as a connected group, so these are mentioned together; others have special properties. As for the ore deposit type, from technological aspects the skarns are preferable targets since (at least at near surface conditions) their carbonate matrix can be dissolved relatively easily, while the relatively stable silicate minerals remain almost intact and may act as proppants, while dissolved carbonates produce secondary permeability enlarging the reactive surface of the minerals. In the pressure-temperature range expected in an EGS project this stability relation might alter, but it remains still probable that carbonates, in contrast with silicates, will be dissolved without significant insoluble residue. As one of our aims was to identify and characterize the ore types which are relevant for the CHPM technology, the samples are grouped accordingly, and a short overview is given on the most important minerals and metals found in them (Table 1).

A key aspect of the CHPM2030 concept is that metals can be transported in solution and extracted at the surface. That extraction process will be more efficient with higher dissolved metal concentrations. Equally however, too large a dissolved load may lead to problems of precipitation within production boreholes or surface infrastructure. Thus, there is a need to balance the potential for increased revenue generation from recovering more metals, against potential increased costs resulting from increased maintenance operations. Dosing the recirculating geothermal fluid with additives could be a way to enhance ore dissolution and maintain metal solubility. However, there is also a need to be mindful of environmental considerations, and consider additives that are relatively ‘environmentally benign’ and which could act as ‘mild’ leaching agents. The experiments conducted within the project were aimed at testing a range of possible additives in terms of their leaching behaviour of several different types of mineralised rocks. The rock types chosen covered a range of mineralisation types and contained a range of ore minerals, though all were dominated by sulphide mineralisation. These were 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), 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 (HNO3) and, 0.01 M hydrochloric acid with 0.003 M nitric acid. Not all fluid-solid combinations were run in this study, and we worked initially at lower temperatures (70°C), reacting all fluids with a sample of UK material in order to rank the leaching potential of the different fluids. Once the most promising fluids were identified, we then used just those fluids for both a wider range of rock types and also a wider range of temperatures (from 100 °C to 200 °C). Comparative assessment was facilitated by reacting all solids with 0.6 M NaCl solution, and also a mixed solution of 0.01 M hydrochloric acid with 0.003 M nitric acid.

Table 1: Major mineral components and metals/metalloids of the samples. Samples are grouped according to the type of ore mineralization they represent.

Id	Site	Ore type	Country rock / gangue minerals	Ore / accessory minerals
1	Baita Bihor	Skarn, sulphide molybdenum ore	*silicate* (gr): Mg, Fe *carbonate*: Ca	*phosphate*: Ca, Y *sulphide*: Mo
2, 18	Pietroasa	Skarn, borate	*carbonate*: Ca, Mg *silicate* (py, amph, gr): Ca, Mg, Fe	*borate*: Mg *oxide*: Fe
15, 16	Budureasa, Pietroasa	Skarn, magnetite	*carbonate*: Ca, Mg, Fe *silicate* (amph): Ca, Mg	*fluoride*: Ca *oxide*: Fe, Mn
17	Baita Rosie	Skarn, sulphide polymetallic ore	*silicate* (py): Ca, Mg, Fe	*fluoride*: Ca *sulphide*: Pb, Zn, Mo, Bi, Cu
12, 13, 14	Cacova Ierii, Baisoara	Skarn, magnetite and sulphide Cu ore	*carbonate*: Ca, Mg *silicate* (gr, amph): Ca, Mg, Fe	*oxide: Fe* *sulphide*: Fe, Cu
9, 10, 11	Dannemora	Skarn, magnetite	*carbonate*: Ca *silicate* (q, Kfs, mica, ep): Ca, K, Mg, Ba	*oxide*: Fe, Mn, Ti, Nb *sulphide*: Fe *silicate*: Zr, REE
19	Malmberget	Skarn, magnetite	–	*oxide*: Fe, Ti, V
20, 21	Kristinebergs-gruvan	Porphyry, sulphide Cu-Zn ore	*silicate* (q, chl): Si, Mg, Fe	*phosphate*: Ca, REE *oxide*: Fe, Cr, Co, Ti *sulphide*: Fe, Cu, Zn
7, 8	Craddock Moor, Herod's Foot	Porphyry and vein, sulphide Cu-Pb ore	*silicate* (q): Si	*oxide*: Fe, Ti, Nb *sulphide*: Fe, Pb, Cu, As
3	Gyöngyösoroszi	Vein, sulphide Pb-Zn ore	*carbonate*: Ca, Mg, Mn, Fe	*sulphide*: Fe, Zn, As, Cu, Pb
5, 6	Recsk	Porphyry and skarn, sulphide polymetallic ore	*silicate* (amph, gr): Ca, Mg, Fe	*oxide*: Fe, Cr, Co, Ni *sulphide*: Fe, Cu, Zn, Pb, Mo
4	Rudabánya	MVT Pb-Zn ore	*carbonate*: Ca, Mg, Fe, Sr *sulphate*: Ba	*sulphide*: Fe, Zn, Pb, Sb, As *oxide*: Fe, Zn, Pb (secondary)
23, 24, 25, 26	Porto de Mel, Corvo inferior	VMS Cu-Zn-Sn ore	*silicate* (q, fs, mica, chl): Ca, Mg, Fe, K, Na *carbonate*: Ca	*phosphate*: Ca, REE *oxide*: Sn, Fe, Ti *sulphide*: Fe, Cu, Zn

