Roadmap for 2030 and 2050

CHPM2030 Deliverable D6.3

Version: June 2019

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement nº 654100.

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Published by the CHPM2030 project, 2019
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CHPM2030 DELIVERABLE D6.3

Roadmap for 2030 and 2050

Summary:

The CHPM roadmap for 2030 and 2050 has been developed using the synergetic combination of three future-oriented layers of studies: 1) The "CHPM component roadmap" study provides a direct follow-up of the current technological components (e.g. metal mobilization/recovery), by describing the state-of-the-art, immediate research plan (2025), pilot research plan (2030), and long term objectives (2050); 2) The "Preparation for future pilots" study investigates the pathway to pilot implementation by 2030, by providing a detailed description of the 5 areas in Europe (Cornwall, Iberian Pyrite Belt, Beius Basin/Bihor Mountains, Kristineberg and Nautanen) for CHPM potential with recommendation for future exploration, stakeholder engagement and funding opportunities. 3) The "Overall concept of CHPM" study investigates the feasibility of combining geothermal energy with mineral extraction with the use of foresight tools such as Horizon Scanning, Delphi survey and Expert workshops. Targets and actions have been identified related to exploration, development, operation, and market, all related to CHPM technology. Using the synergetic combination of these three layers, a timeline has been constructed, including milestones, objectives and target to be achieved in order to arrive to pilots by 2030 and full-scale application by 2050.

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This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement nº 654100.

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LIST OF ABBREVIATIONS

AI: Artificial Intelligence

HS: Horizon Scanning

ML: Machine Learning

NIMBY: Not In My BackYard

SET Plan: Towards an Integrated Strategic Energy Technology Plan

SLO: Social Licence to Operate

TRL: Technology readiness levels

UNFC: United Nations Framework Classification for Resources

UNECE: United Nations Economic Commission for Europe

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0. Preface

CHPM technology is a low-TRL, novel concept that needs further nurturing and future-oriented thinking. WP6 coordinates these forward-looking efforts and aims to set the ground for subsequent pilot implementation by working on three future-oriented tasks: mapping convergent technology areas, study pilot areas, develop research roadmaps. These three areas of study are grouped under three WP6 subtasks: Task 6.1 Horizon scanning & Visions; Task 6.2 Preparation for pilots; Task 6.3 Roadmapping.

The objective of Task 6.1 task is to start up a technology visioning process for the further development of the CHPM concepts with the help of horizon scanning, a Delphi survey and a Visioning process. The outcome of this combined exercise will be the identification of trends and new concepts defining plausible targets where the CHPM technology could evolve in the future. The realisation of these targets will be made plausible with the help of an array of convergent technologies that can support their implementation by 2030/2050.

The aim of Task 6.2 is to support the development of technology and economic feasibility for a pilot implementation of such-system, by evaluating potential pilot areas according to a harmonized framework. This evaluation will also be used for starting up discussions on the financing of such investments. The potential areas, or study areas are: SW England, Portuguese Iberian Pyrite Belt, Romania Beius area, Sweden (Nautanen, Kristineberg). In addition, EFG has been working on EU level in order to set up a spatial database on prospective locations for CHPM technology with the help of EFG' Linked Third Parties (LTPs).

Task 6.3 is focusing on the development of a roadmap from 2019 through 2030 to 2050. The short-term, 2030 aspect is to prepare for early implementation and to provide a timeline and direct support to the first pilots. The long-term aspects aim to provide revision and updates in response to unforeseen, emerging phenomena, supporting breakthrough research for future CHPM development.

1. Executive summary

The CHPM roadmap for 2030 and 2050 has been developed using the synergetic combination of three future-oriented layers of studies:

1) CHPM component roadmap provides a direct follow-up of the current technological components (e.g. metal mobilization/recovery), by describing the state-of-the-art, immediate research plan (2025), pilot research plan (2030), and long-term objectives (2050);
2) Preparation for future pilots investigates how to arrive to pilot readiness level by 2030, by providing a detailed description of 5 areas in Europe (Cornwall in the UK, Iberian Pyrite Belt in Portugal, Beius Basin/Bihor Mountains in Romania, Kristineberg and Nautanen in Sweden) for CHPM potential with recommendations for future exploration, stakeholder engagement and funding opportunities.
3) Overall concept of CHPM investigates the idea of combining geothermal energy with mineral extraction with the use of foresight tools such as Horizon Scanning, Delphi survey and Expert workshops. Targets and actions have been identified linked to exploration, development, operation, and market, all related to the CHPM technology.

CHPM component roadmap, key findings:

Under integrated reservoir management, the creation of an effective fracture network has been demonstrated via simulations. The challenge is the reliability of the fracture creation process. The next research plan, includes the development of numerical modelling, stimulation tests are relevant depth, and new materials at well completion, to create a fully controlled fracture system in a deep metal enrichment.

The concept of metal content mobilization using mild leaching has been demonstrated in lab (effective leaching at a range of additives), with enhancing fluid flow. However further research is required concerning reprecipitation, lack of information on deep waters and metal enrichment. The next steps will require balancing the rate of solution and precipitation, together with improving knowledge on deep (>4km) metal abundance and groundwater chemistry and the development of a regional scale understanding of their parameters.

The concept of metal content mobilization with nanoparticles proved that absorption of relevant metals, under relevant conditions can be achieved in lab conditions. The main challenges are permeability and recovery of particles. The future research on the topic need to focus on materials development, system integration, selectivity, recovery and regeneration.

High-temperature and high-pressure (HTHP) electrode reactor has been designed, material selection has been completed and used for the recovery of metal ions from geothermal brines. The recovery of Cu was studied (temperature, pressure, initial copper concentration, silica content, electrochemical reduction potential, etc. The upcoming research plan includes more testing at real brines, optimization and techno-economic feasibility study, construction of small-scale and then larger pilot reactor using “plant on a truck” concept (Figure 23).

Metal recovery via gas-diffusion electrocrystallization (GDEx) technology developed from low TRL to granting EU patents during the project, with successful metal recovery process with real brines, at small scale. The next steps will involve techno-economic feasibility and optimization study, sizing and upscaling, minimising operation cost and maximise effectiveness of the metal recovery process.

Salinity-gradient power by reverse electrodialysis (SGP-RE) showed a good potential for extracting chemical energy through reverse electrodialysis, at high salinity brines at small pilot applications. The next steps are to improve membrane/stack design, construction of a full pilot on test site, and then optimise engineering issues.

A simplified mathematical models of main component has been delivered under system integration, based on expected parameters. Rough description of the physical processes involved has been described and coded. The development shall continue with improving the mathematical description of the components, models for optimisation, to deliver a detailed mathematical model of the integrated CHPM system at large.

Preparation for future pilots, key findings:

The Cornwall report describes the geological environment, geothermal characteristics, potential for deep metal enrichment, technical, environmental, social and regulatory factors.

3 new models have been developed during the project: Cornubian Batholith (geothermal energy development, fracture mapping), site scale 1 at the HDR project site (fracture data, hydrogeological properties, district fracture network models, potential flow paths) site scale 2 at the NW Carnmenellis granite, UDDGP site. The future recommendations cover 1) future exploration plans including 3D seismics, magnetotellurics, deep fluid flow, leaching experiments, mineral filled fractures, etc., 2) funding opportunities, 3) stakeholders' requirements, and 4) overall issues.

The report on the Portugues Iberian Pyrite belt evaluated the Variscan metallogenic province, massive sulphides deposits, prospect for deep mineralization for CHPM potential. The study area report provided an update on the geoscientific data and information on SW IPB, 3D modeling, geophysical data. The future research programmes should investigate the deeper ore deposits, with 3D/4D modeling, new deep seismics, 3D electromagnetic forward modeling, 3D inversion. Lombador orebody, is present at 2-3 km, has the potential to extend the lifetime with CHPM technology. Strong cooperation with the mining company and government is recommended.

The report from Romania provided information about the CHPM potential of Beius Basin (up and running DHS, Mg skarns, high geothermal potential), and Bihor Mountains (granodiorite-granite plutonic body related, skarn (Fe, Bo, Bi, Mo, W), vein (Cu, Zn, Pb, sulphides). The recommendations are related to 1) geothermal modeling, 2) refraction seismic for the plutonic body and mineral indications, 3) fracture network modeling for understanding reservoir characteristics.

The Swedish report described 2 ore provinces: Kristineberg area (Skellefte district, volcanogenic massive sulphide deposits, Zn, Cu, Au), and Nautanen area (Northern Norrbotten district, IOCG, Cu, Fe, Au). The challenges here are the low geothermal gradient, limited information at 5-7 km depth, low permeability and hydraulic conductivity, lack of information about deep-seated fluids. It is recommended that future exploration includes identification of metal bearing formation at crustal depths (seismic velocities, electrical resistivity), 3D/4D modelling, stimulation, involvement of the mining industry and ER regional development funds, achieving public acceptance, etc.

Overall concept, key findings:

When investigating the future for combining geothermal energy and metal extraction, the CHPM roadmap delivered concrete targets, actions, signposts and wild cards linked to exploration, development, operation, and market, all related to the CHPM technology.

The Exploration theme investigated emerging issues related to geophysics, data processing (AI, ML) and drilling depths. Identification and use of existing datasets, increased resolution (e.g. magnetotellurics), cost reduction (e.g. drilling), are some of the highlights. Advanced data processing techniques can develop and train machine learning (ML) algorithms for EGS/CHPM datasets. Guidelines for reinterpretation and re-evaluation datasets for CHPM potential and generating classes/models for CHPM exploration targeting are both assets. As a result, it is envisioned to reach a good understanding of mineral provinces with potential deep continuity, reduced data acquisition costs for CHPM, successfully application of AI/machine learning algorithms for (re)interpretation of datasets.

Under reservoir stimulation, the objective is to mobilise metals, improve reservoir performance, and reduce seismic risk, which will require testing soft leaching technology at real geothermal sites. First operators have to involved and individual components can be tested to prove the technology. These case studies can be used to attract major investors. A comprehensive information platform has been envisioned to share geoscientific information and best practises, monitor ongoing projects, and to create a platform for networking and matchmaking for potential CHPM partners. Alternative business cases have been pointed out, such as health, tourism, spa, manufacturing, where CHPM could act as a catalyst to create value for the local community.

The main topics related to the development of a CHPM system were metal mobilization, geochemical modelling, metal recovery. It is anticipated that the first CHPM pilots recover already solved metals. The advanced leaching component is added later that is first tested at well-known site, balancing solution and precipitation. Geochemical modelling is envisioned to be used for economic and business forecasts, to attract investors. Alternative recovery business cases are water treatment, non-metallic elements (Si), fluid treatment in flash steam system, abandoned mines.

The market theme investigated market penetration, investors and revenue streams. The key actions outlined here are strategic partnership with geothermal players and operators; modular/flexible approach for the minerals/metals recovery component; CHPM plug-in integration for up-and-running project with high metal content in the geothermal brine; advance framework for classifying geothermal + mineral resources has to be developed, through dialogues with UNFC; government incentives (e.g. tax related) as joint partnerships (PPPs); Branding & Stakeholder engagement. As a result, it is intended to establish a network of stakeholders, by 2025 and to have at least one full business case developed for both energy and mining sector by 2030.

In conclusion the CHPM roadmap, with 2030 and 2050 main timelines, has delivered concrete actions and targets, in the form of recommendations related to the current CHPM technological components (describing the state-of-the-art, immediate research plan (2025), pilot research plan 2030, and long term objectives 2050), potential future pilot areas (detailed description based on a common evaluation framework, and recommendations for future exploration, stakeholder engagement and funding opportunities), and about the overall concept of the combination of geothermal energy and metal extraction (targets, actions, signposts, wildcards linked to exploration, development, operation, and market).

2. Introduction

Work Package 6 - Roadmapping and Preparation for Pilots' objective is to set the ground for pilot implementation of the CHPM technology. However, considering the relatively low TRL[1] level, the first pilots and commercial applications are envisioned in 2030 and 2050, respectively, decades beyond the duration of the project. In order to tackle this challenge, it is required to set a roadmap that outlines the desired future vision and the necessary steps required to meet the targets by 2030 and 2050. In order to deliver this roadmap document,

[1] https://ec.europa.eu/research/participants/data/ref/h2020/wp/2014_2015/annexes/h2020-wp1415-annex-g-trl_en.pdf

several intermediate steps needed to be taken, with the utilisation of foresight tools, along Task 6.1 and Task 6.2 (Figure 1).

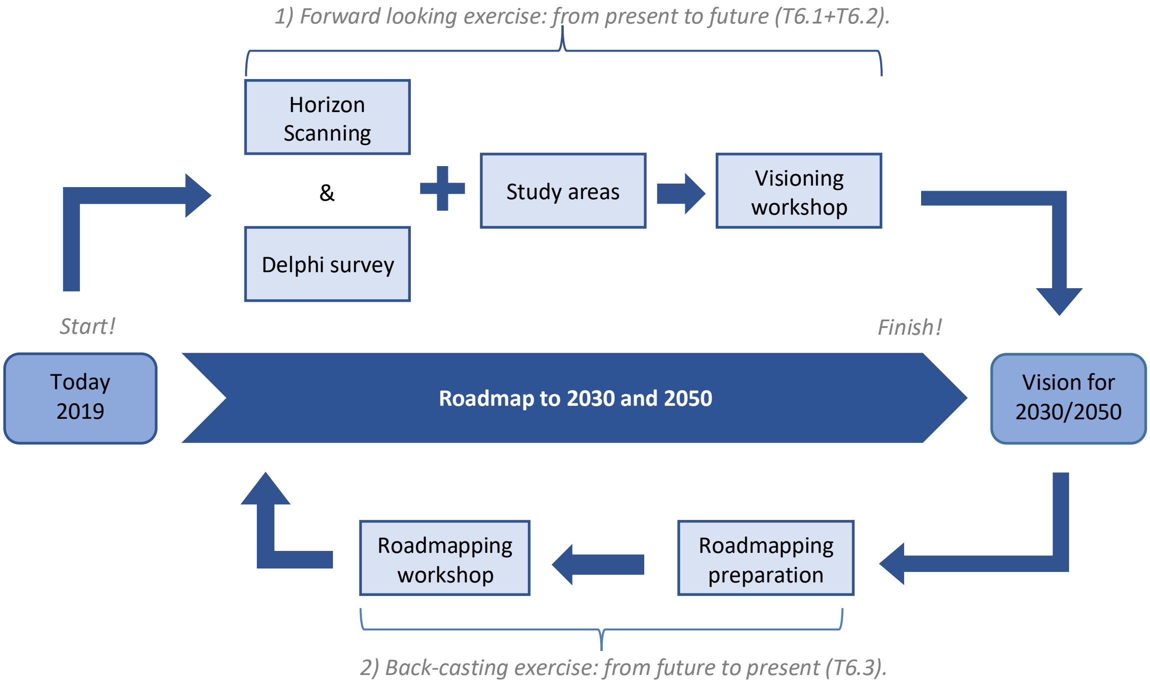

Figure 1: WP6 Roadmapping and Preparation for Pilots workflow

The first, forward looking exercise started from the present technological baseline towards the desired future, through Horizon Scanning, Delphi survey, and Visioning workshop. This line of activity includes the investigation of potential pilot areas, with a European outlook for the application of CHPM technology in the future, with the development of a harmonised study area evaluation template document.

The second line of activities started from the desired vision and used backcasting exercise to identify how to achieve the targets identified in the vision. Parallel to this activity, the technology developers were also involved in the process with a specific focus on the current CHPM components. In other words, each aspect of the roadmap provides information about a different area (Figure 2) of the same technology, and all of them equally important to cover in order to describe a complete picture towards 2030 and 2050.

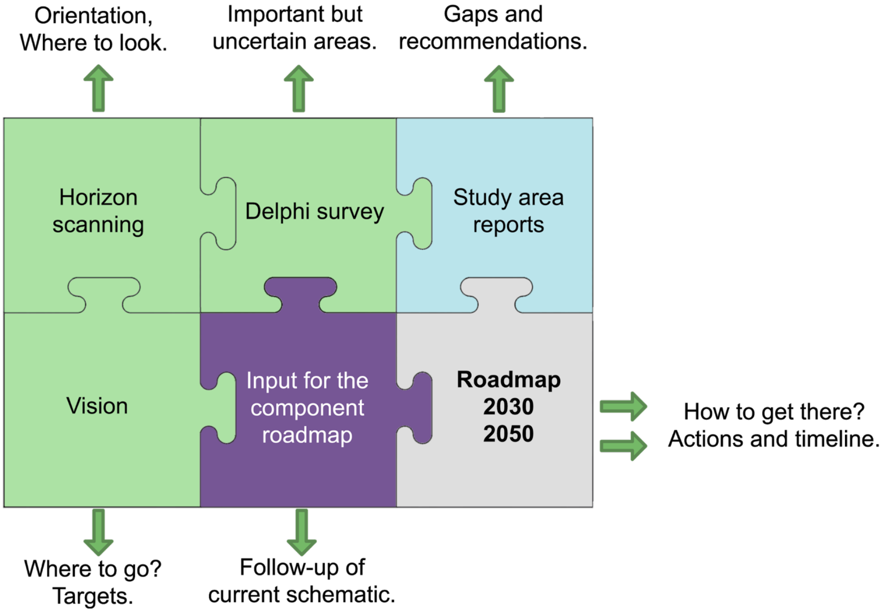

Figure 2: Pieces of Roadmapping "puzzle"

The different roadmap elements outlines three major themes or layers of the technology roadmapping, which has been developed in 1) CHPM component roadmap 2030-2050, follow-up of the current technological components, 2) Preparation for future pilots 2030, for direct support for early implementation at the pilot sites 3) Overall CHPM concept 2030-2050, as the definition of overall geothermal-mineral extraction technology may evolve.

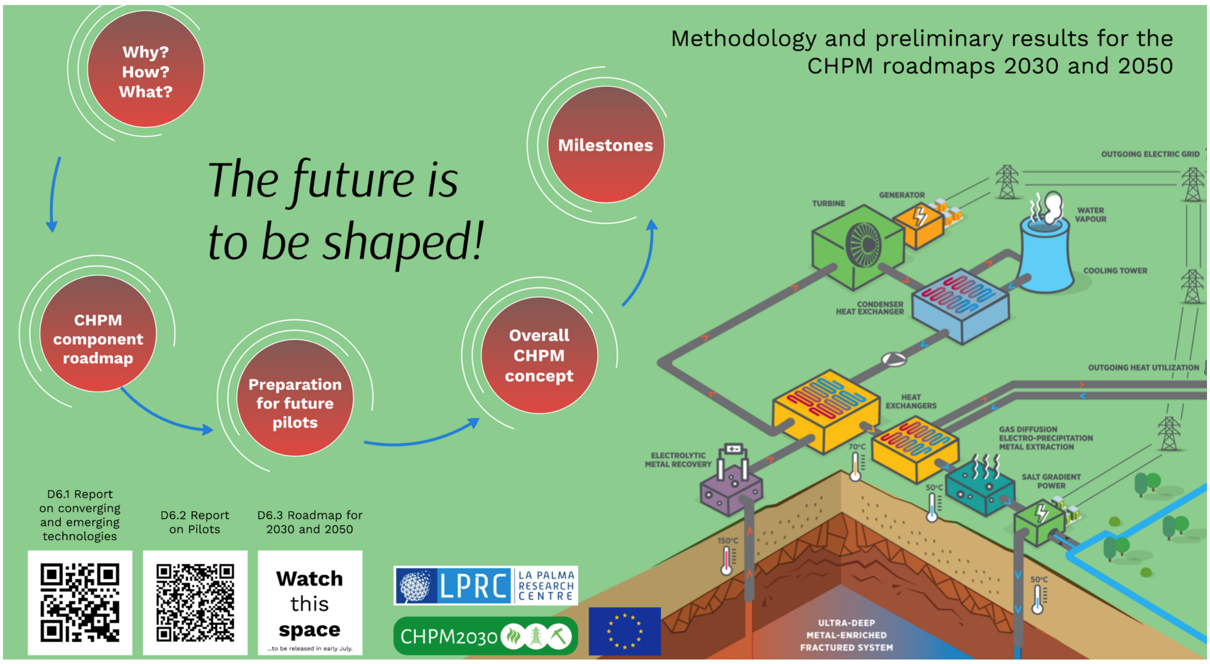

Figure 3: Methodology and results for the CHPM roadmaps 2030 and 2050 (Prezi slideshow)

The methodology and results for the CHPM roadmaps 2030 and 2050 are also visualised in a Prezi (Figure 3) slideshow (circulated in the CHPM2030 Newsletter 4) under the following link: https://prezi.com/view/ZMa90y7KRlMfP3NATk8s/

3. Methodology

A Roadmap is a foresight tool for strategic planning. It helps to define targets and actions, and it provides a timeline for arriving to the desired vision. It has been defined as a "flexible planning technique to support strategic and long-range planning, by matching short-term and long-term goals with specific technology solutions (Phaal et al. 2004, Alexander, 2006). It is also used as an "extended look at the future, or to communicate visions, attract resources, stimulate investigations and monitor progress" (Robert Galvin, Chairman and CEO of Motorola). The main questions to be asked when strategic planning, are the following: Where are we now? Where do we want to be? How do we plan to get there? How will we monitor progress? These questions can be translated to Situation Assessment, Strategic Direction, Implementation Planning, and Monitoring (Wilkinson, 2011). This scheme is well applicable for the current roadmapping process for CHPM. The vision is an essential part of the roadmap, describing, what is the desired future that the roadmap is aiming to achieve with the set of recommendations (Figure 4).

Figure 4. Vision and Roadmap concept word clouds

The two major time horizons in the CHPM roadmap are 2030 and 2050. However, the study describes a continuous development in a single document, rather than separating the roadmap to two documents. When it comes to 2030 targets and actions, the roadmap is focusing on practical and goal-oriented issues, while dealing with 2050 it is aiming at breakthrough research. The roadmap also includes milestones, signpost and wildcards.

According to CSF (2015), signposts are indicators that mark milestones or waypoints between a given future and the present day. In relevance of CHPM technology, signposts are issues to be observed and considered in regular time intervals for safeguarding the implementation of the roadmap (2030). It is also used to provide revisions and updates in response to unforeseen, emerging phenomena (2050). On the other hand wildcards are “low probability, high impact opportunities and threats that would be disruptive should they occur, but for which there may not be any evidence today that they will eventually happen”.

Similar roadmaps has been developed by the International Energy Agency (Technology Roadmaps[2], e.g. for Geothermal Heat and Power), EU’s Strategic Energy Technology (SET) Plan[3], European Technology & Innovation Platform on Deep Geothermal (ETIP-DG), Mining equipment, technology and services (METS) roadmap[4], with different methodologies and objectives. While these roadmap documents, especially the recently published *Implementation Roadmap for Deep Geothermal by ETIP-DG*[5]*,* are covering the broad spectrum of geothermal/mineral development, sector wide, the CHPM roadmap aims to complement these studies, without trying to compete with them, by focusing on the areas that directly affects the development of the novel technology. Therefore, this study does not aim to reproduce these previous results, but instead adds to them, for a full picture of the future of CHPM.

The methodology developed for this roadmap combines three layers: CHPM component follow-up, preparation for pilots, overall CHPM concept.

CHPM component follow up

The first part of the CHPM roadmap is a direct follow-up of the individual technological components of the current technology, with the contribution from the responsible partners. It provides short-, mid- and long-term research plan. This includes a one paragraph description of the current state-of-the-art, immediate research plan, midterm (2030)

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[2] https://www.iea.org/topics/renewables/technologyroadmaps/

[3] https://setis.ec.europa.eu/sites/default/files/setis%20reports/2017_set_plan_progress_report_0.pdf

[4] https://www.csiro.au/en/Do-business/Futures/Reports/METS-Roadmap

[5] https://www.etip-dg.eu/publication/implementation-roadmap-for-deep-geothermal/

requirements for pilot readiness level (in the range of TRL 6-7[6]), and long term (2050) objectives for the commercial level (TRL 8-9[7]) application, for each technological component. This layer of the roadmap gives concrete guidance and direction at the technology component level. However, CHPM is a very complex system and it is important to note that the TRL levels of the different components can be very different today and, in the future, therefore a functioning first CHPM pilot may not include all of the current (2019) technological components (Figure 5).

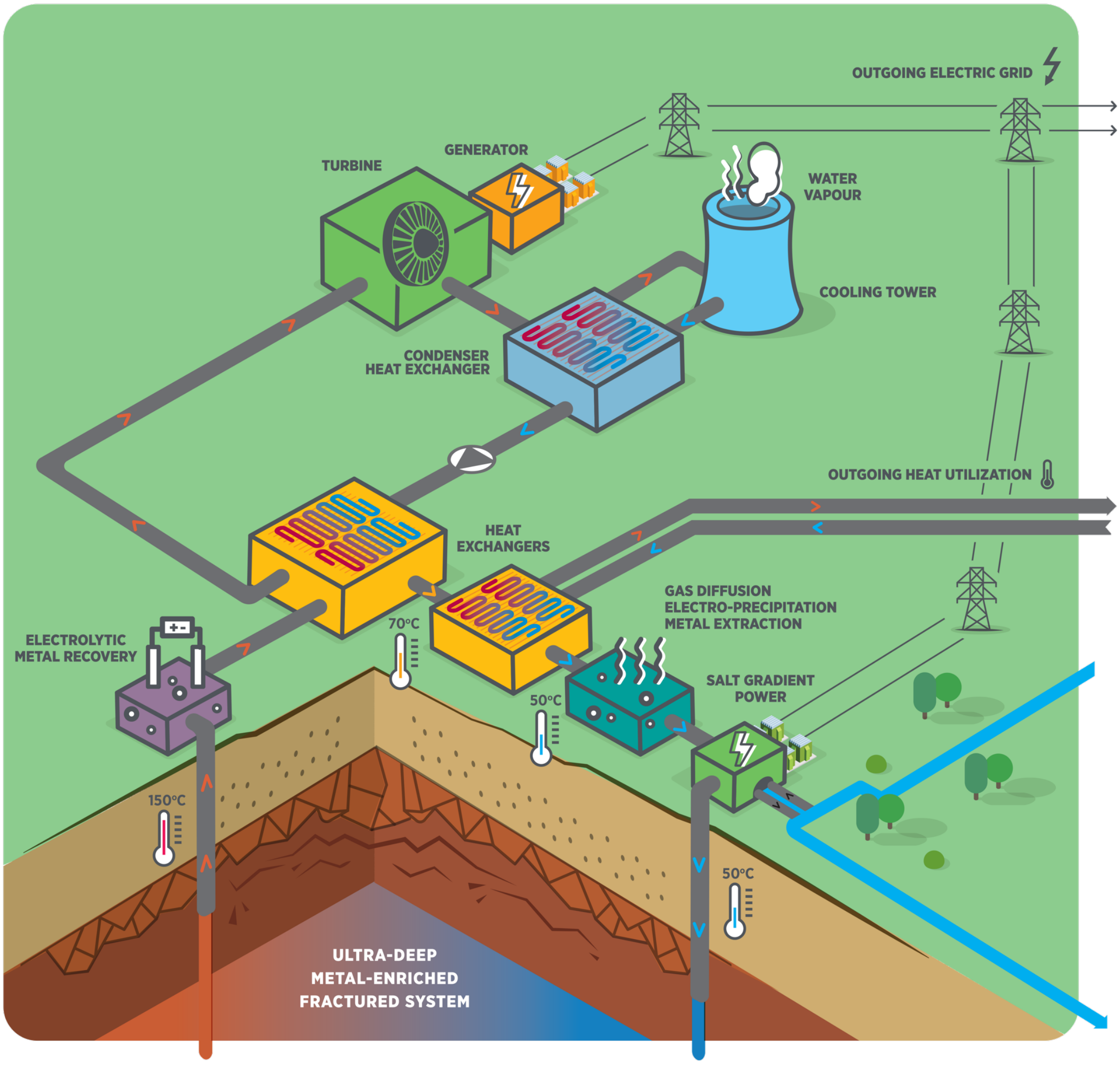


Figure 5: CHPM schematics, 2019 (©CHPM2030 Team)

[6] TRL 6 – technology demonstrated in relevant environment; TRL 7 – system prototype demonstration in operational environment

[7] TRL 8 – system complete and qualified; TRL 9 – actual system proven in operational environment

The aim of this part of the roadmap is to provide a framework for the next research programme and coordinate future development of the CHPM technological components. It describes:

1. what is the state-of-the-art: Current state of the component, achievements, results during the project, referenced to the relevant deliverable,
2. what are the immediate research needs after the project: Next actions, next targets to continue the research on the technological component after the project.
3. what needs to be done to reach pilot level application (TRL 6-7): Requirements of the component before integrating it into a CHPM pilot application.
4. what are the long term objectives for commercial scale applications (TRL 8-9): Requirements of the component before integrating it into a CHPM commercial application.

These four points have been investigated with the help of technology developers.

Altogether, this study describes the next steps, after the project, and it identifies concrete research needs and actions to be taken to arrive at the desired future: pilot readiness level by 2030 and commercial application by 2050. The current technology components (Figure 5) are the following:

1. Integrated reservoir management,
2. Metal content mobilization using mild leaching,
3. Metal content mobilization with nanoparticles,
4. Metal recovery via gas-diffusion electrocrystallization (GDEx),
5. High-temperature and high-pressure (HTHP) electrolytic metal recovery,
6. Salinity-gradient power by reverse electrodialysis (SGP-RE),
7. System integration.

Preparation for pilots - Study area recommendations

The study area recommendation layer of the roadmap is investigating potential future pilot areas. It is building on the findings of CHPM2030 Deliverable 1.2 (Report on data availability) and Deliverable 6.2 (Report on Pilots). It includes a summary of the evaluation results of the areas, delivered in CHPM2030 D6.2, and recommendations for the next 10 years about how to arrive to pilot readiness level by 2030. In other words it is an exploration and development plan including actions and timeline for implementation and recommendations for the next research programme, with the focus on "setting the ground" for subsequent pilot implementation.

Roadmapping has been previously defined as a tool to "attract resources from business and government, stimulate investigations and monitor progress" (Robert Galvin), which fits well in the context for preparation for pilots. In terms of roadmapping questions, this aspect investigate 1) "where are we now?", based on D1.2 and D6.2 reports, 2) "where do we want to go?", which is pilot readiness level by 2030, to be ready for the first pilots, and 3) "What are the ways of getting there?", in the form of recommendations, which is the main content of the study area roadmap. The chapter on study areas also includes an extended summary of the study areas describes in CHPM2030 Deliverable 6.2 Report on Pilots (compiled from 5 reports). This report was developed in collaboration with geological surveys (BGS, LNEG, IGR, SGU). The first results was the development of a harmonised methodology to evaluate the different areas, which was created through workshops, online and consortium meetings, and field trips (Figure 6).


Figure 6: Field trip in Cornwall (22-24.05.2018) organised by BGS, and in Romania (24-27.07.2018) organised by IGR

Furthermore, the study area roadmap also includes future pilot recommendations regarding 1) technological components, 2) funding opportunities, 3) stakeholder engagement, 4) other recommendation, described as follows:

1. Exploration plan for the technological components (metal enrichment, EGS system, SGPG, etc.)

   a. The focus is on exploration: getting new geoscientific information.
   b. Exploration methods and tools to obtain relevant information regarding the technological components (outlined in the evaluation template).
   c. Based on D1.2 (data availability) and D6.1 (data evaluation) what are the next steps on the field, with data processing, modelling, interpretation, etc.
2. Funding opportunities
   a. The focus is on financing: CHPM concept getting re-funded locally.
   b. Funding opportunities: who is going to pay for it? E.g. public, government, EU funded projects, PPP, private investors.
   c. Financing at different stages, e.g. early on mostly on public, then more private funding.
3. Stakeholder engagement
   a. The focus is on the involved parties, end users, stakeholders.
   b. Policy and regulatory recommendations.
   c. E.g. investors conference, policy outreach.
4. Other
   a. Any site-specific additional issue.

All this is to be used for starting up discussions on the financing of such investments. This is a plan or instruction for the future, what needs to be done locally to reach pilots readiness level.

Overall CHPM concept

The third layer of the roadmap is the continuation of the T6.1 foresight exercise, building on the results from the Horizon Scanning, Delphi survey, and Visioning Workshop, at the initially identified topics. This part will use the Roadmapping Workshop to develop actions and timeline, with the addition of signposts and wildcards, in order to arrive the Vision described in T6.1. This exercise identified the overall trends and opportunities at important but uncertain areas for CHPM future developments in the future for the overall CHPM concept of combining geothermal energy and mineral extraction.

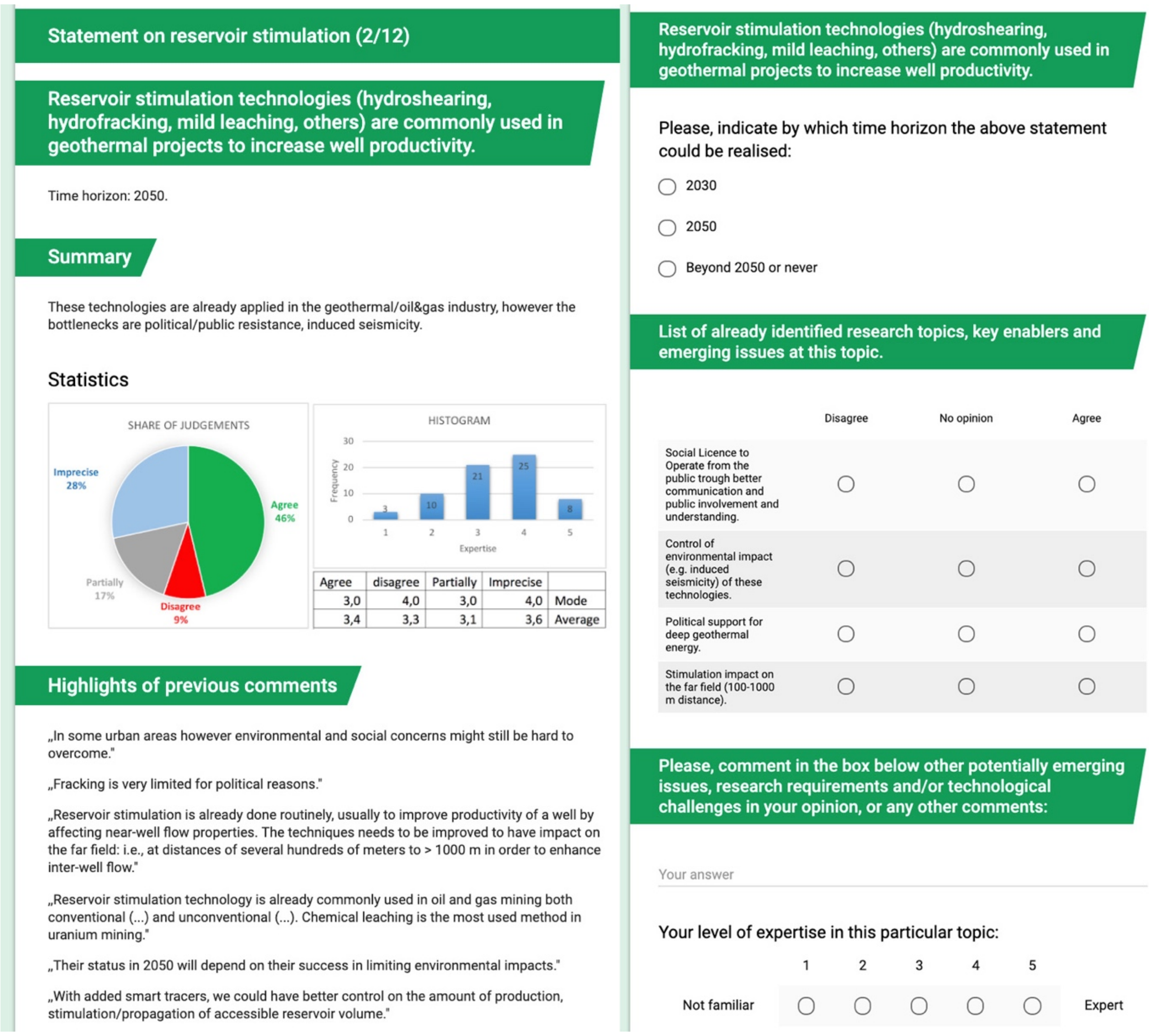
Horizon scanning is a systematic outlook to detect early signals, trends, wildcards, persistent problems, risks, important issues (Cuhls et al, 2016). Therefore, Horizon Scanning is not for predicting the future, but to identify, compile and analyse the various signals of change (Hines et al, 2018). It has been used to define important but uncertain areas that may shape the future of CHPM technology.

Figure 7: Lanzarote Consortium meeting and workshop (21-23.03.2018.) organised by LPRC

This included an Experts workshop in Lanzarote, Spain (Figure 7), where the partners were asked to go through the following steps:

1. Mapping key interest areas to identify broader topics that will require a detailed look in the forward-looking process,
2. Gap analysis to investigate what are the bottlenecks, challenges, enablers within a given key interest areas.
3. Statement formulation to generate concrete ideas for topics in the Delphi survey.

The next step was the development of the CHPM Delphi survey. The Delphi method or survey was originally developed as a technological forecasting technique, which aimed at reaching consensus over relevant technological developments. It can be described as a method for structuring a group communication process so that the process is effective in allowing a group of individuals, as a whole, to deal with a complex problem (H. A. Linstone and T. Murray, 2002). The Delphi is based on anonymous opinions of experts that are fed back into the results of a round-based survey, allowing these experts to rethink their judgement and converge to consensus over key identified areas.



Statement on reservoir stimulation (2/12)

Reservoir stimulation technologies (hydroshearing, hydrofracking, mild leaching, others) are commonly used in geothermal projects to increase well productivity.

Time horizon: 2050.

Summary

These technologies are already applied in the geothermal/oil&gas industry, however the bottlenecks are political/public resistance, induced seismicity.

Statistics

Agree	disagree	Partially	Imprecise	
3,0	4,0	3,0	4,0	Mode
3,4	3,3	3,1	3,6	Average

Highlights of previous comments

„In some urban areas however environmental and social concerns might still be hard to overcome."

„Fracking is very limited for political reasons."

„Reservoir stimulation is already done routinely, usually to improve productivity of a well by affecting near-well flow properties. The techniques needs to be improved to have impact on the far field: i.e., at distances of several hundreds of meters to > 1000 m in order to enhance inter-well flow."

„Reservoir stimulation technology is already commonly used in oil and gas mining both conventional (...) and unconventional (...). Chemical leaching is the most used method in uranium mining."

„Their status in 2050 will depend on their success in limiting environmental impacts."

„With added smart tracers, we could have better control on the amount of production, stimulation/propagation of accessible reservoir volume."

Reservoir stimulation technologies (hydroshearing, hydrofracking, mild leaching, others) are commonly used in geothermal projects to increase well productivity.

Please, indicate by which time horizon the above statement could be realised:

- 2030
- 2050
- Beyond 2050 or never

List of already identified research topics, key enablers and emerging issues at this topic.

	Disagree	No opinion	Agree
Social Licence to Operate from the public trough better communication and public involvement and understanding.	○	○	○
Control of environmental impact (e.g. induced seismicity) of these technologies.	○	○	○
Political support for deep geothermal energy.	○	○	○
Stimulation impact on the far field (100-1000 m distance).	○	○	○

Please, comment in the box below other potentially emerging issues, research requirements and/or technological challenges in your opinion, or any other comments:

Your answer

Your level of expertise in this particular topic:

	1	2	3	4	5	
Not familiar	○	○	○	○	○	Expert

Figure 8: CHPM Delphi survey, 2nd round

The CHPM Delphi contained 2 rounds of surveys as an iterative process (Figure 8). The final survey included 12 statements on topics from both geothermal (scaling, geothermal drilling, metal mobilization, etc.) and mineral (geophysical methods, use of AI and ML for data interpretation, deep exploration drilling, etc.) topics, together with overall operational challenges (Social Licence to Operate, market penetration, etc.). The participants were asked to freely comment on the statements in the 1st round. In the 2nd round[8], the previous comments and insight were already included, and the participants were invited to comment in light of previous Expert opinions, working towards a consensus.

[8] CHPM2030 Delphi survey, open round: https://forms.gle/T6PscT23y98mEjXq8

The last step in the forward-looking exercise was the Visioning workshop, with the creation of target related to the previously identified areas. The Vision can be described as "idealized goal state" (Conger & Benjamin, 1999), "a set of blue-prints for the future" (Tichy & Devanna, 1986), or "an agenda" (Kotter, 1982), "a map for members to follow" (Barge, 1994), and "an image of what needs to be achieved" (Baum et al, 1998). The vision is herein defined as a sum of the targets need to be achieved to complete the core visions by 2030 (pilot readiness level, TRL6-7) and 2050 (commercial applications readiness level, TRL8-9). The targets have been defined during the Vision workshop (Las Palmas, 04.12.2018), which brought together 20 Experts (Figure 9) from both the mineral and geothermal sectors, industry, academia and research centres. The objective of the Visioning workshop was to create a shared vision, clear picture, description about where we would like to be by 2030/2050 and set tangible/measurable targets.

Figure 9: Visioning workshop participants

Having defined the desired vision, the next step was the backcasting exercise, through the Roadmapping workshop (Las Palmas, 07.03.2019). The objective was to create a strategic plan, exploring how to arrive to the desired vision. In comparison, the Vision defines "Where to go?", with tangible targets to be achieved, and the Roadmaps outlines "How to get there?", with actions and timelines for implementation. The roadmapping process was building on the Back-casting exercise, that was building on the previously identified vision, as a desired future technology scenario, and identified concrete actions which are required to achieve the targets.

Since new Experts joined the roadmapping process (Figure 10), the workshop started with the introduction of the CHPM technology state of the art, by the coordinator Tamas Madarász, followed by two presentations about previous CHPM foresight results and the roadmapping workshop methodology, by LPRC team. This workshop also implemented "no-laptop" policy, so participants could be distraction free from their daily work.

Figure 10: Roadmapping workshop participants

After the introduction presentations, the 20 Experts were split into two parallel groups for the sake of the exercise: development and exploration, and operation and market (Figure 11), with 3 subtopic each. However, these topics cannot always treated separately, but more often interlinked and overlapped. The facilitators were from LPRC, Tamas Miklovicz and Marco Konrat. This group distribution was the same as the Visioning workshop groups, however the group subtopics were updated. The participants received the previous workshop results, and the outline of the workshop exercise, one week before the workshop, so they arrived with ideas at hand. The presentations were circulated after the workshop. The main task of the group work was the validation of previously identified targets (vision) and the backcasting exercise itself. The targets are related to the two time horizons: 2030 pilot level (TRL 6-7), and 2050 full scale application (TRL 8-9).

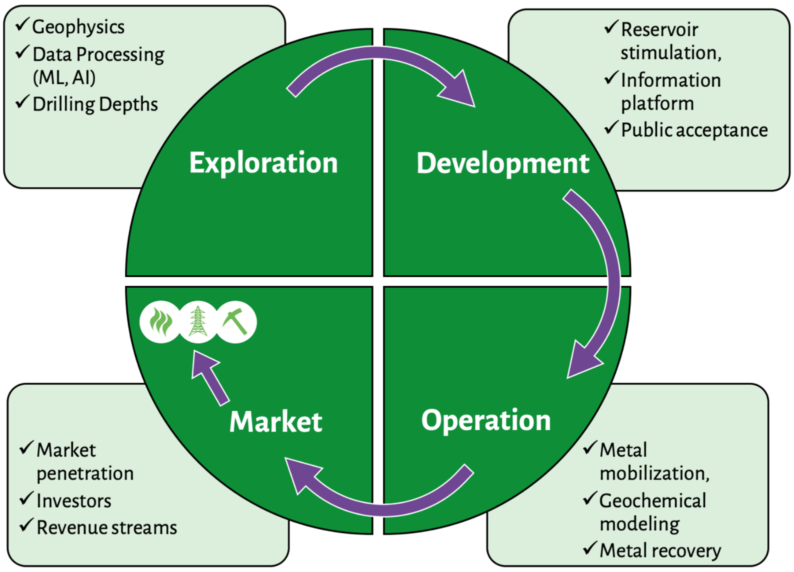


Figure 11: Main themes and subtopics of the overall CHPM concept: exploration, development, operation, market.

The sum of the targets is the vision description, and it is formulated as the desired end-state to arrive by 2050. The proposed targets were delivered from the Visioning workshop with the use of the results from the Delphi survey, and the Horizon Scanning exercise earlier.

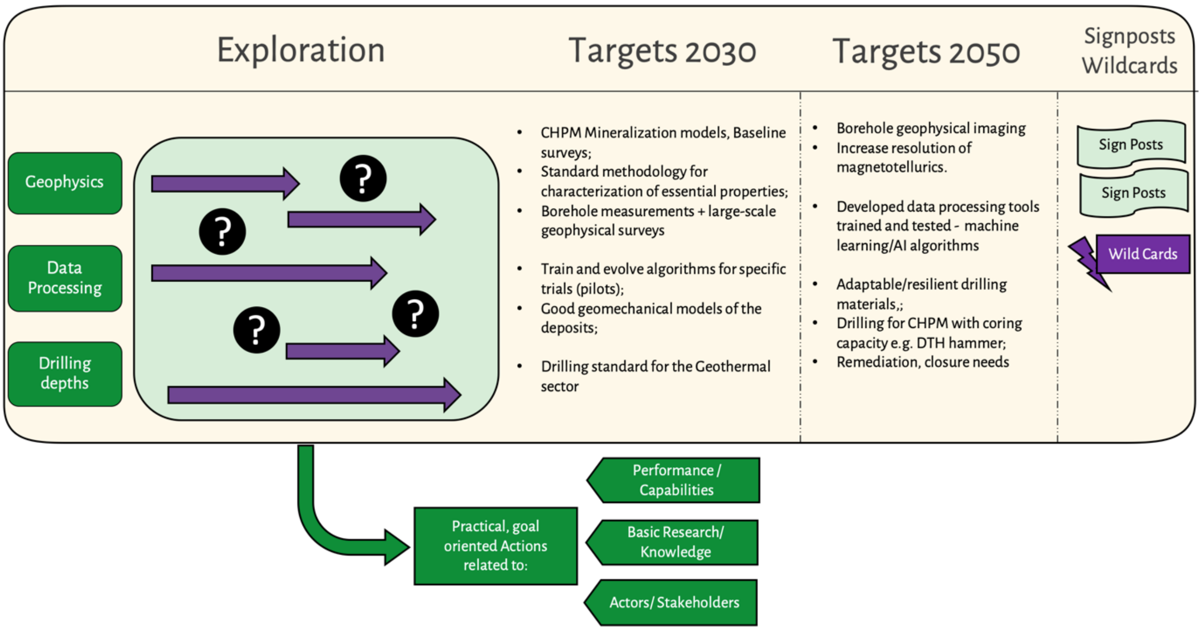


Figure 12: Roadmapping workshop canvas design (group Exploration)

The back-casting exercise investigated how to reach the goals and what actions need to be taken. Whenever considering a target, the group investigated three aspect when formulating the actions: 1) underlying research & knowledge, 2) capabilities, performance & technologies, 3) partnership and actors (Figure 12).