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 high density polyethylene bottles filled with approximately 200ml of leaching solution and 5 g of granulated ore. This equipment was maintained at 70 °C inside an oven and used to react the ore samples with a wide variety of different leaching solutions.

- Titanium or PTFE-lined stainless-steel autoclaves, which held approximately 330 ml of leaching solution and 8.8 g of granulated ore. These were periodically, rather than continuously, stirred, and ran at 100 °C, 150 °C and 200 °C and 200 bar pressure.

- 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 200 bar 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 orebody. Most experiments ran successfully for approximately 4 weeks, apart for the 200 °C rocking autoclave experiments, which suffered major corrosion issues and had to be terminated early. Most 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.

Analysis of reaction products showed that we were successful in enhancing the mobilisation of a range of metals (relative to water or dilute brine), and leaching occurred relatively quickly (reaching steady-state concentrations in the first few tens of hours). However, not all metals behaved in the same way – some were leached relatively easily (e.g. lead, which reached approximately 1000 ppm in some experiments) whereas others proved much harder to mobilise (e.g. tin, tungsten, which did not rise above 1 ppm in most cases). Metal concentrations were initially controlled by the rates of dissolution/oxidation, which appears to have been fast within the first few hours of the experiments. Subsequently however, the concentration of many metals reached steady-state values after just a few tens of hours, and minerals such as anglesite (lead sulphate) precipitated.

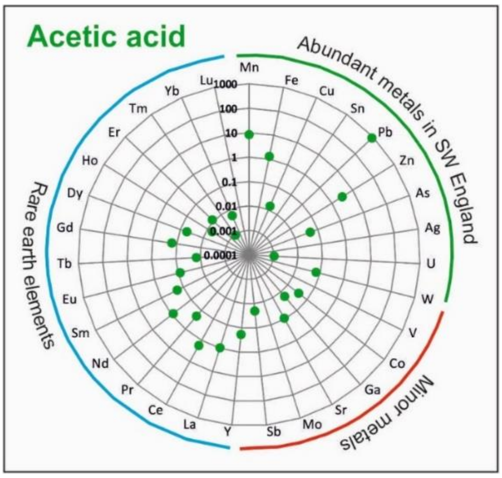


Figure 3: Sample data of metal mobilisation using acetic acid

The mixture of mineral acids was the most effective solution used for liberating a range of metals (Figure 3), however solutions containing organic compounds (EDTA, acetic acid, SDS) also proved effective. However, 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 (e.g. in experiments with hydrogen peroxide or ones that were regularly exposed to the atmosphere). However, too much oxygen could potentially lead to dissolved iron being precipitated as Fe oxide/oxy-hydroxide. As well as also potentially occluding fluid flow, these phases are also effective sorbants of metals of interest and can reduce their concentration in solution.

Where Fe^{3+} ions did stay in solution, then 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 Fe^{3+} 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. Whilst acidity, together with a range of ligands, may aid metal mobility, the addition of phosphate reduced concentrations of rare earth elements and possibly uranium. There could be benefits in the prevention of uranium mobilisation, as this may reduce the amount of naturally occurring radioactive material scale deposits.

Whilst we acknowledge that our study was somewhat 'idealised' in places, it has provided data on metal release behaviour from samples sourced from pilot site areas being studied within the CHPM2030 project. We were constrained by lack of data from appropriate depths, with key uncertainties including: lack of knowledge about fracture mineralogy, and plus lack of deep fluid chemistry. Reducing such uncertainty requires newly-drilled deep boreholes that can facilitate gathering new sampling and providing valuable new data (Kilpatrick et al. 2017).