However not only already identified targets were considered, but instead the group dynamically created new targets, the relevant actions, or actions that cover more targets.

When exploring long term targets in 2050, “wildcards” were identified, unexpected disruptive events that may influence reaching the vision. Signposts were also considered at both Visioning and Roadmapping workshop. The last session of the workshop was about presenting the group results and bringing all ideas to a plenary session for discussion (Figure 13). Participants were commenting and sharing new ideas regarding the parallel groups which helped to organise all input after the workshop.

Figure 13: Roadmapping workshop last session: presenting the group results (Photo credit: D. Marchese)

Even though the Visioning workshop aimed to identify targets, and the Roadmapping workshop to identify action, there were no strict line between these activities. Therefore, action and targets were identified at both workshops, and it was the postprocessing of all input that clearly separated the two category and condensed the workshop input into a list of action towards a list of targets with timeline.

Table 1: Evolution of topics during the Roadmapping process

Horizon Scanning	Delphi Survey	Vision workshop	Roadmapping workshop
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	**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	**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	**Exploration** • Geophysics • Data processing • Drilling depths **Development** • Reservoir stimulation • Information platform • Public acceptance **Operation** • Geochemical modeling • Metal recovery • Metal mobilization **Market** • Investors • Revenue streams • Market penetration

In conclusion the foresight process for the overall CHPM concept investigated a range of topics (Table 1) and showed convergence towards the final four main themes where targets, actions and timeline has been identified.

4. CHPM component follow-up 2030-2050

4.1 Integrated reservoir management

Responsible researcher, institution: Szanyi János, University of Szeged. Reference document: Recommendations for Integrated Reservoir Management, CHPM2030 D2.1

State-of-the-art (2019)

Demonstrated the effectiveness of rock mechanical investigations in laboratory using fracture network simulation. The validation of the models built on these data is not done yet; therefore, all the outcomes (flow rates, temperature, productivity, metal production) are estimates. The methodology is somewhat established to investigate the efficiency of the proposed system.

On a reservoir scale, drilling of new wells is quite reliable, the target reservoir is reached in most of the cases, however the physical properties of that is always a risk until the first well is successfully drilled.

There are a few examples where additional elements are produced from the geothermal brine parallel to the operating electricity generating power plant.

An unsolved challenge is establishing a reliable, communicating fracture system, in which the surface for heat exchange and chemical reactions could be determined.

Immediate research plan, 2025

A critical aspect is the creation and stimulation of fractures between wells, for this laser enhancement could be involved by this timeline.

The validation of numerical modelling on a geological scale would be a breakthrough in terms of hydrogeological, mass and heat flow, fracture network modelling. The validation would have a feedback on fracture establishment and fluid flow practices which could lead to new reservoir stimulation technologies and innovative additives.

Pilot research plan, 2030, TRL 6-7

Selection of a potential metal enrichment in 4+ km depth (with proper geothermal gradient) and complete stimulation (possibly with the combination of cyclic injection and hydroshearing technologies) would be possible under constant monitoring.

By 2030 the application of reservoir enhancement by laser (permeability boost and laser lateral establishment) could happen in a real geothermal system, in situ.

Long term objectives, 2050, TRL 8-9

In this timeframe we assume the availability of new materials at well completion, which can withstand high temperature and large pressure and potentially would not be dissolved and corroded by leaching fluids.

New technologies of well completion are also crucial so the energy producing system could tolerate supercritical fluids and leaching with these fluids.

Creation of fully controlled fracture system within the vicinity of the targeted metal enrichment (or orebody) and economic operation have the potential to be ready by 2050.

4.2 Metal content mobilization using mild leaching

Responsible researcher, institution: Christopher Rochelle, BGS. Reference document: Report on metal content mobilization using mild leaching, CHPM2030 D2.2

State-of-the-art (2019)

Demonstration that metal concentrations in solution can be enhanced with a range of additives. These include simple organic acids (e.g. acetic acid) which can be effective leaching agents.

Demonstration that some additives have a greater or lesser ability to liberate other elements (such as Al and Si) which, though likely enhancing flow in the rock, may cause issues with reprecipitation in other parts of the system or surface plant.

However, the work also pointed out areas where more work is required. These include: lack of knowledge about the quantity and types of metal-rich minerals at depth; the composition of deep groundwaters.

Immediate research plan, 2025

A key objective is to obtain firm information about conditions at depth. Lack of samples and data limits experimental quantification and modelling simulations of metal release processes. The research needed includes two key aspects:

1. Metal content and distribution within deep, hot rocks at one or more sites. There is very limited direct evidence about the nature of phases containing economic metals - largely as a result of lack of samples. A requirement is therefore to have boreholes and core samples from 4 km or more deep. Due to the nature of the CHPM process, relatively low concentrations of metal-rich phases may still provide a suitable resource, and those phases need not be 'traditional ores' (i.e. limited to sulphide or oxide phases).
2. Fluid composition at depth at one or more sites. We need to constrain this accurately as it will have a key control metal solubility - even if we use additives. In particular, salinity will have an important control via the formation of metal chloride complexes. The presence of sufficient concentrations of chloride ions will prevent competition between metals, and limit reprecipitation (as seen in CHPM2030 experiments). Test already identified leaching agents.

Pilot research plan, 2030, TRL 6-7

Firm evidence from research boreholes that constrain temperature, metal abundance and mineral phases at >4km, and also groundwater chemistry and flow at these depths. Such observations will serve to:

1. Focus laboratory leaching experiments at exactly the right conditions to provide accurate data on processes and metal release rates at sites of interest. Optimise additives to aid leaching.
2. Provide data on fractures and flow rates into boreholes.

Also need to optimise additives to aid leaching - matched to groundwater chemistry and minerals of interest.

Use modelling to build on the above and produce models with an increased (and quantified) degree of confidence.

Long term objectives, 2050, TRL 8-9

Develop a (semi)regional scale understanding of both metal content at depth and also deep groundwater chemistry and flow rates/directions etc. These would require numerous boreholes and at least one smaller-scale pilot site(s) each testing one or more of the technology components.

Sufficient understanding of systems to be able to select from a 'catalogue' of additives those that will perform best under the conditions of the site of interest.

4.3 Metal content mobilization with nanoparticles

Responsible researcher, institution: Steven Mullens, VITO. Reference document: Report on metal content mobilization with nanoparticles, CHPM2030 D2.3

State-of-the-art (2019)

Demonstration that carbon nanoparticles have the ability to adsorb relevant metal ions (e.g. rare earth elements) under relevant conditions (pressure, temperature, high salinity) and in presence of high content of other metal ions.

Demonstration that the surface chemistry and porous architecture are dominant factors to obtain a highly performant sorbent material.

However, a more fundamental approach is required to fully develop the concept of an "ideal material" for this application. Knowledge is lacking on the exact nature of the interacting site on the material, in combination with the speciation of the metal ions under relevant conditions. Also with regard to permeability and recovery of the particles more knowledge should be developed.

Immediate research plan, 2025

The objectives for continuation should be focused on the following aspects:

1. Development of new functionalization routes (new complexing agents attached to the surface of the material), yielding a higher capacity and selectivity of the metal adsorption. This also includes dynamic testing under the relevant conditions (especially the presence of competing elements).

2. Research into the regeneration strategy: how to recover the attached metal ions from the material in an economically feasible way and environmentally sound.
3. Material development from the perspective of permeability of the particles through the rock porous network and recovery from the underground.

Pilot research plan, 2030, TRL 6-7

The integration of a designed material into a CHPM pilot application requires a detailed view of the porous nature of the rock and chemistry of the fluids used to improve the leaching of the metal. The surface chemistry of the sorbent material must be tuned to enhance the selectivity of the sorption process.

Size, size distribution and shape of the particles must be matched with the permeability constraints of the rock.

Modelling and advanced analysis techniques will be a useful tool to optimize material characteristics.

Long term objectives, 2050, TRL 8-9

A catalogue of functionalized nanoparticles with diversity in nature, size and shape with varying functional groups onto the surface, to selectively sorb the metal(s) of interest at a specific site, taken into account all the conditions.

4.4 High-pressure, High-temperature electrolytic metal recovery

Responsible researcher, institution: Ramasamy Palaniappan, Jan Fransaer, KU Leuven, Xochitl Dominguez-Benetton, VITO. Reference document: Report on performance and design criteria for high-temperature, high-pressure electrolysis, CHPM2030 D3.1

State-of-the-art (2019)

Electrolytic metal recovery is a common method to recover dissolved metals from metal finishing wastewaters, being able to recover up to 95% of some metals. However, despite its broad applicability and high effectiveness in highly concentrated metal solutions, it is underdeveloped for application in streams where metals are highly diluted (e.g., ppm to ppb concentrations), such as geothermal brines, wherein also the presence of other much more concentrated chemical species is prevalent. Electrodeposition has been nevertheless employed to recover some dilute metals such as copper, silver, gold, lead, etc from waste streams at room temperature and atmospheric pressure with various types of electrochemical reactors such as: (1) packed bed reactors (2) continuous rotating cylinder electrode reactors, and (3) hydrocyclone reactor, etc. Electrolytic metal recovery at HT-HP conditions is underexplored.

Besides being typically characterized by a high ionic strength, geothermal brines are sometimes rich in silica as well as some heavy metals. Currently, within the geothermal extraction steps, these metals precipitate along with silica as a result of drops in temperature and pressure as the brine passes through different process equipment, resulting in the fouling pipeline walls, heat-exchangers, etc., and often times in significant corrosion and heat-transfer losses, among other problems. To the best of our knowledge, no method exists to recover metals at such conditions.

Within this project, electrodeposition was evaluated as means to recover metal ions from geothermal brines. A HT-HP rotating electrode reactor (RER), for operation in batch mode, was developed to study the recovery of metal ions from geothermal brines. Copper was selected as a representative specimen, to investigate fundamental aspects of this process. The first part of the project involved the construction of the reactor, as well as the selection of materials to be employed as substrate for deposition (working electrode) and counter-electrode. Stainless steel, titanium, vitreous/glassy carbon, and graphite were evaluated as substrates and counter electrodes for metal recovery. Reticulated vitreous carbon was identified as the most suitable material to be used as both substrate and counter electrode, as the material was a poor catalyst for unwanted secondary reactions such as oxygen reduction, water electrolysis, etc. Additionally, when functioning as counter electrode, this material was also not prone to oxidation.

The recovery of metals was studied by using copper as a representative specimen. The effect of the following parameters on the recovery of copper was studied: temperature, pressure, initial copper concentration, silica content, electrochemical reduction potential. High temperature allowed for enhanced recovery of copper, when compared to the recovery at room temperature. On the other hand, pressure did not show a significant influence on the recovery of copper. It was found that a silica content of 15 g L^{-1} was sufficient to negatively affect the amount of copper recovered. Thus, indicating that the HT-HP electrolytic recovery technology, with the current know-how, is suitable for recovery where the silica content in the brine is low, aka <15 g L^{-1}.

For brines rich in silica and above 100 °C, prior to electrodeposition, the brine has to be vaporized upon lowering the pressure, e.g., by passing the stream to a flash drum. This would result in the precipitation of any silica, to be thus separated via an outlet at the bottom of the vessel. The heavy metals precipitated with silica can be extracted by acid leaching as in a mining process, followed by electrodeposition from the metal-concentrated leachate solution.

Immediate research plan, 2025

The next immediate step in this research will include testing the reactor built during this project, in a wider range of relevant operational conditions, and using different batches of real geothermal brines. A thorough investigation of the effect of selected metals cations and relevant anions should be conducted. An additional immediate step will be to develop an adequate model that describes the electrolytic recovery process with the boundaries imposed by the current reactor. Based on these fundamental investigations, an optimization study will follow based on the modelling outcomes, as well as the development of dimensionless variables to further propose improved or alternative reactor designs, as well as to set the premises for rational scale-up.

For instance, for brines with low silica content, the next steps will include the design and construction of e.g., an electrochemical hydrocyclone reactor (EHCR) or another optimal reactor configuration, to study the recovery of metals by electrolytic deposition on a continuous basis. A complete parametric study would be thus performed at lab-scale in such reactor, to evaluate the metal recovery from geothermal brines. Based on the new results obtained and the improved model, the construction of an upscaled pilot reactor should be feasible, given that not only the technical proofs are successful but also that the economics of this approach makes sense in the context of a CHPM concept. For instance, the energy requirements for metal recovery (g Wh^{-1}) are required to make sensitive conclusions. The optimal temperature and pressure for maximum metal recovery should be estimated, among other relevant parameters.

For the reactor constructed, basic and detailed engineering, including instrumentation and control will be in place.

The ultimate conclusion of these subsequent studies should be to determine if HTHP electrolytic metal recovery from geothermal brines will be a process that is techno-economically effective and supportive of a CHPM concept.

Pilot research plan, 2030, TRL 6-7

If the results from the previous steps show promising conclusions, a model suitable for scale-up should be developed. A dimensionless computational fluid dynamics model has to be developed based to include the effect of temperature, metal ion concentration, anion effect for the recovery of metals using. Assessing if the flow should be integrally processed by this reactor or if a by-pass from the geothermal flow should be instead considered, should come out of this exercise. A simulation with the obtained model, tailored for different geothermal brines, can then be used for sizing the reactor dimensions and electrode surface area, among others, and estimating the energy required corresponding to the brine characteristics.

Based on such a model and its results, a small-scale pilot reactor should be designed and constructed. After it is available, validation tests should be conducted to ensure that the expected performance is maintained at larger scale. Safety assessments will also be conducted, as this is a key step on the successful operation of this technological alternative. Ideally, this small-scale pilot reactor would be constructed on the basis of a mobile concept, so that it can be flexibly adapted to different sites, as necessary. This should allow to make relevant tests on different sites of study (although probably not yet connected directly to a real geothermal flow, ultimately allowing to assess the boundaries of operation of this technology and its adaptability to different geothermal plants (even non-CHPM candidates).

On the basis of such results, extrapolations on its applicability to operate in the context of a larger pilot-scale CHPM plant should be made.

For the small-scale pilot reactor constructed, basic and detailed engineering, including instrumentation and control will be in place. This development will be conducted in cooperation with a suitable engineering company.

Long term objectives, 2050, TRL 8-9

Upon reaching this stage, a quasi-linear scale-up from the smaller-scale pilot reactor could be considered towards a larger-pilot scale reactor. This larger scale reactor will follow the "plant on a truck concept", to be deployed at the target testing site for the CHPM pilot application. For the large-scale pilot reactor constructed, basic and detailed engineering, including instrumentation and control will be in place. This development will be conducted in cooperation with a suitable engineering company.

The pilot reactor will be operated at a CHPM site selected throughout the future developments of this project. Through this phase, accurate and speedy cost estimations will be made, alternatives to post-process the recovered metals should be explored, as well as ways to deal with the residual matrix that should either go into other processing units or return to the CHPM closed loop flow, and by testing at the target circumstances it will be discovered how to best optimize the pilot reactor start up in function of the whole CHPM system requirements. It will also become clear how to minimize operational costs and maximize the effectiveness of the electrolytic metal recovery process. All safety risks and assessments will be in place for an adequate operation.

4.5 GDEx

Responsible researcher, institution: Xochitl Dominguez, VITO. Reference document: Report on performance, mass and energy balances and design criteria for gas-diffusion electroprecipitation and electrocrystallization, CHPM2030 D3.2

State-of-the-art (2019)

The GDEx process entered this project at a very low TRL level. Experiments had been conducted for a few metals in synthetic solutions and the applicability of this new technology in the context of geothermal brines was not clear. In the course of the project, the patent for the GDEx technology was granted in Europe, providing a solid prospect towards future valorization opportunities.

Within the project, we successfully proved that the GDEx process was applicable to CHPM model and real brines, at small scale. We were able to recover most of the metal content of the different matrices tested, without retrieving unwanted elements such as Ca and Mg. For Li-containing brines, both synthetic and real, it was feasible to extract Li and form value-added components. From the results obtained it became clear that the cost of processing (operational costs) provided by GDEx was much lower, for removing dilute metals in solution, compared to classical processing technologies for metal recovery. Besides, it became clear that on the basis of the products formed, the process could be profitable. It was feasible to recover more than 20 individual metals from different solutions, and selected metals from mixed solutions and geothermal brines.

Lab-scale experiments were achieved, but also a larger-scale testing was feasible (i.e., 400 L of brine, as opposed to most tests conducted with 250 mL to 5 L of brine).

The following achievements can be summarized:

1. GDEx is a novel way to recover metals from dilute solutions: patent granted.
2. It allows nearly full recovery of metals present, selectivity can be achieved in the cases tested (i.e., real and simulated brines).
3. Energy consumption is competitive vs other existing alternatives.
4. It is upscalable, although conditions to upscale in the context of geothermal industry high flow rates need to be further explored.
5. It works for most of critical raw materials and other industrially-interesting materials,
6. First economic feasibility calculations show it as a promising option.
7. Generating interest of multinational companies (contract research has been performed and more planned).

Immediate research plan, 2025

Although the GDEx process was proven successful, additional experiments at lab-scale are necessary, operating at higher temperatures and pressures (in conditions more suited to the CHPM concept). Thus, a GDEx reactor for operation in such conditions will be designed, constructed, and tested. Both at low-temperature and low-pressure and higher-temperature and higher-pressure, the effect of silica should be rationally investigated.

Testing the new GDEx reactor in a wider range of relevant operational conditions, and using different batches of real geothermal brines will be anticipated. An additional immediate step will be to develop an adequate model that describes the electrolytic recovery process with the boundaries imposed by the current and high-T, high-P GDEx reactor. Based on these fundamental investigations, an optimization study will follow based on the modelling outcomes, as well as the development of dimensionless variables to further propose improved or alternative reactor designs, as well as to set the premises for rational scale-up. The modelling should include possible scalable configurations, i.e., stacking in series, in parallel, and a larger size reactor. In the previous phase an upscaled reactor was tested, however, it may not have been an optimal reactor configuration. In this phase, the optimal reactor configuration will be elucidated from the modelling exercise and the new reactors will be built on this basis to gather relevant data for further phases.

A complete parametric study will be performed at in such new reactor, to evaluate the metal recovery from real geothermal brines. Based on the new results obtained and the improved model, the construction of an upscaled pilot reactor should be feasible, given that not only the technical proofs are successful but also that the economics of this approach makes sense in the context of a CHPM concept. For instance, the energy requirements for metal recovery (g Wh^{-1}) are required to make sensitive conclusions. The optimal temperature and pressure for maximum metal recovery should be estimated, among other relevant parameters.

For the reactor constructed, basic and detailed engineering, including instrumentation and control will be in place.

The ultimate goal of these subsequent studies is to determine if metal recovery from geothermal brines by GDEx could be a process that is techno-economically effective and supportive of a CHPM concept on a pilot industrial scale.

Pilot research plan, 2030, TRL 6-7

If the results from the previous steps show promising conclusions, a model suitable for scale-up should be developed. A dimensionless computational fluid dynamics model that further allows a tertiary-current distribution model has to be developed based to include the effect of temperature, pressure and other relevant processing conditions. Assessing if the flow should be integrally processed by the GDEx reactor or if a by-pass from the geothermal flow should be instead considered, should come out of this exercise. A simulation with the obtained model, tailored for different geothermal brines, can then be used for sizing the reactor dimensions and electrode surface area, among others, and estimating the energy required corresponding to the brine characteristics.

Based on such a model and its results, a small-scale pilot GDEx reactor should be designed and constructed. After it is available, validation tests should be conducted to ensure that the expected performance is maintained at larger scale. Safety assessments will also be conducted, as this is a key step on the successful operation of this technological alternative. Ideally, this small-scale pilot GDEx reactor would be constructed on the basis of a mobile concept, so that it can be flexibly adapted to different sites, as necessary. This should allow to make relevant tests on different sites of study (although probably not yet connected directly to a real geothermal flow, ultimately allowing to assess the boundaries of operation of this technology and its adaptability to different geothermal plants (even non-CHPM candidates). On the basis of such results, extrapolations on its applicability to operate in the context of a larger pilot-scale CHPM plant should be made.

For the small-scale pilot GDEx reactor constructed, basic and detailed engineering, including instrumentation and control will be in place. This development will be conducted in cooperation with a suitable engineering company.

Long term objectives, 2050, TRL 8-9

Upon reaching this stage, a quasi-linear scale-up from the smaller-scale pilot GDEx reactor could be considered towards a larger-pilot scale GDEx reactor. This larger scale reactor will follow the “plant on a truck concept”, to be disposed at the target testing site for the CHPM pilot application. For the large-scale pilot GDEx reactor constructed, basic and detailed engineering, including instrumentation and control will be in place. This development will be conducted in cooperation with a suitable engineering company.

The GDEx pilot reactor will be operated at a CHPM site selected throughout the future developments of this project. Through this phase, accurate and speedy cost estimations will be made, alternatives to post-process the recovered metals should be explored, as well as ways to deal with the residual matrix that should either go into other processing units or return to the CHPM closed loop flow, and by testing at the target circumstances it will be discovered how to best optimize the pilot reactor start up in function of the whole CHPM system requirements. It will also become clear how to minimize operational costs and maximize the effectiveness of the electrolytic metal recovery process. All safety risks and assessments will be in place for an adequate operation.

4.6 Salt gradient power reverse electrodialysis

Responsible researcher, institution: Joost Helsen, VITO. Reference document: Report on performance, energy balances and design criteria for salt gradient power reserves electrodialysis, CHPM2030 D3.3

State-of-the-art (2019)

It was shown that geothermal brines have a good potential for extracting chemical energy through reverse electrodialysis. Specifically, high salinity brines (>2 mole) at elevated temperatures are promising. Preferably the content of multivalent ions is low (<5% of TDS), however a higher temperature of the brine compensates at least partially for the presence of multivalent ions in terms of power loss.

Immediate research plan, 2025

Although pilot scale equipment exists for this technology, some additional development/engineering is needed for some of its components:

1. Membranes: there is a need for development of thin, conductive, highly permselective membranes that are stable up to higher temperatures (80°C or higher). The development of monovalent selective membranes with these properties would also be beneficial
2. Stack: improvements need to be made in terms of integrating very thin membranes (<20µm) and thin spacers (<250µm) with a high open porosity (>75%) into a leak-free and robust assembly. Moreover, it would be interesting to start exploring the option of a SGP-RE stack able to work at high system pressures (>40 bars)

More attention should also be paid to characterisation of the membrane transport properties in order to evaluate migration of species across the membrane towards the low salinity water source (typically surface-, ground- or wastewater). This technology is inevitably going to release some of the dissolved solids from the geothermal brine into the low salinity source. The total transport of ions will be dependent on the concentrations in the brine and the transport properties of the membrane. A good understanding should be developed in this sense to be able to estimate the impact of implementing SGP-RE on the low salinity water source.

Pilot research plan, 2030, TRL 6-7

A full-blown pilot test on-site should target at elucidating the real potential of SGP-RE in a specific environment. First off, site selection is crucial and should aim at the best case possible for SGP-Re implementation. This implies geothermal brines with a high salinity (>2 mole), specifically on monovalent ions, presence of a low salinity source with a high volumetric capacity and little restrictions in terms of discharge limits (e.g. surface water near river mouths). The stack should have cell pair dimensions which are directly related to the potential of the test site. More concretely, this means that the active cell surface should reflect a full-scale unit (e.g. 1m^2). The dimensions (path length/width) should be determined as a function of the required specifications, either focusing on maximum power output or maximum efficiency.

Parameters to be evaluated during pilot testing:

- Power output
- Energy efficiency
- Fouling control
- Low salinity water source quality
- Stack integrity (leakages)

Long term objectives, 2050, TRL 8-9

For full-scale implementation, and assuming all of the above questions and developments have been tackled, the focus will be mainly on engineering issues, related to:

- Upscaling pilot stack to hundreds or thousands of cell pairs
- Implementing a stack working at higher system pressures
- Heat recovery from the low salinity outlet (SGP-RE stack acts as a heat exchanger)
- Monitoring protocols for stack integrity and performance
- Monitoring of low salinity effluent (temperature, components)
- Integrating SGP-RE electricity production (DC) with EGS electricity production (typically AC)

4.7 System integration

Responsible researcher, institution: Árni Ragnarsson, ISOR. Reference document: Conceptual framework for CHPM power plant, CHPM2030 D4.1

State-of-the-art (2019)

Based on the results of the research that has been performed within the project so far, mainly laboratory tests, simplified mathematical models have been developed to describe the behaviour of each of the main components in the overall CHPM system. These models are based on a set of parameters that ideally are expected to describe what happens within the components in a satisfactory way. In practice these parameters are mostly limited to parameters that have been used in the laboratory experiments within the CHPM2030 project.

A mathematical model has been developed to combine the individual components in an overall system, thus linking the downstream and upstream engineering subsystems.

Most of the component models developed so far must be considered as a rough description of the physical processes involved.

Immediate research plan, 2025

The work so far has revealed the need for improved mathematical description of the individual components in the system. Further research on the metal extraction components (electrolytic metal recovery and gas diffusion electro-precipitation) as well as power generation (salt gradient power) will provide additional knowledge and opportunities to improve the mathematical description of what happens within the components.

At the same time the mathematical basis for the system integration should be developed further. This would include the use of a more advanced system analysis approach and problem-solving technique with the purpose of studying how well the components work and interact. Risk and sensitivity analysis as well as technical optimization should be central in this work.

In further work, more attention should be given to the geothermal reservoir and the production and reinjection wells. Existing and well-known reservoir models should be developed further to include the influence of additives to aid leaching. Also, studies and modelling of precipitation of minerals has a great potential for improving the knowledge about the expected amount of minerals that can be extracted in the surface equipment.

Pilot research plan, 2030, TRL 6-7

An important consideration related to a pilot plant is how upscaling of the laboratory tests to a full-scale pilot plant can be done. The laboratory tests are for example based on very low flow rates and partly simulated brine. Further studies on how these results can be used to predict what happens in real full-scale pilot plant is needed.

In future development of the technical model of the CHPM system it would be natural to study also the economy of such systems and develop mathematical models for optimization strategies based on economic results.

Long term objectives, 2050, TRL 8-9

The long-term objective of the system integration will be to use the most advanced techniques available to develop and maintain as detailed mathematical model of the integrated CHPM system as possible. It's difficult to foresee how the available tools will develop in the future, but they will play an important role in identifying the best strategies for combined heat, power and metal extraction in the future.

5. Pilot area recommendations 2030

5.1 Cornwall, South West England

Authors: Paul A J Lusty, Richard B Haslam, Christopher Rochelle, British Geological Survey. Reference document: CHPM2030 D6.2.1 Report on pilots: evaluation of the CHPM potential of Cornwall, South West England.

Extended summary of the pilot area report

This pilot covers south-west England, considering the availability of geoscience information, the geological environment, geothermal characteristics, potential for deep metal enrichment, and technical, environmental, social and regulatory factors that could influence the future development of CHPM extraction technology in the region.

The geothermal energy potential of the UK was investigated by research funded by the UK government and European Commission between 1977 and 1994. The UK has a fairly uniform background heat flow field, with areas of greater heat flow associated with the radiogenic Permian granites in south-west England, buried Caledonian granites of northern England and the batholith in the Eastern Highlands of Scotland. South-west England was selected as the UK CHPM2030 study area as it is a major magmatic province, with high heat production, and hosts extensive polymetallic mineralisation. Its long history of metal production, and economic geology research means it is a data-rich region. It is also the focus for contemporary deep geothermal research and development in the UK.

South-west England forms an integral part of the European Variscides and has been influenced by rifting, convergence and passive margin inversion and extensional reactivation. Crustal extension and orogenic collapse during the late Carboniferous and lower Permian resulted in extensive granitic magmatism in the region, forming the Cornubian Batholith. The granites were emplaced into largely Devonian sedimentary rocks, hosted in fault-bound basins. Crustal extension and shortening resulted in large-scale faulting and folding across the region. A major structural feature of south-west England is approximately NW-SE-trending fracture systems, locally termed 'cross-courses', which are considered to play a significant role in the overall permeability of the region. Extensive, internationally renowned granite-related mineralisation occurred during the early to mid-Permian, which contains metals including tin, tungsten, copper, zinc, and arsenic. A separate, Mid-Triassic phase of mineralisation related to basinal fluids, and containing lead, zinc, silver, fluorite and barite developed in the cross-course fractures.

This review whilst considering the broader scale geological context, principally focuses on a study area covering the northern part of the Carnmenellis granite, one of the six exposed granite plutons that form the Cornubian Batholith. At surface the Carnmenellis granite is roughly circular in shape and covers an area of some 135 km^2. However, in common with the other plutons its shape at depth and thickness remains uncertain. This project used borehole data in conjunction with existing gravity models to better constrain the position of the upper granite surface.

Geological research in south-west England spans over two hundred and fifty years and has been greatly enhanced by geophysical surveys. Gravity modelling of the Cornubian Batholith has resulted in variable estimates of its thickness. The most recent interpretation suggests that the batholith consists of two sheets, with an upper granite, with a base at 6–8 km, and a lower more extensive granite sheet, with a base at 12–15 km. This is supported by the magnetotelluric (MT) and seismic data. Modelling of the Carnmenellis granite suggests it may have a centrally located feeder zone. Seismic surveys have been conducted across south-west

England and its adjacent areas. However, no reflectors were identified in the granite, the granite/country rock contact was not imaged, and it was concluded that the granite is seismically featureless. MT data from the Carnmenellis granite indicates a very homogenous body, with joint closure by a depth of 7 km, and a change to pore-dominated resistivity below this depth. High resolution magnetic and radiometric datasets for south-west England were obtained during the recent Tellus South West survey. This data has been widely used in research projects, resulting in new structural interpretations, improved correlations of stratigraphic units and a re-evaluation of the heat production across the batholith.

The study area is extensively mineralised, hosting the highly productive Camborne-Redruth mining district. The granite-related mineralisation can be broadly defined as quartz–wolframite and tourmaline–quartz–cassiterite veins, with subordinate copper, arsenic, and minor bismuth, silver, and lead, which typically occur in swarms in both the granite and the metasedimentary country rock. Grade and tonnage of these deposits are comparable to significant vein-stockwork tin-tungsten deposits globally. Cobalt has been produced from this type of mineralisation in the Redruth area. The Mid-Triassic, variably metalliferous, cross-course veins cross-cut and displace the granite-related mineralisation in this area. They are primarily lead, zinc, silver, fluorite and baryte-bearing, and virtually all the mineralised veins occur in the metasedimentary rocks.

The Carnmenellis granite was the focus of a major geothermal experiment, the UK hot dry rock (HDR) research and development programme that ran for more than 15 years, and produced a huge amount of data and analysis on the geothermal energy potential of south-west England. The project, based at Rosemanowes Quarry, near Penryn in west Cornwall, aimed to demonstrate the feasibility of establishing a ‘full-scale prototype’ HDR power station in Cornwall. A contemporary project, operated by operated by Geothermal Engineering Ltd (GEL), is the United Downs Deep Geothermal Power (UDDGP) project, located near Redruth and about 7 km north of the old HDR project site. The HDR project focussed on engineering an underground heat exchanger in the low porosity and permeability rock mass using reservoir stimulation. In contrast the UDDGP project is based on a new concept of exploiting the natural permeability that may exist in major fault zones in Cornwall, eliminating the requirement for artificial stimulation of the rock mass. Much of the data, information and analysis presented this review arises from these two deep geothermal development projects.

The temperature of the Carnmenellis granite at 5 km depth is estimated to be 200°C. This estimate is consistent with the actual temperatures measured in the HDR project boreholes. Heat production maps define clear zones of greater heat production in the Carnmenellis granite outcrop. In the United Downs project area, heatflow modelling predicts that at a vertical depth of 4500 m the temperature will be between 180–220°C.

Cornish granites typically have very low primary permeability, but relatively high hydraulic conductivity as a result of faults and joints. The latter are particularly important for controlling fluid flow in Cornish granites. Fluid circulation has been a continuous feature of the Carnmenellis granite and its host rocks since emplacement. Fluid circulation is evident in the local mines where thermal, saline brines discharge from crosscourse structures. It is concluded that a dynamic system driven by convective and hydrodynamic forces has allowed continuous water-rock reaction to occur within the upper 3–4 km of the currently exposed pluton. It is thought that a large reservoir of probable diluted palaeobrines exists at depth in this area. However, these are not viewed as static, trapped paleofluids, but rather part of a dynamic system of fluid circulation, involving continuous mixing of saline and meteoric waters, and water-rock reaction that continues today. These brines contain lithium concentrations of up to 125 mg/l, probably as a result of the mica breakdown during fluid-rock interaction.

An extensive programme of both direct and indirect stress measurement was undertaken in the Carnmenellis granite during the HDR project in an attempt to understand how the stress regime would influence the shape, extent and orientation of the growth of a geothermal reservoir. Initial tests to develop a ‘commercial-scale’ heat exchanger at the Rosemanowes site were largely unsuccessful, as when water circulation commenced fluids losses were excessive and the pumping pressures required to maintain circulation were excessive, due to the poor connectivity between the boreholes. A configuration, involving a third borehole orientated to maximise the number of joint intersections and use of viscous gel to open up the rock volume had lower impedance and water losses, and injection and production flow rates in the system were measured over a continuous four-year period. It was concluded that the 'optimum hydraulic performance' that could be achieved at the Rosemanowes site was an injection flow rate of 24l/s, with impedance of 0.6 MPa per l/s and with a water loss of 21 per cent. A decline in the thermal performance of the system was also observed over the monitoring period, due to a short circuit between the boreholes. The UDDGP project is currently working on the basis that if the Porthtowan Fault Zone PTFZ is assumed to have a width of about 200 m and two fractures occur every metre that have an aperture of 90 µm, the entire zone would have a transmissivity of 123 mD, resulting in a transmissivity of about 25 Dm. Based on this and heat flow modelling the project aims to produce water at the surface at about 175°C, with a circulation flow rate of between 20–60 l/s.

It has been demonstrated that the stress regime in Cornwall means fluid injected into a deep borehole will migrate downwards, along favourably orientated joints, hence the requirement for the injection borehole to be shallower than the production hole. The UDDGP project boreholes have a large (c. 2000 m) separation, in order to exploit a sufficiently large heat exchanger and reduce the risk of short-circuiting of flow, and will be driven by a downhole pump that will create a pressure sink above the production well. It is predicted that even at moderate injection pressures shearing will occur on favourably oriented fractures.

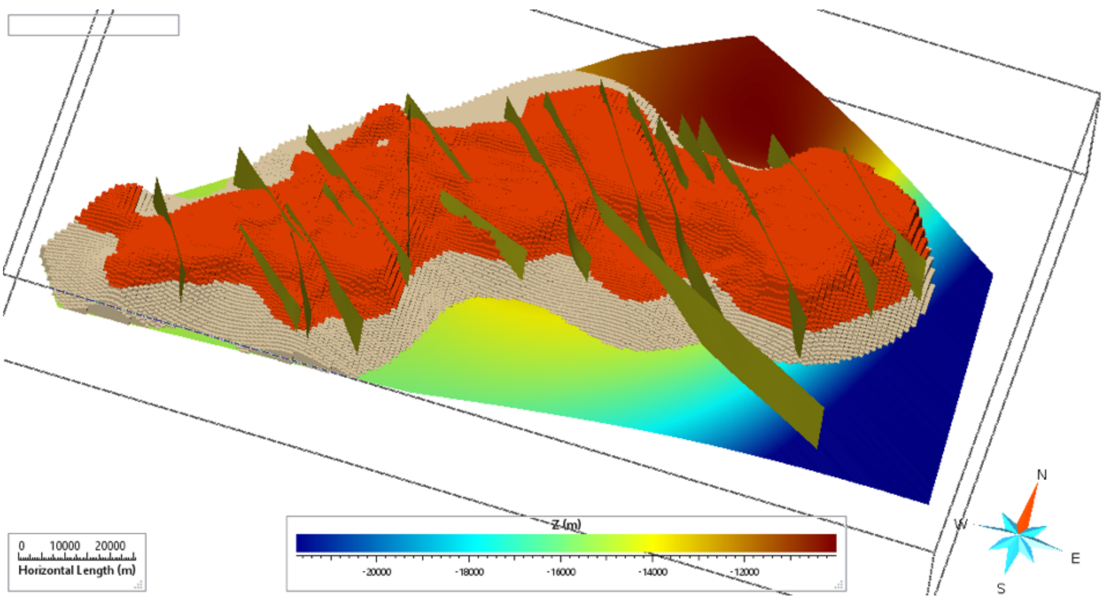


Figure 14: 3D view of the voxelated granite model showing the two granite sheets and the SE dipping base of the granite. British Geological Survey © UKRI.

Preliminary modelling of the Cornubian Batholith has been undertaken to improve understanding of its properties relevant to geothermal energy development. A regional model was constructed to understand the spatial relationship of key geological parameters that were used for the development of subsequent site-scale models (Figure 14). One of the site-scale models is based on data from the HDR project site, and covers a volume of 2.6 km^3, with a depth range of -1000 to -3000 mbsl. The model is centred on the HDR project boreholes, incorporating fracture data from two of the deep boreholes and site-specific hydrological properties. Data and assumptions about the fracture network were used to generate three discrete fracture network (DFN) models for the HDR project reservoir. These were up-scaled to include porosity and permeability in order to understand the potential flow pathways within the reservoir. The second site-scale model considers an area located to the NW of the Carnmenellis granite, where the current UDDGP project is located. The target geothermal reservoir is still considered to be the Carnmenellis granite, and the model covers a volume of 12 km^3, with a depth range of -1500 to -5500 mbsl. In the absence of any published data on the fracture network in the UDDGP project target reservoir and given the consistency of fractures mapped at surface in the Carnmenellis granite the two fracture sets identified and characterised in the HDR project site model were also used in this model. Due to the uncertainty associated with the location and scale of the fault that the UDDGP project is targeting it was represented in the model as a fractured volume of rock, based on DFN modelling methods. An additional fracture set that is parallel to the fault strike was added to the two regional fracture sets in the UDDGP project site model. Compared to the HDR site project model the modelled volume shows a clear increase in permeability within the fault zone, despite the background permeability being similar. However, the model is likely to overestimate the permeability in the UDDGP project reservoir as the fracture apertures used in the modelling are based on the measured flow within the shallower HDR project boreholes. Although this modelling informs our understanding of the properties of two potential deep geothermal reservoirs in contrasting structural settings in the Carnmenellis granite, there are a number of uncertainties and limitations to these models, which future research will have to address.

The presence of mineralisation at EGS depths (≥4 km) in Cornwall is highly uncertain due to a lack of direct evidence. The deepest mine workings in Cornwall extend to about 1000 m depth, and until 2019 the deepest drilling in Cornwall reached about 2600 m, with only trace quantities of sulfide identified in the core. Significantly, the drilling at the UDDGP project has encountered a number of mineral lodes and cross-course structures. However, the CHPM concept does not necessarily rely an ore body in the traditional sense. Any metal enriched geological formation is a potential target for leaching. The Cornubian Batholith is notable globally for its high bismuth concentrations and the granite is strongly enriched in lithium. Disseminated niobium and tantalum phases also occur in some of the granites. The Carnmenellis granite predominantly comprises quartz, orthoclase feldspar, biotite and muscovite. Micas represent sinks for many minor metals. Preliminary leaching experiments on a mica concentrate produced from a Carnmenellis granite sample were disappointing in terms of the concentrations of metals recovered.

The UDDGP project provides the best indications of the potential environmental impacts of future geothermal resource development in Cornwall. There is a strong preference for new developments to utilise brownfield sites in the region. Proximity to the National Grid and network availability to connect new generation projects will also be a major consideration in the location of future developments. The planning permission application for geothermal exploration and development on the UDDGP project site received no objections from both statutory consultees and local residents. Private housing exists along the western, northern and eastern perimeters of the industrial estate, and the nearest village is less than 1 km away. Background monitoring and predictive modelling was undertaken to predict the noise levels in the area surrounding the site. The drilling rig being used has been designed to minimise environmental impact in urban and noise-sensitive environments, and a range of noise mitigation and attenuation measures have been implemented at the drilling site. Induced seismicity is a concern in all projects that involve deep drilling and water circulation through fractures. During the HDR project tens of thousands of micro-events were recorded, however, very few were felt at surface. In the planning consent for the project the local planning authority included a requirement for both seismic monitoring and a control protocol. Data from the monitoring system is made publicly available. Mining in south-west England stretches back millennia, and the mining landscape is testament to the impact mineral extraction has had on the development of the region. The last decade has seen a renewed interest in metals and mining in south-west England. The extent of mineral extraction in south-west England and its impact on the heritage of the region probably means local communities have a relatively receptive attitude towards natural resource development. GEL have undertaken an extensive education and community outreach programme targeting the full cross-section of potential stakeholders. The UDDGP project consultation programme suggests that the local community and politicians are supportive of deep geothermal power development in Cornwall. Plymouth University, in south-west England are researching the issues relating to public perception of geothermal energy exploitation in the UK.

Geothermal heat is considered to have the potential to make a significant contribution to meeting the emissions targets set out in the UK Climate Change Act. One of the key challenges with ownership and regulation of geothermal heat in the UK is that it is regarded as a physical property, not a recoverable material such as a metallic mineral ore. As such, 'heat' is not a legally-defined entity and this causes some difficulties for assigning legal ownership and regulating it. Revision of geothermal regulations is one of a number of measures required to encourage the exploitation of geothermal resources in the UK. The current regulatory approach in the UK for deep geothermal developments requires environmental permissions and licences from the Environment Agency. Development falls under environmental permitting and groundwater regulations, as defined by the Water Framework Directive.

The National Planning Policy Framework in England states that Local Planning Authorities should develop positive strategies to help increase the use and supply of renewables and low carbon energy and heat. The Overarching National Policy Statement for Energy, sets out national policy for the delivery of major energy infrastructure, and indicates that the Government is committed to increasing dramatically the amount of renewable generation capacity. It includes a list of generic impacts that must be considered by energy development proposals. Cornwall Council are keen to understand the potential for geothermal resource development in the county, and strategies it could take to stimulate the deep geothermal sector. Cornwall has produced a 'Sustainable Energy Action Plan', which describes the importance of supporting and promoting geothermal opportunities. The Cornwall 'Local Plan' contains a specific 'Renewable and low carbon energy' policy, which seeks to increase the use and production of renewables and low carbon energy generation. The Council is particularly supportive of developments that 'create opportunities for co-location of energy producers with energy users, in particular heat, and facilitate renewable and low carbon energy innovation.

The mineral ownership situation in Great Britain could present a challenge for the CHPM2030 concept of recovering metals from a geothermal system. The rights to non-energy minerals in Great Britain, with the exception of gold and silver, are mainly in private ownership, and only the mineral rights owner can legally grant rights to explore and mine. Hence a critical stage in the exploration and development process is determination of mineral ownership. This can be difficult and time consuming in Great Britain, particularly in regions with a long history of mineral extraction such as Cornwall.

During the HDR project analysis was undertaken on the economic costs of HDR systems. The capital costs associated with a 'post-prototype' commercial-scale HDR power station in south-west England was estimated to be in the range of £71–100 million (equivalent 2018 prices). If an operational geothermal system can be established at the UDDGP project there are plans to construct a demonstration power plant to supply power to the UK national grid. Demand for renewables (and bio-fuels) is projected to increase in Cornwall, reaching 101 ktoe in 2030. Previous estimates of the electricity generation potential of deep geothermal in south-west England range from 100MW to 4GW, with significant by-product heat. It is suggested that development of this deep geothermal resource could result in Cornwall becoming an attractive destination for power dependent industries. The electricity grid in Cornwall has spare capacity on the network to take more locally generated renewable energy. However, there is very little capacity available for new connections.

In summary south-west England, and specifically Cornwall, is an excellent location for a pilot-scale CHPM system. It has the essential prerequisites of a proven geothermal energy resource and abundant polymetallic mineralisation. It is one of the best surveyed and most data-rich parts of the UK, with a long history of mineral development and geothermal research. The local government and communities are supportive of deep geothermal resource development, and it has a major, active co-funded deep geothermal project.

Pilot area recommendations for the technological components, Funding opportunities and stakeholder engagement.

All the recommendations and research areas identified below contribute to enhancing the knowledge base and establishing a future CHPM industry in south-west England. However, given the economic viability of EGS and funding availability it is important to consider what is practical and of greatest priority to help quickly establish this fledgling industry, so that it can start making a positive contribution to reducing carbon emissions and sustainable regional growth. Given that EGS has traditionally been considered uneconomic, it is important at the pilot project scoping stage to differentiate between what information industry absolutely requires to establish an EGS operation, the information that is desirable to de-risk development and convince investors of economic viability, what information the regulators insist on being provided, and those activities, data and information that are principally of value to the research community.