4. SURFACE TECHNOLOGIES FOR METAL RECOVERY AND SURPLUS ENERGY PRODUCTION

4.1 High pressure, high temperature electrolysis

The CHPM2030 project ventured to explore the recovery of valuable metals from geothermal fluids via various technologies. The surface metal recovery technologies were developed and tested by the Flemish Institute for Technological Research (VITO). 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 pressures also prevents silica from precipitating further in the reactor, which can potentially interfere with the metal electrodeposition. The objective of our work as a part of the CHPM2030 initiative, was the feasibility, performance, and establishing design criteria for trace metal electrodeposition from geothermal brines at elevated temperatures and elevated pressures. 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, based on the reduction potential.

Mesoporous platinum deposits on a Pt disk, with pore size ranging between 5 nm and 10 nm, was achieved on Pt. The electrodes showed a rapid and stable potential response. Additionally, the stability of the electrode with temperature was confirmed. The mPt quasi-reference electrode was calibrated with the help of Fe(II)/Fe(III) redox couple.

Cyclic voltammograms indicated that the electroreduction of Cu2+ ions and subsequent electrooxidation of Cu in aqueous medium at pressures of 50 bar exhibit no significant difference when compared to 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 the 373 K and elevated pressures, the cyclic voltammograms exhibited currents that were at least 10 times higher than that obtained at room temperatures. Additionally, the deposit morphology at 373 K does not exhibit a crystalline-type deposit as observed at room temperature and showed layered deposit which was rather scattered and porous. The porous nature of this deposit can be attributed to the Cu dissolution due to the increased rate of comproportionation reaction at higher temperatures, resulting in the formation of Cu+ ions, which has been shown to be a primary reason behind a uniform conformal coating (Fransaer et al. 2018).

4.2 Gas-diffusion electrocrystallization

Literature review has been done on geothermal brines to identify relevant characteristics and compounds of interest (i.e., metals, rare earth elements) that can be potentially recovered using the gas-diffusion electrocrystallization (GDEx) technology and are prone to form functional materials with potential commercial interest. Within the frame of the project experiments were conducted by VITO in a flow-by three-chamber electrochemical cell. Platinum (10 cm2) was used as a counter anode, and a (GD) electrode (using compressed air 200 ml min-1) of the same size was used as the working cathode (Figure 4).

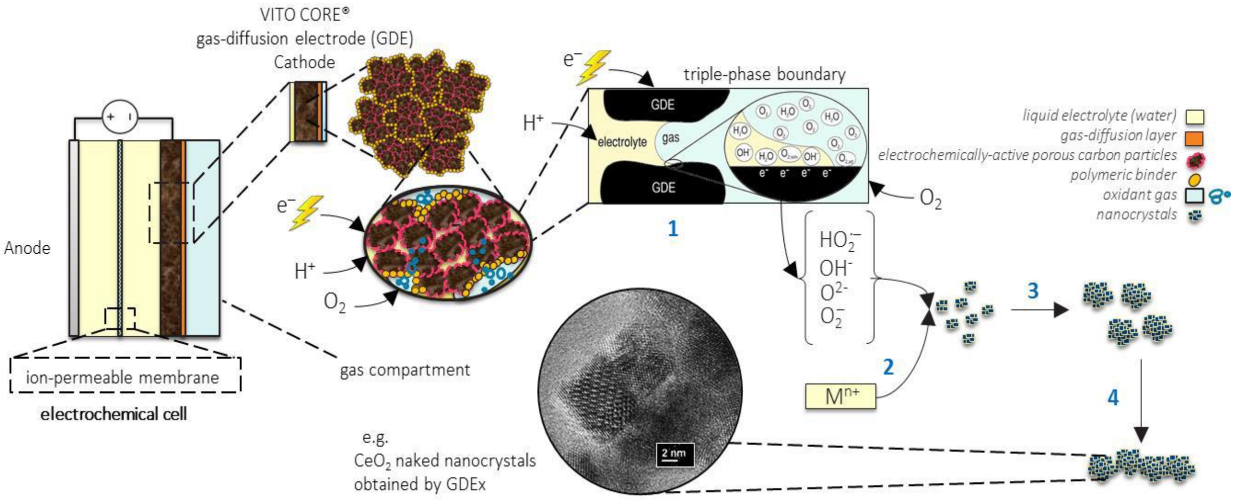


Figure 4: General scheme of the gas-diffusion electrocrystallization (GDEx) concept. An oxidant gas, provided through the gas compartment of the electrochemical cell (left), is electrochemically reduced at the triple-phase contact of the gas-diffusion cathode (1). The products of the electrochemical reduction of the oxidant gas react with the metal ions in solution (Mn+) and provide the decisive pH and redox potential conditions to form inorganic nano-crystallites which may remain in a stable colloidal dispersion (2). The nano-crystallites formed aggregate into nanoparticles (3), which may eventually sediment to be further recovered as powders (4).

It was also observed that temperature can affect the performance of the system, and since the brine treated by the GDEx technology can be within 20-60°C (as defined by the CHPM proposal), 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 and the production of Li/Al LDH has been demonstrated by GDEx process. However, more in-depth analysis is needed to evaluate its properties and how the varied parameters can affect them. The feasibility of employing microbial-electrochemical systems (i.e., bioanodes coupled to GDEx cathodes) was also tested, proving that the GDEx system could be operated with lower or negligible power consumption, as well as it could even be used for the co-generation of electricity. Overall, the GDEx process is 2-3 fold more economical than classical mineral processing at the metal concentrations of geothermal brines and its upscalability is feasible (Dominiquez et al. 2018).

4.3 Salt gradient power generation

The CHPM project concept involved the feasibility assessment of extracting surplus electrical energy from the geothermal brine. Chemical energy is stored in the brine as in the form of dissolved salts. Using a process called ‘reverse electrodialysis’ this energy can be tapped. Reverse electrodialysis (RE) has been tested at 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. Four steps were taken to elucidate the most important factors influencing the performance: examination of the performance of three commercially available membrane pairs (1), effect of increased temperature (2), effect of multivalent ions (3), combined effect of multivalent ions and increased temperature (4).

Testing three combinations of commercially available ion exchange membranes in the lab setup revealed that FUJI membranes were the most performant at high salt concentration, but their performance dropped significantly when the brine concentration lowered. The other two pairs were more suitable at moderate to low concentrations and also less prone to a decrease in concentration of the brine.

The experiments at increased temperature showed a very clear benefit of using geothermal brines at 60°C or even higher. The power density of the FKE/FAS membranes at high temperatures increased 10 times compared to the tests at room temperature, even though the cell potential was less than expected due to a deteriorating permselectivity at high temperatures (Helsen et al. 2018).

The final lab experiments consisted of determining the effect of multivalent ions on the performance. Calcium and Magnesium were chosen as the most common multivalent cations observed in real brines. The effect was studied on the FUJI and FKE/FAS membrane pairs. It was found that the presence of Ca and Mg had little or no effect on the cell potential (given equal molarities). As a single salt, neither Ca nor Mg had a big influence on the performance of the single cell. In a combined set of experiments however it was found that the performance reduced significantly when both cations (Ca^{2+}, Mg^{2+}) were present. In those case the performance was reduced approximately 50%, compared to the case without multivalent ions. This performance loss was consistent throughout the entire temperature range that was studied (25-60°C).

5. IDENTIFICATION OF TECHNOLOGY ELEMENTS AND SYSTEM DYNAMICS

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

1. Underground heat exchanger
2. Production wells
3. Electrolytic metal recovery
4. Heat exchanger
5. Gas Diffusion electroprecipitation
6. Salt gradient power generation
7. Injection wells

Design parameters are those critical technical conditions identified for each of the CHPM technological building blocks that must be met for the technology to be operational. The availability of design parameters is not trivial especially for those technology steps that are in the early laboratory testing phase. However, even if lab-scale systems are run under well-constrained conditions, it does not necessarily mean that these exact conditions will exist during full-scale operation, or that a full range of these parameters will be known.