Exploration plan for the technological components

1. Better constrain the upper and lower surfaces of the granites and geometry of the Cornubian Batholith, fluid flow pathways, and verify the presence of mineralisation at reservoir depths:
    - 1.1. A detailed 3D magnetotelluric tomography survey across the batholith.
    - 1.2. Localised 3D deep seismic surveys, using broad band and side shooting seismic methods. Utilise seismic anisotropy to improve definition of fault zones, better characterise fracture orientation and intensity, and identify mineralisation.
2. Improve understanding of the physical properties of the granite at reservoir depths:
    - 2.1. Acquire drill core from depths of >2.6 km to measure properties including porosity, permeability, heat flow, heat production, strength, thermal conductivity and sonic velocity. These data could also be used to calibrate existing and future wireline well logs.

3. Improve understanding of the magnitude and orientation of the stress field, to determine optimum well trajectories to maximise structural intersections, predict how the reservoir will develop, and minimise induced seismicity:
    3.1. Insitu stress measurements at depths >2.6 km, and acquisition of orientated core for differential strain analysis.
    3.2. Detailed borehole image logging and interpretation of wireline logs.
4. Improved characterisation of fault zones:
    4.1. A programme of directional drilling to intersect fault zones of varying orientation.
    4.2. Pump tests using tracers to measure absolute permeability and fluid residence times.
5. Reduce current uncertainty about the relative lengths, apertures and the extent of mineral-fill in fractures within the Cornubian Batholith and country rock, at varying depths:
    5.1. Studies of fracture systems in granites across south-west England to raise regional knowledge to at minimum the current knowledge available for the Carnmenellis granite.
    5.2. Obtain a comprehensive dataset on accessible fractures at depth using orientated core, conventional borehole logging and more novel electromagnetic and electrical fracture detection methods.
6. Develop an improved model for the geothermal gradient in the Cornubian Batholith, to guide regional exploration:
    6.1. Acquire systematic in-situ temperature measurements from a grid of boreholes across the batholith.
7. Improve understanding of deep fluid flow in the Cornubian Batholith:
    7.1. Conduct an isotopic and chemical investigation of the deep water system using fluids acquired from deep boreholes.
    7.2. Advanced numerical modelling of the regional deep groundwater flow pathways, including assessing the potential for convection cells within or at the

margins of the granite (due to the relative change in heat production between the granite and the country rock).

8. Undertake leaching experiments on fresh and unaltered rock samples that contain metal-bearing phases, to improve understanding of the reaction rates of minerals that exist at reservoir depths:
    8.1. Obtain fresh core samples, containing economically important phases, from reservoir depths.
9. Improve understanding of the effect of subsurface water residence times on mineral reaction rates and solution chemistry:
    9.1. Model systems in which the length of the fluid flow pathways does not allow for sluggish mineral reaction rates to reach chemical equilibrium, resulting in unsaturated deep groundwaters.
10. Improve understanding of nanoparticle behaviour in rock, to enhance metal selectivity and prevent clogging of pore space:
    10.1. Undertake a study to functionalise the nanoparticles to be metal specific and ensure they do not interact with each other or minerals within the rock, and remain as isolated particles.
11. Is it possible to manage a CHPM system to minimise problematic waste-streams/by-products (e.g. radon gas, radioactive scales/fluids) that require treating and disposal:
    11.1. Investigate a closed loop system that would prevent radon emissions at the surface.
    11.2. Investigate the ways in which it is possible to modify the solution chemistry to keep specific deleterious elements immobilised in the reservoir.
12. Use actual EGS plant designs in future modelling work:
    12.1. Make EGS plant design documents publicly available for the research community to use in modelling experiments.
13. Determine the minimum amount of data and information required by industry to establish a commercial-scale CHPM system on a new site:
    13.1. Assimilate all legacy data for a region prospective for CHPM.
    13.2. Robustly characterise and model a pilot site.

13.3. Work with industry and regulators to define what is absolutely required.

Funding opportunities

1. Involve industrial partners with relevant data/infrastructure at an early stage in any future CHPM development project:
    1.1. Promote the added value of metal recovery technology to the geothermal community, and in particular commercial developers (e.g. Geothermal Engineering Ltd and Eden Project) and local authorities.
    1.2. Establish a strong collaborative network, spanning industry, government, funding bodies, and academics, in regions that are promoting geothermal energy development.
2. Pursue a consortium funding approach for CHPM projects (as exemplified by the United Downs Deep Geothermal Power project):
    2.1. Identify funding bodies and commercial companies interested in promoting and investing in novel and cross-over technology development.
3. Ensure CHPM research and proof of concept projects are aligned with existing commercial and/or publicly-funded EGS development projects:
    3.1. Identify existing EGS projects in areas suitable for CHPM that could provide the necessary baseline data and infrastructure for future proposals.

Stakeholder engagement

4. Understand community concerns specific to a CHPM operation (i.e. there are additional challenges compared to a conventional EGS, e.g. if you are mobilising metals, locals may ask “Will these get into local drinking water?”):
    4.1. A consultation programme with local communities to disseminate information on the CHPM process, outline plans for the operation and provide the community with the opportunity to discuss and interrogate the proposal.
    4.2. Explain leaching agents: very dilute organic acids, found naturally, and relatively benign = acetic acid (key component of vinegar), and citric acid (found in citrus fruit).

4.3. Assess the views and concerns of the community, and propose technical mitigation measures for potential risks.

4.4. In areas such as south-west England where there is a long history of mining, build upon this heritage, by emphasising that this could be a way to re-invigorate metal production in the region with reduced environmental impact, and numerous economic benefits for the community.

Other recommendations

1. Determine the effectiveness and cost of adding leaching agents or ‘metal carrying’ chemicals to the recirculating EGS fluid:
    1.1. Conduct a study to model injection and consumption rate of leaching agents, levels of degradation and potential system losses, and associated simulation and economic analysis of using different leaching agents.
2. Understand the regulatory challenges associated with adding leaching agents or ‘metal carrying’ chemicals (including nanoparticles) to an EGS system:
    2.1. Engage with the relevant authorities to determine the permitting process for a CHPM operation in the UK, and the regulations that have to be compiled with (e.g. groundwater protection), and monitoring requirements.
    2.2. Conduct a site-specific environmental impact assessment for a CHPM operation.
3. At the pilot stage it is unlikely that it will be possible to test all the technology components of a complete CHPM system at a single site. Therefore, be opportunistic and pragmatic, by testing specific system components at existing suitable sites.
    3.1. Undertake metal mobilisation/in-situ leaching experiments at existing mining/mineral processing operations, which have a readily available supply of ore, suitable facilities, and existing environmental permits for metal leaching.
    3.2. Test the metal recovery process at a mine water treatment operation, which has a readily available supply of metal-contaminated water, an operating plant, and existing environmental permits for metal recovery and waste management.

   3.3. Integrate the additional technology components of a CHPM system into the circuit at an existing EGS.

4. Improve knowledge and data flow, and integration between relevant tasks in a CHPM research project:
   4.1. At the project planning stage ensure tasks/experimental activities do not take place in isolation, but feed directly into and/or support other parts of the research programme (e.g. the stress, fracture, flow work, when coupled with leaching data, provided information on the amount of metal that would be contained in each m3 of water; University of Szeged calculations, but highly relevant to quantifying some of the BGS experimental work).
5. In some cases, non-geological or so called 'modifying factors' may represent the most significant barrier for CHPM projects:
   5.1. Give these factors (e.g. local politics, regulatory environment, mineral rights ownership, land access, proximity to and availability of grid connections, proximity to heat consumers, sufficient space for a drilling rig on relatively flat ground, good road access, proximity to communities, conflict with other forms of development and land-use, protected areas, the historic environment) equal or greater weighting than geology in CHPM site selection.
   5.2. Employ a GIS-based modelling approach that can represent all these spatial constraints/planning considerations and geological factors to prioritise development targets.
6. Manage and regulate geothermal heat in a similar way to other natural resources to promote development:
   6.1. Provide a clear definition of the term 'geothermal energy', make it a legally-defined entity, and ensure a clear understanding of heat ownership.
   6.2. Revise the deep geothermal energy regulations in the UK, to move away from a practice of 'first come, first serve', to a system that ensures optimum resource management and long-term sustainability.
   6.3. Change UK law so that it better defines heat, and thereby allows implementation of new geothermal regulations.

6.4. Adopt a model where exploration and development of deep geothermal resources (>500 m depth) are subject to licensing under the same rules that apply in relation to oil and gas activities.

6.5. Ensure the cost for geothermal exploration licences reflects the comparatively lower economic return potential relative to some other energy sources.

6.6. Keep licensing/permitting procedures as simple as possible, and provide licence decisions within a timeframe that is relative to the overall timeframe required for developing the resource. As part of this, it should be ensured that licence requirements for different aspects of the environmental system are integrated in the overall licencing procedure.

7. CHPM relies on the recovery of heat and metals, each with different ownership challenges and permitting regulations:

7.1. Take a more integrated approach to resource management, particularly in terms of environmental permitting regulations, and when safeguarding of one these resources may affect access to the other.

8. Determination of mineral rights ownership in areas with CHPM potential:

8.1. In CHPM target areas determine if the minerals rights are owned by the surface owner or a third party.

8.2. Create a comprehensive, reliable register of mineral rights.

8.3. Establish a national onshore licensing system, for exploration and extraction of all metals.

9. Examine options for abandonment of end-of-life CHPM sites (subsurface parts, i.e. sealing/capping of boreholes, and surface plant, i.e. visible infrastructure) and post-closure obligations:

9.1. Determine the nature of the potential hazard (e.g. by-products, radioactive scales etc.).

9.2. Assess reclamation approaches e.g. borehole sealing.

9.3. Estimate direct reclamation costs.

9.4. Assess the long-term obligations of contractors (e.g. site monitoring), post-closure liabilities (including duration, i.e. at what point does this get handed over to the state) and how these can be calculated.

5.2 Portugal Iberian Pyrite Belt

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Extended summary of the pilot area report

The CHPM project provided an update of geoscientific data and information relating south-west Iberian Pyrite Belt (IPB), Portugal, massive sulphides deposits and the possibility to use there the CHPM new-developed technology, combining heat, power and metal extraction from ultra-deep ore bodies. The IPB is a Variscan metallogenic province located in the SW of Portugal and Spain that hosts the largest concentration of massive sulphide deposits worldwide, covering about 250 km long and 30–50 km wide. These massive sulphides are associated with volcano-sedimentary sequences present in sea floor environment (http://geoportal.lneg.pt). This geographical area, with particular geological volcanic and sedimentary sequences of Carboniferous and Devonian ages, runs from NW (Alcácer do Sal, Portugal) to SE (Seville, Spain), and, in the Portuguese side, covers two active mines: Neves-Corvo mine, owned by Lundin Mining (www.lundinmining.com), and at the Aljustrel mine, owned by Almina (www.almina.pt). Because of its potentialities and ongoing mining operation with good perspective of increasing in depth, the Neves-Corvo Mine was chosen for test site, to be studied for CHPM purposes. The reasons behind this choice were related with its depth of exploitation and undergoing research projects (SmartExploration and Explora EU funding projects). These projects are reviewing a deep 3D geological and geophysical model, with old mining data and recent acquired geophysical acquisition, reprocessing and reinterpretation. At the same time, its relation with EGS potentialities was considered. The Neves-Corvo mine area includes presently 7 massive sulphide ore lenses and is mainly a copper and zinc mine, producing copper, zinc and lead concentrates. Although this mine still does not explore any ultra-deep orebodies that allow the application of the CHPM technology, prospecting in depth is underway to check for the continuity of the Lombador, the deepest orebody that is identified in the Lundin permit area orebody. Geophysical modelling and reflection seismics were conducted under the scope of SmartExploration (H2020) (https://smartexploration.eu/) and Explora (Alentejo2020) projects and a more refined model for the ore body will turn out with the available data. It gives good prospects since a ultra-deep geothermal study estimates a geothermal gradient that allows reaching adequate temperatures to produce energy (~70 °C) at relatively shallow depths (~2.5-3 km), compatible with both energy production and metal recovery in the geothermal brine, to increase mining production.

An overall look upon the external requirements to the implementation of CHPM technology was studied. Emergent external factors such as energy transition, financial requirements and possibilities, and environmental, social and political backgrounds and future prospects are also referred in the report, as well as possible future agreements between the mining management and the Portuguese government.

Finally, some new data was incorporated into a GoCad 3D model as an update to the GoCad model published in ProMine. This update includes supplementary information, such as deeper and all other recent boreholes information, from 2012 to 2018, to cross-check with geophysical data, reprocessed gravimetric, magnetic, electromagnetic and surface and deep reflection seismic data.

So far, it is clear that the Lombador ore body strikes in depth, but it was crossed by very few drillholes by the time of the Promine project.

The inclusion of transient electro-magnetic (TEM) cross-section resulting from the inversion of 1D surface loops, overlapped to the 3D geological model shows the prolongation of the Lombador orebody host rocks till at least 1600 m, as suggested by TEM data and confirmed by a drillhole (Figure 15). The existence of 3 loops with 3 lines inside of it, with 3000 meters long and 23 cross sections as the inversion of 1D surface loops will be processed with Maxwell, will allow a much more detailed view of the Lombador orebody, based on its electromagnetic characteristics.

The result of the inverted 1D surface loop, chosen by crossing the recent borehole (see D6.2), clearly shows a distinctive layer with higher electrical conductivities that may correspond the prolonging in depth of Lombador orebody. This same figure shows an area where a borehole, drilled from the mine gallery at 600 meters depth intercepted a stockwork mineralization at 1400-1500 meters depth. This leaves good prospects to the 3D modelling that will be carried out in the TEM inverted sections, to build the 3D model, including the recently acquired reflection seismics in the mine.

The reprocessing 2D seismic profiles overlapped to the 3D geological model are part of the SmartExploration project (see CHPM Deliverable 6.2). The prolongation of the Lombador orebody host rocks till at least 1600 m is also suggested by 2D seismic data conducted by Promine (see CHPM Deliverable 1.2).

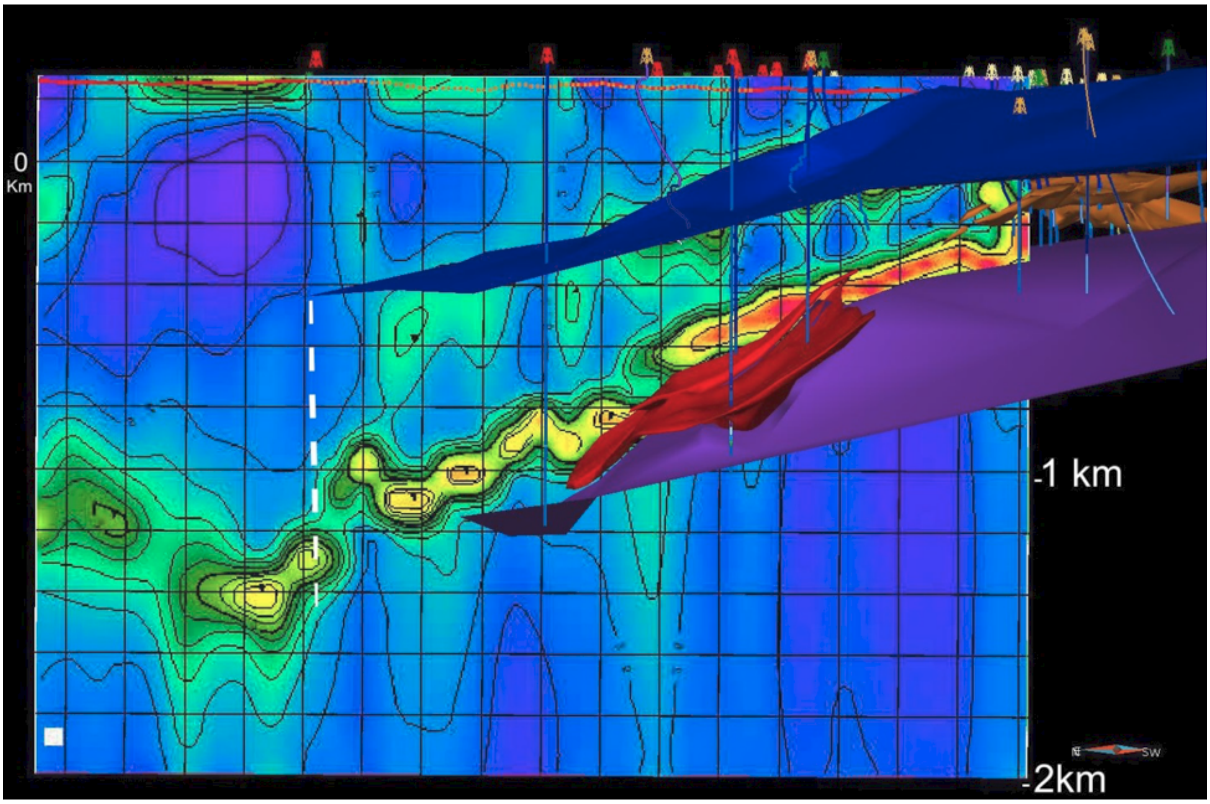

Figure 15. Transient electro-magnetic (TEM) cross-section resulting from the inversion of 1D surface loops, overlapped to the 3D geological model. Legend: Blue - Top of ore-bearing

Volcanic-Sedimentary Complex (VSC) geological unit. Purple - top of the basement unit Phyllite-Quartzite Formation. Red - Semblana and Lombador orebodies. Orange - Neves, Corvo and Graça orebodies. The prolongation of the Lombador orebody host rocks till at least 1600 m is suggested by TEM data. Dash white line represents approximate location of recent borehole that intersected stockwork mineralization at 1400-1500 m depth. Blue corresponds to low electrical electrical conductivities, yellow and finally red correspond to high and very high electrical conductivity. Drillholes are plotted in different colours because they belong to different surveys.

The mine galleries intersecting the Neves-Corvo and Lombador orebodies are depicted in CHPM Deliverable 6.2.where purple parts correspond to location of receivers that were used to collect the in-mine recent seismic data, at the level 640 m. The purpose was to investigate how deep mineralization extends down dip. There are good prospects that the Lombador orebody extends in depth, but only with the data processing that will be carried out by SmartExploration and Explora projects, further information can be added to CHPM purposes.

This 3D modelling contains the information that will be used in the first stages of Roadmapping. In fact, due to unfinished character of this subject, it is an important part of the Roadmapping.

Pilot area recommendations for the technological components, Funding opportunities and stakeholder engagement.

Main goal of the recommendations that will be stated are related with pilot readiness level by 2030, to be ready for the first pilots. These recommendations comprise exploration plan to gather more data for designing the technological components, funding opportunities and stakeholder engagements.

Exploration plan for the technological components

Technological components comprise in a first stage, the use of Oasis Montaj and GoCad to build a 3D model of the joint geological, geophysical and mining information gathered in Neves-Corvo Mine concession area. Besides the drillholes data, superficial geological mapping and underground mining data were considered in the generation of key surfaces related with the major geological units (CHPM2030 Deliverables 1.2 and 6.2). To constrain the geological and geophysical models with previous data, it is crucial to infer the existence of deeper mineral orebodies that can be useful for CHPM purposes.

These technological components include a special focus is on the Lombador orebody, that shows good prospects of continuity at depth. This orebody may serve simultaneously the goals of the ultra-deep mining activity, by prolonging the mining activity, and temperatures in depth high enough to produce energy.

The actions to be taken a Roadmap 2030, inserted in a realistic timeline will be:

1. To process the seismic data acquired inside the mine (at level ~-600 m) and at the surface over the Lombador orebody using seismic reflection, tomographic and seismic interferometry approaches – due November 2020
2. 3D geological model building using reprocessed 2D and 3D seismic reflection, drill-hole, updated geological outcrop and transient electromagnetic data – due December 2019
3. Perform constrained 3D electromagnetic forward modeling in the Lombador region – Due December 2019
4. Complete 3D gravity inversion to identify new targets (mineralized bodies) at depth – Due December 2019
5. Drilling over selected targets – due 2020
6. Possible ongoing research projects with SmartExploration team focused in Neves Corvo – from 2020 on.
7. Evaluation of the possibility to use CHPM technology in 2020-2025 by:
    - 7.1. conducting temperature logging and to estimate geothermal gradient temperature in depth to confirm the site ability to produce energy.
    - 7.2. characterizing the geothermal brine to verify the possibility to extract metal from it using CHPM technology.
8. If the evaluation is positive, study for a pilot from 2025 to 2030.
    - 8.1. studying the feasibility of the use of energy obtained with CHPM technology.

8.2. showing to the stakeholders the environmental and mining advantages of the implementation of such a technology as well as long term profits.

8.3. preparing physically the implementation of the test site, together with the stakeholders, studying all the possibilities that will be faced.

8.4. showing the importance of the implementation of this technology to local, regional and national authorities, and if possible, the return that each side of society will benefit from it.

9. Possible readiness for a pilot by 2030.

Funding opportunities

For the next few years, the paradigm of energy transition will become more and more important for the public entities and governments will be more focused in alternative sources of energy. In the particular case of CHPM, dealing with delicate problems related with metal recoveries, the new use of renewable energy would take place at the same time as crucial methods to recover metals from geothermal brine are developed.

In this case, the mix of energy and metal recovery can be really useful to the mine by recovering extra Cu and by generating power to support Neves-Corvo Mine needs and surrounding villages and small towns.

Keeping in mind this time horizon, many disruptive developments can happen, such as changing in the mining plans, no other deeper ore bodies are found, changing market prices could make the technology unfeasible for minerals exploitation due to uncertainty of geo-economical conditions.

In the case of a junction of favorable conditions:

1) At this moment, the Portuguese government does not contribute continuously to private initiatives regarding the implementation and use of any renewable energy or any innovative projects regarding the paradigm of energy transition. Special calls with special objectives are therefore at the moment launched in a non-periodical way. Anyway, the Fundo de Apoio à Inovação (FAI) (http://fai.pt/) is presently one of the

national governmental organizations that can provide some financial aid to the implementation of new concepts of generating heat in a renewable and clean way.

2) European Union is co-funding the research and development projects undergoing in Neves Corvo that will allow inferring the possible prolonging in depth the Lombador orebody. If the Lombador is prolonged in depth, then Neves Corvo Mine will have a longer lifetime. Therefore, the possibility to use it to produce energy with CHPM technology will be a reality.
3) At this stage, government and European Union funding using Energy and Environmental calls will be applied to be complemented with investments of Lundin Mining should be implemented.

Stakeholder engagement

1) Development of a Grant Agreement between the Portuguese Government (geological resources, either mining deposits or geothermal energy) and stakeholders may be assured in order to aggregate successfully CHPM technology.
2) The weak dissemination in public opinion and the total absence of tradition in this type of geothermal exploitations are key areas to tackle this Roadmap. Participation in roundtables, green events, mining events, Energy Forums and publication of studies in scientific journals will help to make this technology clearer for the next years.
3) The regular communication among the CHPM2030 Consortium members will help to follow developments in other sites and exchange experiences with each other.
4) Regarding legislation, Portugal is still very low focused in geothermal energy. Indeed, there is a lack of legislation adapted to the new reality of shallow geothermal installations. Geothermal resources are generally ruled by the Portuguese Law 15/2015 of June 22nd and the Decree-Law 87/90, from March 16th. Having a mixed technical component in the Geology and Energy areas, there are not many companies with skills to ensure the quality of these projects and to implement these type of energy. Synergies must be assured if this type of technology will ever be implemented.

4) Finally, it is recommended to focus on the deep involvement of Lundin Mining to implement the CHPM technology, if the identified geological, mining and geothermal conditions will be favorable by 2030.

5.3 Beius Basin - Bihor Mountains, Romania

Authors: Cătălin Simion, Diana Perșa, Ștefan Marincea, Delia Dumitraș, Geological Institute of Romania. Reference document: CHPM2030 D6.2.3 Report on pilots: Evaluation of the CHPM potential of the study site, Romania.

Extended summary of the pilot area report

The purpose of this study is to provide relevant information that leads to the selection of a pilot site, an area that has indications of deep mineralization and high geothermal potential at the same place. In Romania, the Beiuș Basin – Bihor Mountains has been selected as a study area. The site is situated at the border of two major structural units, sharing similar characteristics. Thus, the Beiuș Basin, which is a part of the Pannonian Basin, has high geothermal potential. At the same time, Bihor Mountains' structural unit is a part of the North Apuseni Mountains, and it is part of the metallogenic province Banatitic Magmatic and Metallogenetic Belt.

Both Pannonian Basin (Romanian part) and Beiuș Basin have the following relevant elements:

- The thin crust, (which is estimated at 25-27 km), and the thin lithosphere (60 -70 km) that resulted during regional extensional processes of Pannonian Basin that started in Miocene;
- Below Neogene deposits, Triassic deposits host a geothermal aquifer;
- The existence of intrusive magmatic bodies in the depth.

Both North Apuseni Mountains and Bihor Mountains have the following relevant elements:

- Existence of a granodiorite - granite pluton with regional extension that has been extruded during Late Cretaceous.

- The existence of mineralized areas, specific to the Banatitic Magmatic and Metallogenetic Belt, among which we mention the skarns that have been formed at the contact between the pluton and the Mid-Triassic and Upper Triassic limestones.
- Existence of a large geothermal aquifer recharge area that is represented by karst deposits of mainly by Triassic deposits

In terms of geothermal potential, the eastern limit of the Pannonian Basin, Rădulescu and Dimitrescu (1982) estimated the mean heat flow of 96 mWm^{-2}. Geothermal gradients for Pannonian Basin are high, varying from 6.2 to 5.6 $^{o}C/100$ m at 500 m and at 2000 m b.s.w.l respectively. Due to the thin crust and the thin lithosphere, Beiuș Basin is characterized by high heat flow, with values up to 90 mWm^{-2}. In Apuseni Mountains, in areas affected by Tertiary tectogeneses usually referred to terrains younger than 50 Ma, the three components of the regional heat flow: crustal radiogenic, thermal transient perturbation, and background heat flow from deeper sources, contributes with 36, 27 and 27 mWm^{-2}, respectively, to the mean value 90 mWm^{-2}. Thermal conductivity [10-3cal/cm x ^{o}C x s] of the rocks belonging to the Romanian part of the Pannonian Basin and the surrounding areas has been determined through laboratory methods, and has high values varying from 3,5 – 12 for granites, 4.8 – 5.0 for diorites and 6 – 7 for dolomitized limestone.

Based on these data the conclusion is that in Bihor Mountains, the heat flow of granitic – granodioritic bodies from Pietroasa and Budureasa are expected to have high values in the depth. Also, the heat flow of the rocks that host the geothermal aquifer (limestone, dolomite and quartzite, marble) has high values. But an important cooling agent is represented by the continuous circulation of the surface water through the karst areas of Bihor Mountains into the geothermal aquifer from Beiuș Basin. It is expected that in the depth of 4 km, where the access of water is prevented by the aquiclude Lower Triassic layers the heat flow of the batholith to be considerable.

Beiuş town has an extensive geothermal heating system (GDHS), which provides heat for approximately 70% of the population, covering about 60% of the urban heating demand, operated by Transgex S.A. Currently, the geothermal energy exploitation system consists of 2 geothermal water production wells drilled to a TVD of 2576 m and 2700 m, with a production capacity of 450 m^3 / h, and one reinjection well having a TVD over 2,000 m.

The geothermal aquifer from Beiuș and Ștei is hosted in fractured Triassic dolomites that have a regional extension. Triassic aquifer from Beiuș Basin is a confined aquifer with negative piezometric levels (-18.48 m 3001 H Beiuş and unstable – 45m 3003 H Beiuş) or artesian (3002 H Ştei), depending on the position of the tectonic block. Beiuș aquifer is an open geothermal system, where recharge equilibrates with the mass extraction and its reservoir pressure stabilizes. Its recharge can be both hot deep recharge and colder shallow recharge. The latter can eventually cause reservoir temperature to decline and production wells to cool down. In fact, this second alternative was demonstrated when the increase of the volume of injected water was accompanied by the decrease of the water temperature within aquifer. More research is needed to improve the knowledge on this subject. The aquifer is exploited by 2 extraction wells and one injection well in Beiuș, and one extraction well in Ștei, situated at a distance of 18 km from Beiuș. The most productive well is 3001, from Beiuș, that has a wellhead temperature of 88^{o}C, coming from 2460 m depth. The fresh supply for a CHPM system can be assured by Crișu Negru River and its tributaries. The average flow rate of rivers varies between 0.46 and 6.22 m^3/s.

In terms of deep metal enrichment, the mineralization is widespread in the mountain area and is expected to be found in the basin area. In Bihor Mountains the mineralization was generated during the banatitic calc-alkaline magmatism (Post-Lower Masstrichtian-Palaeogene), which is represented by bodies of intrusive rocks, generally hypabyssal as well as plutonic ones, which are widely developed in the depth. Plutons of granodiorite-granite rocks, to which the main sulphide mineralization is genetically linked, constitute main mass of banatitic bodies in the Apuseni Mountains; in Bihor Mountains they crop out on small areas, but they develop in the depth. Magmatic bodies intruded Permian-Mesozoic sequences and produced contact-metamorphic aureoles, at Pietroasa, Budureasa and, most extended at Baița Bihor. In the contact aureoles of the granodiorite-granites plutons, skarns with Fe, B, Bi, and Mo have been formed. At Valea Seacă, Valea Mare-Budureasa etc., the skarns are overlapped by sulphide mineralization. Brucite (magnesium hydroxide) deposits from Budureasa and Pietroasa were investigated by surface pits, drillings and underground galleries. They have been formed at the contact of granodiorites with the Anisian dolomites and have a structure with four zones, ranging from granodiorites to pure dolomites containing holocrystalline hypidiomorphic granodiorites, magnesian skarns, Brucite-bearing zones, recrystallized Anisian dolomite. Borate deposit is situated in the middle basin of the Aleului Valley (Bihor Mountains), at its confluence with the Sebisel Valley, at the Gruiului Hill. The formation of the borates from the contact aureole of the Pietroasa granitoid body is the result of an infiltration metasomatic process. W-bearing and base metal skarns are characteristic only for Baita Bihor. At Baița Bihor, some magnesian skarn bodies or ore pipes such as those at Antoniu, Bolfu-Tony, Hoanca Motului, and Baia Roșie are boron-bearing skarns and represents well-defined metasomatic columns. A sole similar body, or metasomatic column, that from Dealul Gruiului was identified at Pietroasa.

Laboratory experiments performed during the implementation of this project lead to promising results.

- Two rock samples from Romania were used for leaching experiments by Chris Rochelle et al., in 2017 (CHPM2030 Project Deliverable 2.2): a skarn from Pietroasa and a mineralized rock from Cacova Ierii. The experiments used a range of fluid types and pressure/temperature conditions to identify fluid-rock reactions and quantify the potential for enhancing metal release. For conditions of temperature/ pressure of 100 °C, and 200 bar the efficient substances proved to be 0.6 M NaCl, and HCl/HNO3 mix for both samples. The main elements recovered are: Co, Sr, Mo, Sb, Mn, Zn, and W.
- In 2018, using GDEx technology, Xochitl Dominguez et al. (CHPM2030 Deliverable 3.3) completed the experiments to recover metals from the geothermal brine provided by a Beiuș Basin well. According to this study, the results are promising. Especially the content of Sr in one of the brine samples and the content of Sr recovered are remarkable.
- A considerable enrichment of magnesium minerals was highlighted in the precipitate resulted from the geothermal water extracted from a Beiuș Basin well compared with

spring and water coming from a mine. Thus, the magnesium content is less than 5% in surface, and at least 13% in the geothermal waters.

Integrating all the data available in a 3D geological database and creating the 3D geological model of Beiuș Basin – Bihor Mountains study site provided an overview on the spatial distribution and the geometry of the main elements that are relevant for this study.

Thus, middle and upper Triassic sedimentary deposits within Beiuș Basin and their contact with the Upper Cretaceous intrusive body, from Bihor Mountains are represented.

The 3D model shows the extension of Upper Triassic deposits, both in Beiuș Basin and in Bihor Mountains, linking the two structural units, generating magnesian skarns on one side and transporting geothermal water on the other. This dual role in the perimeter explains an increased content of magnesium in geothermal waters from Beiuș Basin.

The 3D model revealed the fact that there is a region bordering Beiuș Basin where the batholith extends: at Budureasa, where there is an increased possibility to have both mineralisation and high geothermal potential within a small area (Figure 16).

The 3D model emphasizes the large areas on which Triassic deposits outcrop. Being represented by highly fissured karst deposits they, on one side, assure a continuous recharge of the geothermal aquifer, but, on the other side, they have an important contribution to the decrease of the geothermal potential of the rocks, being a cooling agent. The batholith's apophyses that were detected by complex geophysical methods within Beiuș Basin are represented by the model.

The 3D model helps us to visualize and understand the spatial relations at the border between the basin and the mountains, and provides the data that are necessary to set the parameters for planning new exploration work.

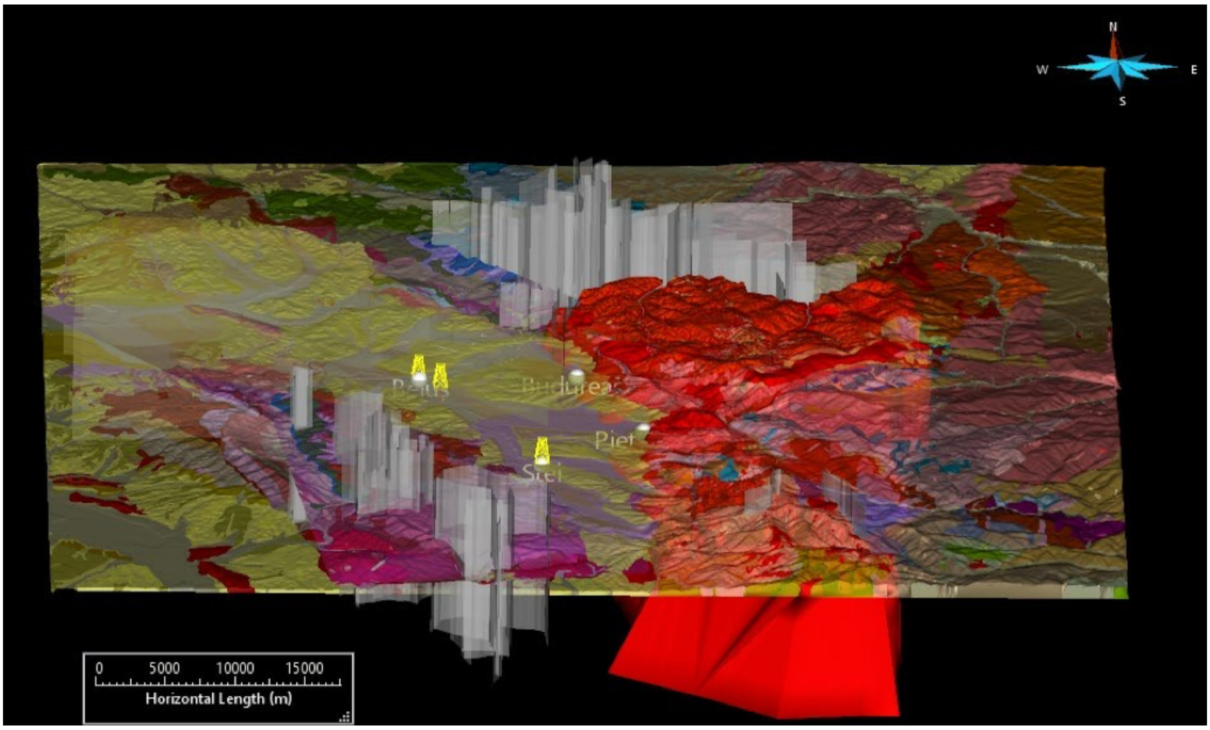

Figure 16: 3D model of the study area Beius Basin Bihor Mountains

At the same time, the 3D model helps us to reduce the original area for new future investigations to a smaller area with an increased probability that it is suitable for a CHPM system.

Exploration plan for the technological components

In Romania the research related to a potential EGS – metal enrichment pilot site started with the implementation of CHPM2030 project. It is for the first time in Romania, when an analysis having in view the basic criteria of an EGS was initiated. At this stage only the available data regarding the region have been inventoried, and, based on the processing of these data the potential pilot site has been delineated. The existing data corroborated with the basic criteria that an EGS pilot area has to meet encourage further research in the area Beiuș Basin - Bihor Mountains.

In order to achieve an Enhanced Geothermal System (EGS) reservoir creation and a plant in operation, roadmap can be configured in several stages, each stage comprising several phases. These phases have been described by the report 'Best practices guide for geothermal exploration'[9] elaborated by International Geothermal Association, in 2014. In order to plan the roadmap 2030 in Romania, the revision of these phases is necessary.

Besides the methodology recommended for an EGS project, CHPM technology, which combines metal extraction from the geothermal reservoir together with electricity has distinct features, and new directions of research must be added to the already mentioned ones. Within the CHPM2030 Project, some of these directions have been described and experimented.

They can be divided into two groups:

- Research regarding development of technologies that are used in designing the whole potential CHPM project. These activities need to have specific inputs from the pilot sites, e.g. composition and temperature of the brines, type of mineralization of the rocks, etc.
- Research regarding the potential pilot sites mainly regarding the potential of certain areas to become pilot sites, considering the existence of geothermal potential, mineralization enrichments of the reservoir rock, etc.

Based on the description above, the research on Beiuș Basin - Bihor Mountains' site can be considered as almost completing the Phase 1 - preliminary surveys. The conclusions of this phase are summarized in the first chapter of this report.

After this a plan for exploration must be designed. This plan has to include both research directions afferent to an EGS project and directions afferent to a CHPM project.

In the short term, for the continuation of the research, the Geological Institute of Romania has determined as priority activities acquiring new data, modelling and interpretation them in a new key. Some field activities are to be mentioned:

- Refraction seismic surveys (2D and 3D)

9 https://www.ifc.org/wps/wcm/connect/dfad690046dcd2ac8f7eef57143498e5/Geothermal+Exploration+Best+Practices-2nd+Edition-FINAL.pdf?MOD=AJPERES

- Electrical resistivity survey
- Magnetotelluric survey - during an MT survey, several different electric-magnetic component field strength ratios can be calculated as a starting point for processing and interpreting
- Fracture network modeling for understanding reservoir characteristics

Performing of these activities will be possible only in cooperation with other research institutes from Romania and abroad, and also with oil companies that already have the necessary data, or equipment.

Cooperation with the partners from CHPM2030 project can lead to a substantial improvement in the level of knowledge of the study area. Some activities that are described in Deliverable D2.1 Recommendations for integrated reservoir management, can be developed for the Romanian study site.

At the same time the roadmap of research for the study site of Romania has to take into consideration the recommendations resulted from the implementation of the project. The priority research activities, with direct applicability for this pilot site, which have to be included into a short-term plan are modelling activities:

- Numerical modelling at geological scale (geological, mass, heat flow, fracture network);
- Creation and stimulation of fractures in different types of rocks belonging to the pilot site;
- Modelling of deep metal content and distribution at depth, experiments on core samples;
- Fluid composition at depth – more experiments with already identified agents;
- Studies on permeability at depth;
- Establish a mathematical model of the pilot site that includes the components of the system and its specific parameters;
- Develop a geochemical model of the pilot site;

Furthermore, in order to be successful in the follow-up project, there are four key elements:

- availability of sufficiently accurate geothermal resource data and other relevant information;
- effective and dedicated institutions;
- supportive policies and regulations; and
- access to suitable financing for the project developer.

Funding opportunities

In Romania the first results are promising, that is why in order to prepare a pilot for applying this technology new steps have to be taken. For this there are sources of funding at national and international level. At national level EU and national funds are grouped in Romanian research programmes whose management authority is Research and Innovation Ministry. Consortiums will be formed at national and international level in order to get funding for new projects.

Stakeholder engagement

Currently two production and one injection wells are used in Beiuș Basin for the exploitation of the geothermal aquifer. In 2018, a partnership formed by the City Hall and private company submitted project proposals in order to get EU funding for the extension of the GDHS. They also showed their interested for the results of CHPM2030 project and expressed their will to be part of a consortium that could consider a CHPM installation in Beiuș in the future.

Also in April 2019, SC Transgex SA announced the public about the Environmental Impact Assessment (EIA) revision in Beiuș determined by the project 'Increasing the production of geothermal water in Beiuş by drilling a production well and interconnecting it to the geothermal water transport network N. Cristescu street intersection St. Gen. L.Mociulski' which is located in Beiuș city. Given the close cooperation with this company, we hope to get rock samples and other information belonging to this new well.

Beiuş town, with 12,000 inhabitants, is one of the few cities in Europe that are heated entirely with geothermal water. This type of energy proved to be cheaper than the conventional one that is why these inhabitants are more open to discussions regarding adoption of new technologies in their region.

A new potential CHPM plant that could be located at Budureasa, would be able to provide geothermal energy for the neighboring villages, or electricity to the national grid. There are clear laws that allow and encourage the production of electricity from renewables. Among other incentives there are the Green Certificates. The Law 220/2008 stipulates the inclusion in the consumer's invoices the payments for green certificates.

The Beiuș city council has contracted SC Transgex S.A., which holds the local geothermal utilisation licence, to operate and expand the GeoDH system. The tariffs for the delivery of central geothermal district heating in Beius are regulated by the state authorities reflecting the real cost of its operation. The way to evaluate the economic advantages of the GeoDH operation is to look at it from the consumer perspective and compare it with the cost and user friendliness of other heating alternatives, being mainly wood burning in Beius. The geothermal energy is delivered and consequently charged in two different ways at the Beius consumers. Those who receive the heat from a secondary distribution loop from a substation are charged per used energy, which is measured in Gcal.

Those who receive the heat directly from the GeoDH system are charged per used amount of geothermal water measured in m^3. The existing two production wells, 3001 and 3002, have different water temperature, hence two different prices/m^3, depending on from where the geothermal water comes. Selling prices for the GeoDH system are regulated by the state organization, National Authority of Regulatory for Community Services (NARCS), according to the Romanian law no. 325/2006.

For new investments the best solution is to use EU funding for different stages of project development that follow. The potential investors that expressed their intent to be partners in such projects are:

- Local public authority – City hall of Beiuș
- Transgex S.A.
- Geological Institute of Romania

Multidisciplinary studies must be done in order to prevent environmental risks such as: water and noise pollution, induced seismicity, land use/subsidence, induced seismicity/landslides, water use, thermal pollution, etc.

Regarding a CHPM system installation, information sessions in order to explain which are the risks for the population are necessary to be organized. The whole range of activities connected to social licence to operate (SLO) have to be provided into a future project.

5.4 The Kristenberg and Nautanen mining areas, Sweden

Authors: Gerhard Schwarz, Benno Kathol, Magnus Ripa, Bo Thunholm, Edward P. Lynch, Johan Jönberger, Geological Survey of Sweden. Reference document: CHPM2030 D6.2.4 Report on pilots: The Kristenberg and Nautanen mining areas in Northern Sweden.

Extended summary of the pilot area report

There are four major ore provinces in Sweden, i.e., Bergslagen, the Skellefte district, the Northern Norrbotten ore province and the Caledonian orogen. In these, we have chosen the areas around the Kristineberg mine in the Skellefte district and the abandoned Nautanen mine in Northern Norrbotten for further screening the applicability of the CHPM technology there.

The Kristineberg area in the southwestern part of the Skellefte district is known for its volcanogenic massive sulphide deposits (VMS). Based on their age and geological history of rock sequences, the bedrock in the Skellefte district and surrounding areas in northern Västerbotten and southern Norrbotten counties can be divided and assigned to three major lithotectonic units. These are the Svecokarelian orogen, the Ediacaran to Cambrian sedimentary cover sequence and the Caledonian orogen. The Skellefte district sensu stricto belongs entirely to the Svecokarelian orogen.

The bedrock in the Skellefte district was formed or reworked by Svecokarelian orogenic processes, which lasted from about 1.96 to 1.75 Ga. This time interval includes subduction-related processes, collision, and extension-related collapse of the thickened crust. The peak of Svecokarelian deformation and metamorphism occurred between 1.85 and 1.80 Ga, but earlier phases of deformation at 1.89 – 1.87 Ga have been reported under the last decade. The Svecokarelian orogen comprises Svecokarelian intrusive rocks, formed by orogenic processes and Svecofennian supracrustal rocks, i.e. early orogenic sedimentary and volcanic rocks, the latter hosting the VMS deposits of the Skellefte district and thus the Kristineberg mine.

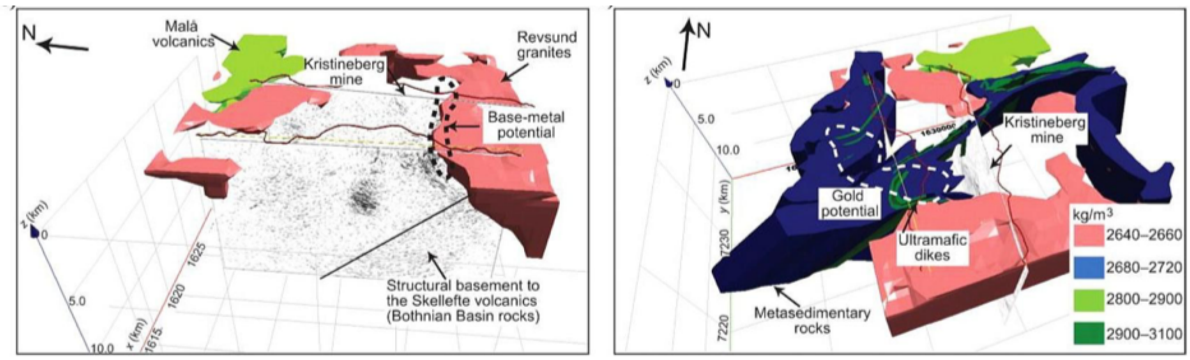

Figure 17 Kristineberg mining area - 3D views showing final geological models of the geological interpretation (after Malehmir et al. 2009) with metal potential from 3D inverse and forward gravity modelling, all data available combined for targeting new prospecting areas. Horizontal to vertical scale 1:1.