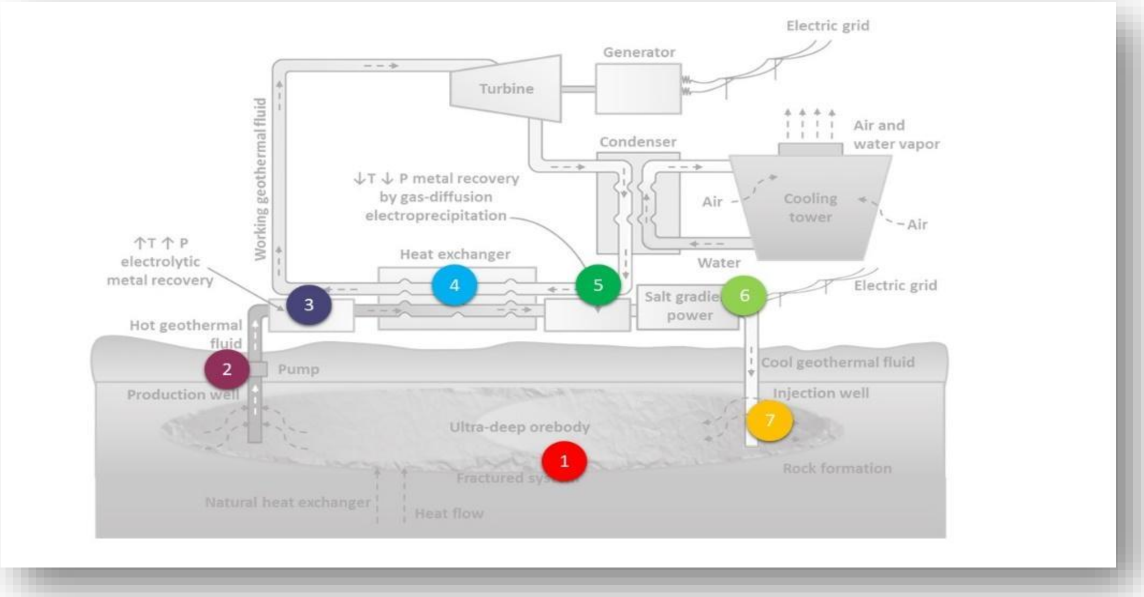


Figure 5: Elements of the CHPM technology loop

Design parameters provide useful information on the operability of the single CHPM technology building blocks, however 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 been connected into a system before.

Figure 6 shows the change of viable temperature ranges between each technology element. The bars illustrate the tolerable temperature ranges for the single technology steps, while the black lines delineate an approximate scenario range for the operation. Thus, where the shift of temperature range between neighbouring elements is positive, the system might require energy input, which needs consideration with regards the feasibility of the technology (Madarász et al. 2017).