The Kristineberg mine (Figure 17) is the oldest and largest massive sulphide mine in the Skellefte district and in continuous operation until today. Mining began in the year 1940 at the ore body outcropping at surface. Since then, production has reached down to around 1 200 m making Kristineberg to one of the deepest mines in Sweden. The ore is a complex massive sulphide with zinc being the main metal, although in some areas copper-gold ores are mined. Until year 2017, 31 million tons have been mined, reserves are 5 million tons and resources about 13 million tons. The combined grades of mined ore, reserves and resources are 3.9 % zinc, 0.7 g/t gold, 44 g/t silver, 0.9 % copper and 0.4 % lead.

The rocks surrounding the Kristineberg deposit have been strongly hydrothermally altered and are multiphase folded and strongly sheared. The schistose rocks are now dominated by quartz–muscovite–chlorite–pyrite in varying proportions, and exhibit marked sodium depletion and co-enrichment of magnesium and potassium. Cordierite, phlogopite and andalusite occur in considerable amounts. Kyanite has rarely been observed, mainly associated with quartz veins. In general, the iron–magnesium alteration minerals are magnesium-rich, and the modal chlorite content increases towards the Kristineberg ore horizon, which is surrounded by a halo of more muscovite-rich rocks.

Geological mapping in Sweden is supported by airborne geophysics, motivated by the low degree of bedrock exposures. Magnetic properties, electrical resistivity and gamma radiation of shallow crustal rocks were thus studied in the Skellefte district and the Nautanen area, completed by ground surveys on these rock properties and on gravity.

During the last two decades, reflection seismic investigations were introduced in Sweden in larger extent by academia in cooperation with the mining industry for prospecting after minerals and ores in the Earth's uppermost crust. The Kristineberg area in the western Skellefte district was studied at depth down to 12 km by seismic methods, complimented by drillhole data down to ca 1400 m below surface. High resolution reflection seismic data provided detailed images of an VMS ore body and associated structures. However, the seismic experiments have also shown that considerable efforts need to be undertaken in geologically complex areas to properly acquire data, i.e., preferably by 3D instead of 2D surveys.

The Nautanen deposit (Figure 18) is situated in the Northern Norrbotten ore province in northernmost Sweden. At this historical mining location, intermittent exploration has been carried out for over 100 years. Approximately 72 000 tonnes of copper and iron ore were extracted between 1902 and 1907. Further exploration in the 1970s and 80s produced a pre-regulatory total resource estimate for the "old" Nautanen deposit of approximately 2.94 Mt grading 0.78% Cu and 0.52 ppm Au. Present-day exploration by Boliden Mines AB has resulted in the discovery of an additional copper-gold mineralisation approximately 1.6 km north-northwest of the old Nautanen mine along the trend of the Nautanen deformation zone (NDZ). This "Nautanen North" deposit has an indicated resource of 9.6 Mt grading 1.7% Cu, 0.8 ppm Au, 5.5 ppm Ag and 73 ppm Mo, with an additional inferred resource of 6.4 Mt grading 1.0% Cu, 0.4 ppm Au, 4.6 ppm Ag and 41 ppm Mo.

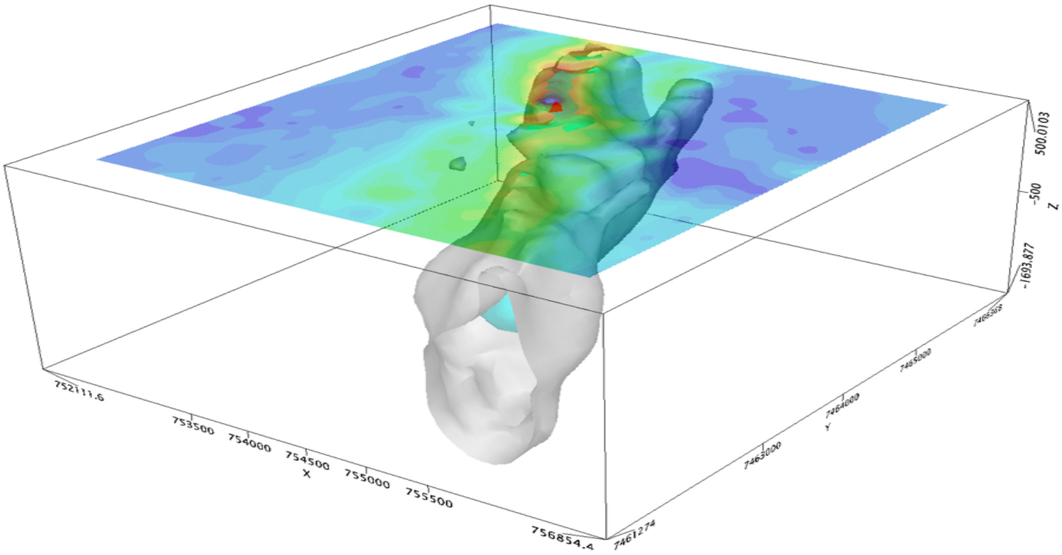

Figure 18 Three-dimensional magnetic susceptibility model for the Nautanen deformation zone. Two isosurfaces coloured in cyan and grey are shown (no scale). Total magnetic anomaly field is indicated at the surface (no scale). View from southeast to northwest. XY-coordinates refer to SWEREF 99 TM, Z is height a.s.l., all in metres.

The bedrock in Northern Norrbotten is part of the 2.0–1.8 Ga old Svecokarelian orogen. The orogen comprises both pre-orogenic rocks formed in the Archaean and early Palaeoproterozoic, as well as rocks formed during the orogeny itself. The bedrock in the Nautanen area consists of a partly conformable succession of syn-orogenic, Palaeoproterozoic volcano-sedimentary rocks. This supracrustal sequence is generally of calc-alkaline, basaltic andesite to andesite composition and has undergone extensive deformation, metamorphism, recrystallisation and hydrothermal alteration. Intrusive rocks, including deformed gabbroic, syenitic and dioritic bodies and younger, deformed to massive granitic and gabbroic-doleritic plutons and dykes, occur in the area.

The mineralisations at Nautanen are part of several hydrothermal copper-gold occurrences assigned to the iron oxide-copper-gold (IOCG) mineral deposit class which occur within the regional approximately north-northwest-trending Nautanen deformation zone (NDZ). The NDZ represents the most conspicuous structural feature in the area and is clearly delineated on magnetic anomaly maps as a somewhat dilational, linear zone of sub-parallel and tightly banded magnetic susceptibility anomalies. The coupling of high-strain deformation and magnetic banding reflects episodic metasomatic-hydrothermal fluid flow, probably enhanced by increased permeability associated with protracted and focused deformation. Two general styles of mineralisation are recognised in the area: (1) an inferred older phase of disseminated to semi-massive (replacement-style) sulphide mineralisation forming sub-vertical lenses and linear zones mainly within the NDZ; and (2) mineralisation associated with quartz ± tourmaline ± amphibole veins occurring mainly east of the NDZ or as a late-stage brittle overprint within the high-strain zone.

Geophysical surveys, mostly using potential field and electrical methods in the Nautanen area were concentrated on the shallow sub-surface down to some hundred metres depth, being of economic interest. No investigations are known in the surroundings of Nautanen that are covering deeper seated structures and formations.

Our understanding of deep-seated fluids in the crystalline bedrock is still rudimentary. Hydraulic conductivity decreases with depth at a high degree of variability. Investigations in boreholes indicate that hydraulic conductivity below 650 m depth varies between 10-7 and 10-12 m/s. Data on the composition of fluids indicate that brines (> 5 % TDS/l) occur far inland at several 1000 metres depth. Their residence time was estimated at the order of some hundred millions of years by the analysis of He-isotopes. Corrected geothermal heat flow density is about 50 mW/m^2. Data on heat production do not show large differences between rock types related to their content in radioactive elements.

The generally low geothermal gradient of less than 20 $^oC/km$ in the crystalline basement of the Fennoscandian Shield was verified by sensing temperature in deep boreholes in the Skellefte district and adjacent to the Nautanen mine. The temperature gradient measured here to about 16 $^oC/km$ should allow for low- to mid-enthalpy geothermal systems as part of a possible CHPM unit.

The study presented here, also shows that it is highly challenging for the development of the CHPM technology to improve drilling techniques, to lower their operational costs, and to further develop hydraulic stimulation of the bedrock at larger depths. Research on these topics presented recently, give hope that the technical progress and further aspects tackled to install EGS at larger depth are on-track.

Pilot area recommendations for the technological components, Funding opportunities and stakeholder engagement.

For the two mining areas in Sweden, presented here, there is a considerable need in developing the technology to install low- to mid-enthalpy EGS. This makes it difficult to set up a practical timetable in this matter.

Exploration plan for the technological components

Technical improvements that must be overcome:

- How to identify metal bearing formations at larger crustal depths, i.e., at about 7000 m or below, where temperatures are more than 120 oC,
- Developing further integrated geophysical studies, e.g., providing seismic velocities and electrical resistivity. Integrate data into 3D/4D model to help the deeper extrapolation, and for better conceptual understanding,
- Making drilling cheaper and faster, introducing new techniques (e.g., BINE 2015, Lehr et al. 2017),
- Handle the pressure regime (at wellhead) that is lithostatic, i.e., about 2 kbar (e.g., Zhuang et al. 2019),
- Pressure-controlled stimulation of the crystalline bedrock to increase hydraulic conductivity by orders of magnitude (e.g., Zang et al. 2019, Zimmermann et al. 2019),
- Increasing volumes of rock involved, i.e., having an almost stable production of heat for at least 30 years (e.g., Sullivan et al. 2010),
- Develop waste water management,
- Explore for fresh water, alternatively for water of very low salinity (needed for salt gradient power generation).

Funding opportunities

With present technology, at temperatures of about 120 oC the energy output of an EGS must be considered as being thermal heat only.

Possible customers interested in heat supply:

- Battery production (e.g., Northvolt company)
- Pulp and paper industry
- Greenhouse gardeners (to be developed)
- Residential heating (though critical because of small communities and very outspread settings in northern Sweden, only)

Stakeholder engagement

Societal and political background

Information campaign for local inhabitants to accept an CHPM system.

Potential stakeholders:

- Mining industry
- Northvolt (company)
- Paper mills
- Norrbotten county
- Towns of Skellefteå and Gällivare-Malmberget
- EU regional development funds

6. Overall CHPM concept 2030-2050

6.1 Exploration

Exploration workflow for CHPM will need to integrate traits from both geothermal and mineral exploration themes. The main topics discussed at the Visioning and Roadmapping workshops, are geophysics, data processing (AI, ML) and drilling depths. With geophysics, the first, and cost effective, approach is to identify and use existing datasets from the hydrocarbon, geothermal and mineral industries. Increased resolution (e.g. magnetotellurics) and cost reduction (e.g. drilling) are highly desirable with future exploration. When it comes to advanced data processing techniques, the objective is to develop, or adopt existing ones, and train machine learning (ML) algorithms for EGS/CHPM datasets. Guidelines for reinterpretation and re-evaluation datasets for CHPM potential and generating classes/models for CHPM exploration targeting are both assets for increasing certainty about CHPM compatible deep metal enriched fractured systems. As a result, it is envisioned to reach a good understanding of mineral provinces with potential deep continuity, reduced data acquisition costs for CHPM, successfully application of AI/machine learning algorithms for (re)interpretation of datasets. The full list of Targets and Actions are outlined in the Table 2 below.

Table 2: Actions and Targets related to future CHPM Exploration

Actions	Targets
Geophysics • Cost-effective approach for identifying available relevant datasets from hydrocarbon, geothermal and mineral sectors (Netherlands, UK, Ruhr and Strasbourg areas, Rhine Graben) advancing pilots for training and developing advanced data processing tools (ML/AI) as well as establishing guidelines for reinterpreting and re-evaluate datasets for CHPM potential in synergy with operational aspects (mineralization suitability x leaching agents), for methods selection - geophysics, magnetotellurics, drilling etc.. • Generating classes/models for CHPM exploration targeting • Recommend funding priorities for advancing innovative approaches for Geophysical in an EGS, CHPM setting • Develop joint initiatives for further exploring existing brownfield areas for heat and metals • Generate classes/models for targeting exploration for CHPM • Establish guidelines for selection of geophysical methods	• Reduced data acquisition costs for CHPM 2030 • Increased ‘readiness levels’ of CHPM exploration packages (as a result of the actions) 2030
Data processing • Develop a detailed "CHPM" map of Europe - mineral + heat + power resources	• Successfully apply AI/machine learning

• Develop and train machine learning algorithms for EGS/CHPM datasets	algorithms for (re)interpretation of datasets 2040
<u>Drilling depths</u> • Recommend funding priorities for advancing innovative approaches for drilling in an EGS, CHPM setting • Develop a standard for CHPM drilling - in conjunction with established geothermal initiatives aiming at full geomechanical characterization	• Establish a full geomechanical characterization of sites 2050

The main actors in this field are existing operators, research institutions and relevant data centres. Bottleneck may be mineral rights, cost of exploration and greenfield exploration risk. The one wild card identified here is that drilling risk may not be the main cost and risk any more, but something else, unexpected emerges. Cooperation with the hydrocarbon industry, emergence of investigative methods and new geological theories, are all listed as signposts (Table 3).

Table 3: Actors, bottlenecks, wildcards and signposts in the Exploration theme

Actors	**Bottlenecks**
- Existing operators - S&I initiatives - Research institutions - Relevant data centres	- Mineral Rights - Lack of data availability - Cost of new data acquisition - Available technology for deep exploration - Greenfield exploration risk levels
Wild Cards	**Signposts**
- Drilling is not the main cost, risk anymore	- Cooperation with oil and gas sector (knowledge, data, know-how sharing, technological spillover) - Cost of drilling operation - Increased availability of deep geology datasets - Emergence of new investigative methods and techniques - Emergence of new geological theories on bedrock developments in deep structural domains - Rate of drilling depths

6.2 Development

The main topics discussed during the Visioning and Roadmapping workshops, related to CHPM development are reservoir stimulation, information platform, public acceptance. Under reservoir stimulation the three main objectives were to create a novel reservoir stimulation technique, coming from CHPM concept, that can be used for mobilising metals, improving reservoir performance, and reducing seismic risk. In order to achieve these objectives, test site(s) has(have) to be identified to further develop a soft leaching technology, test already identified leaching agents and new ones, and ultimately create a proof of concept at a real site.

In order to get operators on board, CHPM could offer free fluid lab test and (pre)feasibility study for pros and cons. Once there is a number of pilot projects, portfolio can be established, showcasing the various advantages of the technology (financial/technical) at real geothermal projects. This could be critical to get major investors into the technology. It has been identified that a comprehensive information platform needs to be set up, in order to share geoscientific information and best practises, monitor ongoing projects, and to create a platform for networking and matchmaking for potential CHPM partners. Alternative business cases has been pointed out, such as health, tourism, spa, manufacturing, where CHPM could act as a catalyst to create value for the local community.

By 2025, the individual components could be tested at real geothermal projects, in 2030 value creating can be achieved for the local community and by 2040 it is envisioned to reach near closed loop system, without any emission. The full list of identified Targets and Actions are outlined in the Table 4.

Table 4: Actions and Targets related to future CHPM Development

Actions	Targets
<u>Reservoir stimulation</u> *Performance and results* • Adopt leaching techniques that mobilise metals and create better reservoir performance (increases the permeability)	*Performance and results* • 2025 Safe stimulation, reduced seismicity, lower risks • 2025 successful SLO of stimulation

• Development of safe stimulation technique: soft stimulation, leaching over a long period of time, lowering the risk of seismic event. • Apply mild leaching at test site with low reservoir performance (e.g. Balmat site), measure added benefits, and monitor results. If successful, use it as a case study to attract investors. *Market penetration* • Offer free fluid lab testing on running/developing geothermal project, 1-5 litre sample, free analysis, provide a pro-contra pre-feasibility assessment report for them • Offer to remove toxic elements, e.g. mercury, arsenic. Develop extraction of specific harmful/valuable elements, that can save money or add value • Provide information on environmental, operational, financial, technical benefits to operators to get them on board.	with safe demonstration examples • 2030 mobilise target metals • 2040 enhanced reservoir performance: better flow rate, better energy output, • 2040 better rate of success for reservoir stimulation than using conventional techniques *Market penetration* • 2025 components are tested at different geothermal projects • 2030 Operators are aware and adopting CHPM technology • 2025-2030 Successful demonstration projects.
<u>Information Platform</u> *Sharing, adopting and integrating results* • Map other projects feeding into CHPM objectives (awareness on running projects providing data and advancements), and build on their results (e.g. EGS projects, US Forge, Cornwall, Helsinki, etc.), for reservoir stimulation, drilling, monitoring. • Capture, absorb, inherit results from parallel project and incorporate for CHPM applications as they become available. • Create a timeline what relevant projects are going on, when results will be available and what added value can CHPM make use of. • Create a share platform for geothermal/mineral geo-information (data, knowledge, measurements, research, knowhow, intelligence) • Adopt best practises from oil and gas industry on water treatment for not blocking the injection wells. • Use ongoing project to borrow, adopt and	 *Sharing, adopting and integrating results* • 2025 geothermal/mineral project results are easily available and ready to be re-used/applied at new CHPM application • 2025 the outputs of parallel projects are integrated into the CHPM/geothermal knowledge base. • 2025 The CHPM vision and implementation is compatible with ETIP-DG and other EU visions

update the CHPM targets and actions, e.g. ETIP-DG (strategic research agenda, vision, and roadmap), SET Plan, SIP raw materials. *Mapping alternative business opportunities and outreach* • Map what industries can develop from CHPM application and promote CHPM with the potential to these new industries and value chains (tourism, spa, bath, health, biotechnology, tourism, algae, manufacturing industry) • Develop alternative business cases, based on new opportunities. • Actively reach out for potential sites, developing/online geothermal projects and inform operators about potential benefits: prepare free feasibility study • Create a CHPM portfolio to showcase (individual components of) the technology and its applications. *Policy recommendation* • Implement regulations on the compulsory publication of (part of) the dataset produced in research/commercial projects. • Implement regulations to monitor and map job creation along the CHPM value chain and related industries. *Features* • create a networking environment for CHPM stakeholder • harmonization and compatibility: make use of EIT, IGA, GRC, ERA-NET platforms for harmonization and outreach.	*Mapping alternative business opportunities and outreach* • 2030 value creation in local community: spas, truism, baths, algae, new industries that can develop/benefit from CHPM • 2025 operators are well informed and aware of the potential for CHPM • 2030 case studies and success stories of CHPM are available to showcase for public, investors, policy makers *Policy recommendation* • 2025 relevant geoscientific data is available that supports the selection and planning of new CHPM sites, to attract investors and to generate interest • 2025 statistics about CHPM activities' impact on the labour market is available. *Features* • 2025 platform for both geothermal and mineral intelligence: sharing knowledge, data, research, best practises, know how • 2025 networking, technology transfer • CHPM knowledgebase: 2030 EU then 2050 global coverage
<u>Social Licence to Operate</u> *Successful SLO* • Adopt and apply SLO studies for CHPM • Provide a full information package to the public, make all information available during development, operation, monitoring.	*Successful SLO* • 2025 SLO studies successfully adopted for CHPM projects • 2025 effective communication, involvement and awareness raising

Transparency. • Make geothermal visible to people, outreach, how it works, reachable, understandable. • Give back the benefits: 1. CHPM can offer cheap stable heat and electricity supply, employment opportunities (especially at start-up), socio-environmental monitoring (seismicity, social community, tourism, economics) system in place. 2. Create local not doing anything scenario: alternatives for heat, power, metals. Where would these come from?	towards local communities for geothermal solution, including CHPM • 2030 public understands and supports geothermal/CHPM energy. Good knowledge on geothermal CHPM in the public. • 2030 safe technology demonstrated to the public
Social engagement • Make public proud that they part of the renewable energy transition, so they'll be more likely to accept the risk. Public sensitisation. • Continuous engagement and involvement (e.g. in New Zealand, Philippines: compulsory social involvement is included in the regulations, they need to be involved from the beginning.	*Social engagement* • 2040 local people are proud that the local uses geothermal energy and be part of the energy transition (e.g. Blue Laguna)
Environment • Reinjection: no waste disposal, closed loop, environmental regulation, brine treatment. • Cleaning process: remove some elements from the geothermal brine.	*Environment* • 2040 CHPM is using near closed loop system, no emission, no contamination

The key actors are going to the geothermal operators and investors. If they are willing to test and invest in CHPM technology, the research community will have the resources to upscale their component from lab-scale. However, public funding is still going to be critical for the early stage of CHPM development. The main bottlenecks may be NIMBY (Not In My Back Yard) attitude, data confidentiality, injection induced seismicity. Wild Cards could be catastrophic seismic event, or the ban on reservoir stimulation. Signpost, to continuously consider, are environmental regulations and political/public support for CHPM. The full list of identified issues are presented in Table 5.

Table 5: Actors, bottlenecks, wildcards and signposts in the Development theme

Actors - geothermal operators, investors, geothermal/mineral community, ORCA, - (public) funding agencies, policy makers, investors, local community, - policy makers, local community, research community	**Bottlenecks** - usually there are problems with injection and reservoir performance, SLO, seismicity, - Data confidentiality, - NIMBY, first application before many examples
Wild Cards - catastrophic seismic event caused by geothermal reservoir stimulation, all similar processes banned - EU prohibit EGS reservoir stimulation! --» CHPM offer a better, safer solution for stimulation, reservoir enhancement, leaching	**Signposts** - political/public support for geothermal - NIMBY mentality: is it going to be typical or will not be a trend - change in regulation/law for environmental protection (stimulation, leaching)

6.3 Operation

When it comes to Operation of a CHPM system, the key topics discussed during the Visioning and Roadmapping workshops, are metal mobilization, geochemical modeling, metal recovery. Under metal mobilization, the first CHPM projects could work on “take what you get” approach, recovering already solved metals. The additional leaching component can be added later with the 2nd generation of agents by 2030. Parallel to this, R&D is required to balance the rate of solution and precipitation. Therefore, already identified leaching agents are to be tested at well-known test sites (e.g. between mine tunnels), in order to develop the next generation of leaching agent: particles that can change the physical properties as they interact with the metals (nanoparticles).

Geochemical modelling is envisioned to be used for economic and business forecasts to show financial and technological benefits for investors by 2025. It is recommended to validate existing EGS models and integrate ore deposits modelling with the addition of fracture flow, action kinetics, permeability.

Metal recovery is expected to achieve a broad selectivity, for metal groups, and focus on separation techniques, once the metals are removed from the brine. Recovering non-metallic elements (Si), contaminated site remediation, water treatment, fluid treatment in flash steam system, abandoned mines, are also potential use cases for the CHPM metal recovery technologies. An alternative metal recovery technique may be the use of microbe for capturing metals (biomass concentrate) and roast the biomass to recover metals. 2040 metal recovery plug in ready. The full list of identified Targets and Actions are outlined in the Table 6 below.