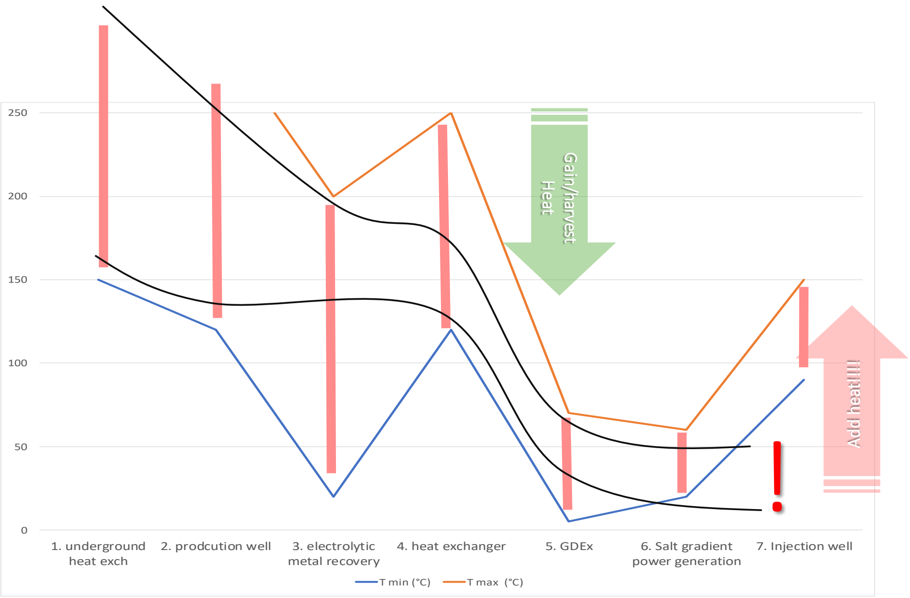


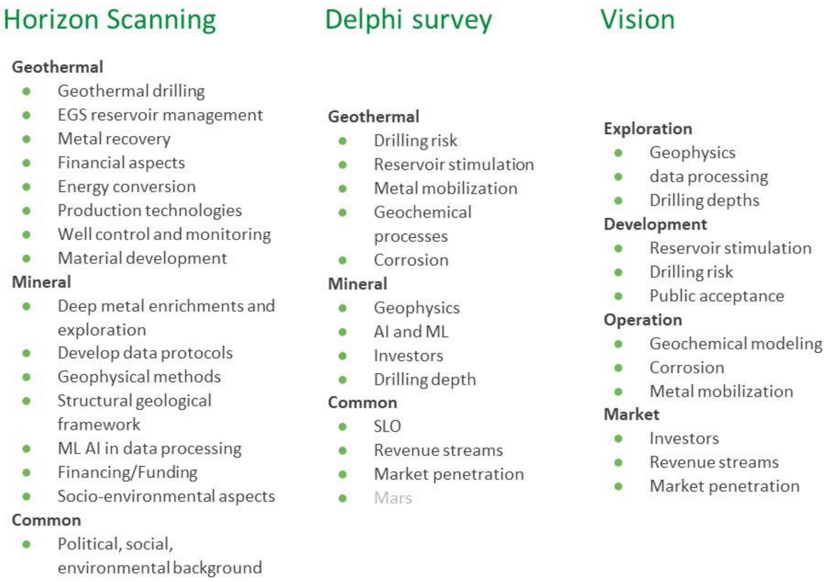
Figure 6: The change of critical temperature range throughout the CHPM technology loop.

6. RESEARCH ROADMAP

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

The first theme involves Horizon Scanning, Delphi survey, and Visioning. Horizon Scanning provided the present technological baseline, with an expert workshop on mapping key interest areas and gap analysis. The results have been formulated into 12 Delphi statements covering various aspects of the technology. The 2-round Delphi provided more pieces of the puzzle of what the future may be at key interest areas. The next step was a visioning workshop, where the participants picked up key topics identified through horizon scanning and the Delphi survey were explored to define preferred targets for two time frames to enable the technology implementation at TRL6-7 by 2030, and TRL8-9 by 2050. The sum of the targets is the Vision that describes what is the desired destination in the future. The second theme is the investigation of 4 pilot areas with the addition of an EU outlook, where the technology may be developed by 2030 at a pilot scale.

The two roadmaps (2030 for early application, 2050 for breakthrough research) describe how to get to the desired future destination (Vision), through emerging issues (Delphi) from the technology baseline of today (Horizon Scanning).


Horizon Scanning

Geothermal
- Geothermal drilling
- EGS reservoir management
- Metal recovery
- Financial aspects
- Energy conversion
- Production technologies
- Well control and monitoring
- Material development

Mineral
- Deep metal enrichments and exploration
- Develop data protocols
- Geophysical methods
- Structural geological framework
- ML AI in data processing
- Financing/Funding
- Socio-environmental aspects

Common
- Political, social, environmental background

Delphi survey

Geothermal
- Drilling risk
- Reservoir stimulation
- Metal mobilization
- Geochemical processes
- Corrosion

Mineral
- Geophysics
- AI and ML
- Investors
- Drilling depth

Common
- SLO
- Revenue streams
- Market penetration
- Mars

Vision

Exploration
- Geophysics
- data processing
- Drilling depths

Development
- Reservoir stimulation
- Drilling risk
- Public acceptance

Operation
- Geochemical modeling
- Corrosion
- Metal mobilization

Market
- Investors
- Revenue streams
- Market penetration

Figure 7: Mapping convergent technologies to support the CHPM concept

7. CONCLUSIONS

The recent activities of the consortium focus on establishing the mathematical model of the single technology elements, which are then connected to create the systems dynamic modelling of various operational scenarios and potential pilots site operations. The technology development takes place at different TRL levels, some of them are still in lab scale, while others were capable of being upscaled. The available data and knowledge gained during the laboratory experiments are now helping us to wisely chose site(s) for the CHPM pilot operation and to identify research road map for the coming years.

It is also clearly recognised by the consortium that convincing proofs of applicability and financial feasibility of the technology can be more easily achieved if single elements of the CHPM technology can be tested as add-ons to existing geothermal sites. By allowing the independent and site-specifically customised testing of the technology compounds the baseline CHPM idea still shall be accomplished: the financial conditions of operating geothermal systems can be enhanced by combined heat, power and metal extraction (Ragnarsson et al. 2018).

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