Table 6: Actions and Targets related to future CHPM Operation

Actions	Targets
<u>Metal mobilization</u> *Leaching* • Develop new, non-acid based leaching agents • R&D in leaching agents that can mobilise and keep metals in solution, nanoparticles, physical sorbents • Screening Europe for relevant sites for pilots testing • Next generation of leaching agent: particles that can change the physical properties as they interact with the metals (nanoparticles)	*Leaching* • 2030 successful small-scale testing of the teaching component at a relevant site (e.g. in between mine tunnels in Neves Corvo) • 2030 affordable cost of the added complexity and risk. Technology pays for itself • 2030 new chemical agents available for mobilization, solution, nanoparticles, physical sorbents • 2040 ability to site tailor leaching agents • 2050 full scale testing of leaching component
Solution • R&D in balancing the rate of solution and precipitation.	*Solution* • 2030 keeping metals in solution, avoiding precipitation
Selectivity • First work on take what you get approach: precipitate all already solved metals, and separate valuable elements, • If successful, apply for advanced leaching agents for selectivity, depending on target metal, brine composition / concentration.	*Selectivity* • 2030 broader level selectivity for target metal groups and unwanted elements • 2050 element level selectivity, or capacity or separate from the concentrate.
Branding	*Branding*

• Communication to the public: cleaning process, removing elements from the waters, no pollution	• 2030 Public accepts the additional metal mobilization technology
<u>Geochemical modelling</u> *Modelling development* • Validate existing EGS models, combination of modelling ore deposits and EGS system • Integrate mineral component to existing EGS models and add fracture flow, action kinetics, permeability • Advance on basic research on fluid rock interaction • Use a well-defined site and compare calculated data with measurement. Create and run models, conduct real test, measure data, compare. *Modelling applications* • Further develop 3D geological models: a good geological understanding of the mineralization, and integrate it to EGS models. • Monitor seismicity, land movement, processes, operation, microgravity, fluid chemistry, CO2, etc. • Regularly sample surface fluid composition, (chemical, thermal, physical analysis), and feed it back to the models. • Exploration while operation: geophysics, fluid chemistry, chemical parameters. *Market penetration* • Develop models that can calculate reservoir improvements with CHPM add-on. • Use modelling for economic/business forecasts to show economic potential	*Modelling development* • 2025 availability of thermodynamic data sets • 2030 Full EGS + mineral enrichment simulation models • 2030 large test at a well describes site: measure flow, thermal, pressure gradients, solution, precipitation. Compare measurements with modelled results *Modelling applications* • 2030 3D-4D modelling is continuously used during exploration, operation, monitoring *Market penetration* • 2025 Shown/calculate economic potential and technological benefits of CHPM for operators.
<u>Metal recovery technologies</u> *Recovery application* • Recover non-metallic elements, e.g. Silica for health/computer industry.	*Recovery application* • 2025 metal recovery technologies are flexible, it can be tailored to different

• Fluid treatment in flash steam geothermal system is expensive: CHPM can save cost here by removing elements from the brine. • Water treatment: use metal recovery technologies at areas with no running water, e.g. Hungarian great plain, arsenic recovery. • Abandoned mines: use shafts and recover already solved metals in the flooded mine. • Use CHPM recovery to boost local manufacturing industry, with securing local supply to raw materials and metals.	situations and for a variety of application for better market penetration • 2040 metal recovery "plug-in" units can be installed on geothermal EGS projects

The key actors, similar to previous themes, are the technology developers, geothermal operators, and funding agencies. The bottlenecks can be early precipitation in the reservoir, mobilisation of unwanted elements and selectivity. Sign posts, to be regularly considered are environmental regulations, development of leaching agents, cost of corrosion resistant materials. The full list of identified issues are presented in Table 7.

Table 7: Actors, bottlenecks, wildcards and signposts in the Operation theme

Actors - technology developers - funding agencies - research groups - geothermal operators	**Bottlenecks** - NIMBY mentality, - early precipitation, - mobilization of unwanted elements, - selectivity
Wild Cards - metals solved in the reservoir only available for 2-3 years of production: reservoir will be "cleaned" after early production. Faster geochemical change than thermal change.	**Signposts** - environmental regulations and trends, for reinjection, maybe only clean water is accepted - level of metal selectivity - development of special leaching agents - state of nanoparticles and their applicability to mobilise metals - cost of corrosion resistant materials - Availability of high-temperature chemical thermodynamic data sets - complete basic research on fluid

	rock interaction - ability to acquire real input data for the modeling

6.4 Market

Market theme is aiming towards the realisation actual pilots and full-scale commercial application. There will require the investigation of market penetration, investors and revenue streams. First, strategic partnership needs to be established geothermal players, it is crucial to get industrial partners, operators on board. Developing CHPM research projects could offer (free) analysis for geothermal projects, sampling brines for existing operations, allowing for establishing cooperation and then modules of CHPM to be tested in real conditions. The minerals/metals recovery component could use a modular/flexible approach, as an "on/off" basis, allowing for more site to be integrated and adopted for the site conditions. Up-and-running project can be targeted first, with already dissolve metal content in the geothermal brine, where CHPM can develop a "plug-in" module for mineral extraction. Advance a framework for classifying geothermal+mineral resources have to be developed, through dialogues with UNFC. Government incentives (e.g. tax related) as joint partnerships (PPPs) can also foster CHPM development. Branding & Stakeholder engagement are also important aspects: CHPM as a low impact, low carbon, clean technology for producing heat, electricity and metals. This message needs to be communicated to raise public awareness, get new funding, and testing technological components at different sites. As a result, it is intended to establish a network of stakeholders (industry associations, academia, manufacturers, government bodies and research institutions), by 2025 and to have at least one full business case developed for both energy and mining sector by 2030. The full list of Targets and Actions are outlined in the Table 8 below.

Table 8: Actions and Targets related to future CHPM Market

Actions	Targets
<u>Investors</u> • Branding & Stakeholder engagement: CHPM as a low impact, low carbon, clean	• 2030 Proven case of project value enhancement through at least one CHPM

technology for producing heat, electricity and metals, Raising awareness, new funding, testing and technological development ideas • Advance a framework for classifying geothermal + mineral resources - start dialogues with UNFC	module. • 2030 Have at least one full business case developed for both energy and mining sectors. • 2030 Established regulatory framework at EU level for fully-fledged CHPM projects. • 2050 Established professional competence for CHPM projects. • 2050 Full characterisation of potential risks – production rate uncertainties, environmental and radioactivity.
Revenue streams • Identification, mapping and evaluation of the addressable CHPM market - customers, product forms, value chain, special applications e.g. low-volume, smart, added-value products (catalysts, batteries, medicine, cosmetic etc.)	• 2025 Scale-up pilot case studies for (critical) metals recovery,
Market penetration • Strategic partnerships with established Geothermal players, offer analyses for projects, sampling brines for existing operations - offer modules of CHPM to be tested individually • Coordination of policy advising for regulating CHPM activity in the EU with special focus to countries with major potential - special attention to mineral rights aspects and advancing appropriate regulatory framework • Geothermal energy targets for 2030 in the EU - advance dialogues with the UNECE	• 2025 Increased awareness levels of Geothermal energy alternatives and CHPM technology with improved public perception, among different stakeholders – industries, civil society, policy-makers etc. • 2025 Established and active network of stakeholders – industry associations, academia, manufacturers, government bodies and research institutions – advancing CHPM potential.

The leading actors are UNECE, UNFC, operators and industrial associations, and research institutions. Mineral rights, reproducibility at scale and reactions of suppliers can be bottlenecks. Possible wildcards are investors mindset about long term sustainable returns, emerging renewable energy floods the grid with cheap electricity. Some of the sign post, to regularly consider, are level of political/public support, and perception of CHPM compared to alternatives (Table 9).

Table 9: Actors, bottlenecks, wildcards and signposts in the Market theme

Actors	Bottlenecks
- UNECE: Help to set targets at EU level for geothermal energy by 2030 - UNFC: Advance a framework for classifying geothermal + mineral resources - Customers: Manufacturers, end-users, location, type of products, profile of consumption for CHPM products - Operators: Existing Geothermal plants (EGS, or non-EGS), mining companies - Research Institutions - Industry Associations: Lobby at EU level specific value chains that can be developed with CHPM solutions	- Combined heat and mineral rights: inexisting regulatory framework - Reproducibility at scale: Extrapolation of rates of metal recovery from pilot to real case - Reaction of suppliers: Highly concentrated raw materials supply can trigger trade disruptions once new sources start to emerge
Wild Cards	**Sign posts**
- Investors completely change their mindset to long-term sustainable returns - Metal recovery levels completely surpass revenues from heat and energy production - New renewable energy source floods the grid with cheap electricity	- Levels of political/public support - Perception of CHPM in comparison with alternatives - operation costs - number of potential CHPM districts - number of metals with commercial potential - concurring techniques

7. Conclusions

CHPM component follow up 2030/2050

The component followup roadmap describes the current state-of-the-art, immediate research plan, midterm (2030) requirements for pilot readiness level, and long term (2050) objectives for the commercial level application, for each technological component: integrated reservoir management, metal content mobilization using mild leaching, and with nanoparticles, metal recovery via gas-diffusion electrocrystallization (GDEx), High-temperature and high-pressure (HTHP) electrolytic metal recovery, salinity-gradient power by reverse electrodialysis (SGP-RE), system integration.

Integrated reservoir management

The creation of an effective fracture network has been demonstrated in lab scale via simulations. The challenge is the reliability of the fracture creation process. The plan for follow-up research (Figure 19), includes the further development of numerical models, stimulation tests are relevant depth, and new materials at well completion, to create a fully controlled fracture system in a deep metal enrichment.

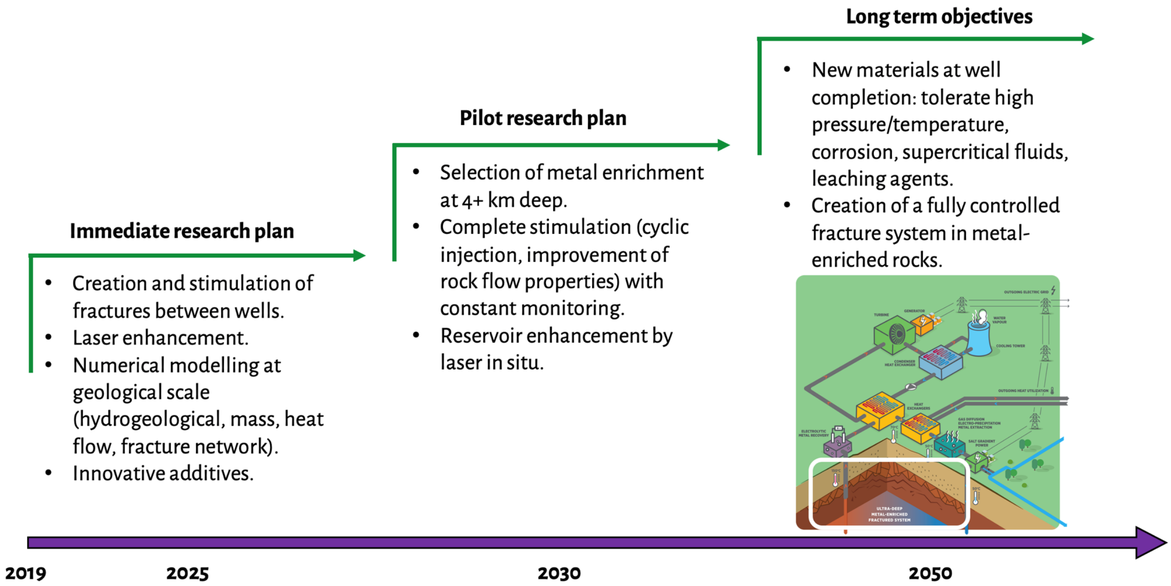

Figure 19: Research plan for CHPM integrated reservoir management

Metal content mobilization using mild leaching

The concept was demonstrated in lab (effective leaching at a range of additives), with promising results on enhancing fluid flow. However, the issue remains with reprecipitation, lack of information on deep waters and metal enrichment. The next steps will require balancing the rate of solution and precipitation, together with improving knowledge on deep (>4km) metal abundance and groundwater chemistry and the development of a regional scale understanding of their parameters (Figure 20).

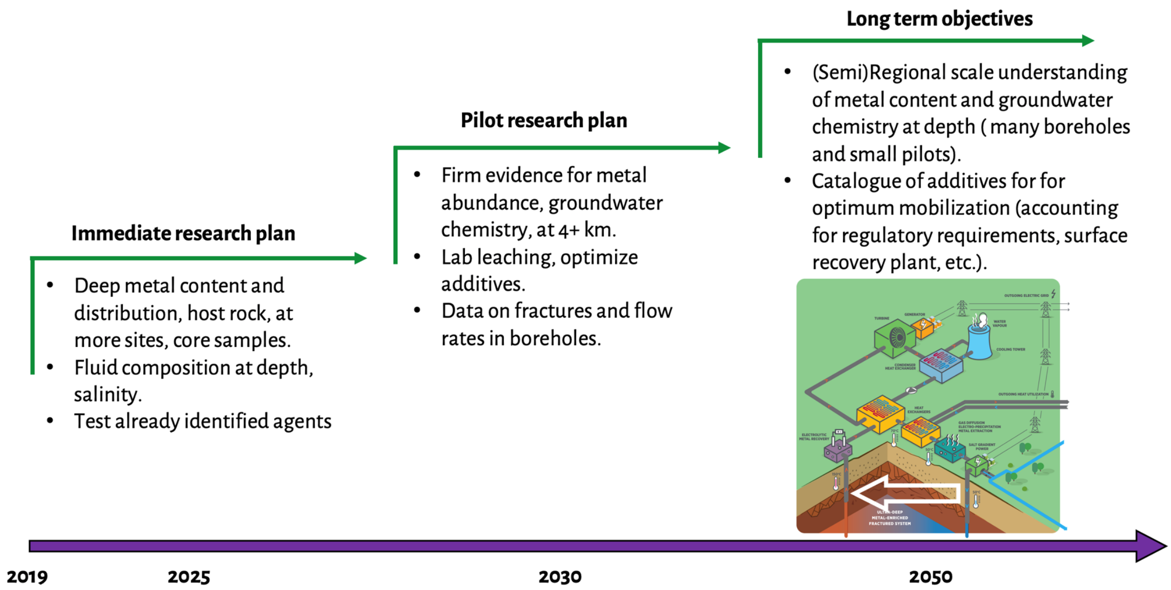

Figure 20: Research plan for CHPM metal content mobilization using mild leaching

<u>Metal content mobilization with nanoparticles</u>

The ability to sorb relevant metals, under relevant conditions has been demonstrated in lab conditions. The main challenges are permeability and recovery of particles. The future research on the topic need to focus on materials development, system integration, selectivity, recovery and regeneration (Figure 21).

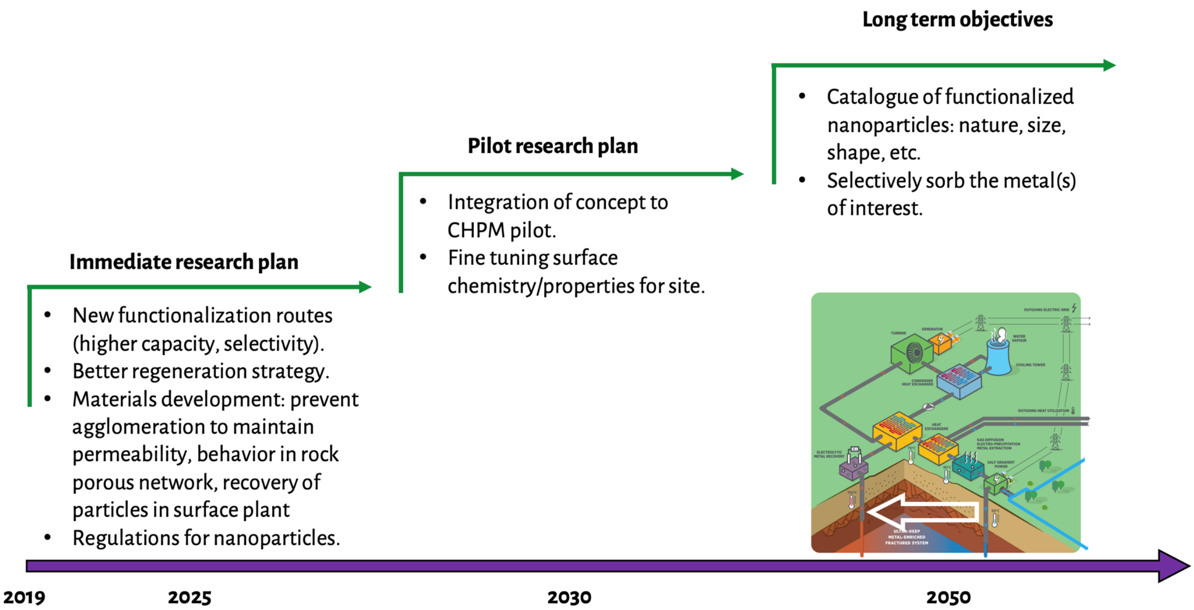

Figure 21: Research plan for CHPM metal content mobilization with nanoparticles

<u>High-temperature and high-pressure (HTHP) electrolytic metal recovery</u>

HT-HP rotating electrode reactor design and material selection has been completed and used for the recovery of metal ions from geothermal brines. The recovery of Cu was studied (temperature, pressure, initial copper concentration, silica content, electrochemical reduction potential, etc. The upcoming research plan includes more tests using real brines, optimization and techno-economic feasibility study, construction of small-scale and then larger pilot reactor following a “plant on a truck” concept (Figure 23).

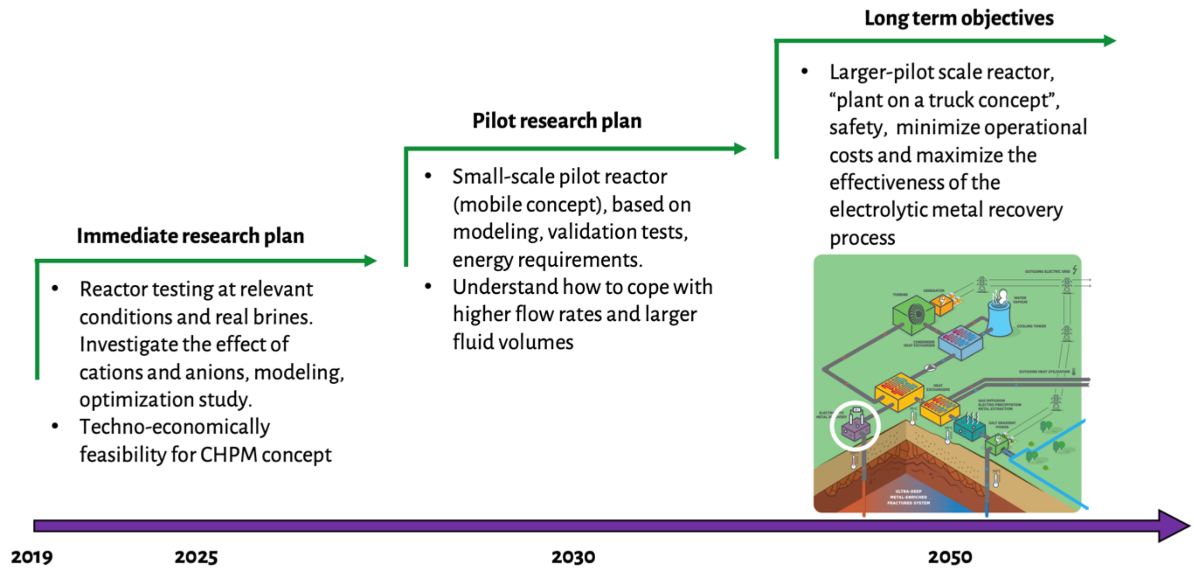

Figure 23: Research plan for CHPM High-temperature and high-pressure electrolytic metal recovery

<u>Metal recovery via gas-diffusion electrocrystallization (GDEx)</u>

During the project, GDEx technology developed from low TRL to granting EU patents, with successful metal recovery process with real brines, at small scale. The next steps will involve techno-economic feasibility and optimization study, sizing and upscaling, minimising operation cost and maximise effectiveness of the metal recovery process (Figure 22).

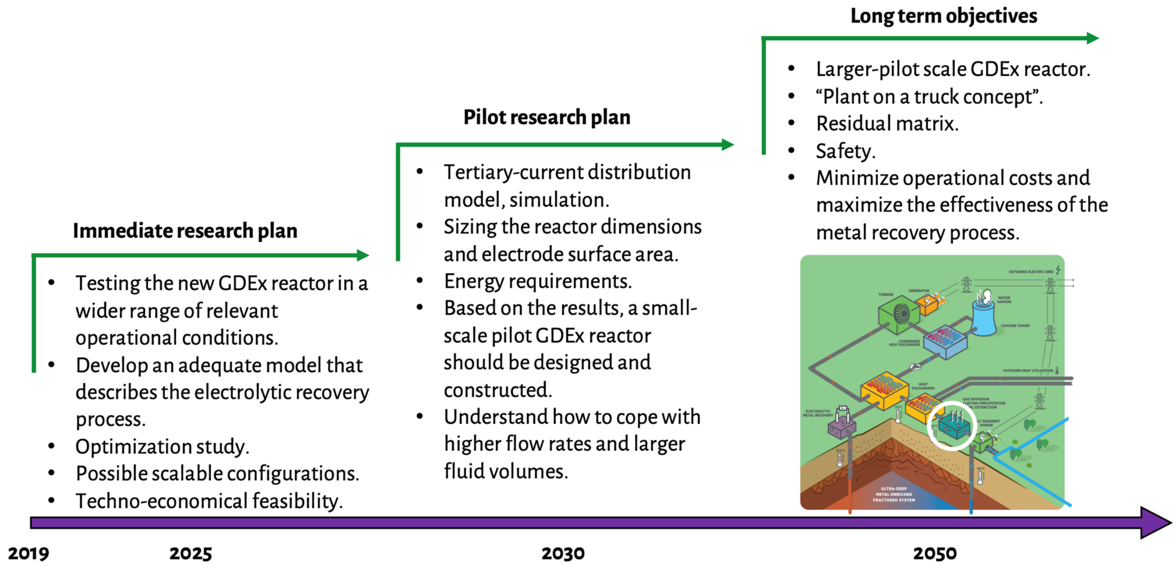

Figure 22: Research plan for CHPM Metal recovery via gas-diffusion electrocrystallization

<u>Salinity-gradient power by reverse electrodialysis (SGP-RE)</u>

SGP-RE showed a good potential for extracting chemical energy through reverse electrodialysis, at high salinity brines at small pilot applications. The next steps are to improve membrane/stack design, construction of a full pilot on test site, and then optimise engineering issues (Figure 24).

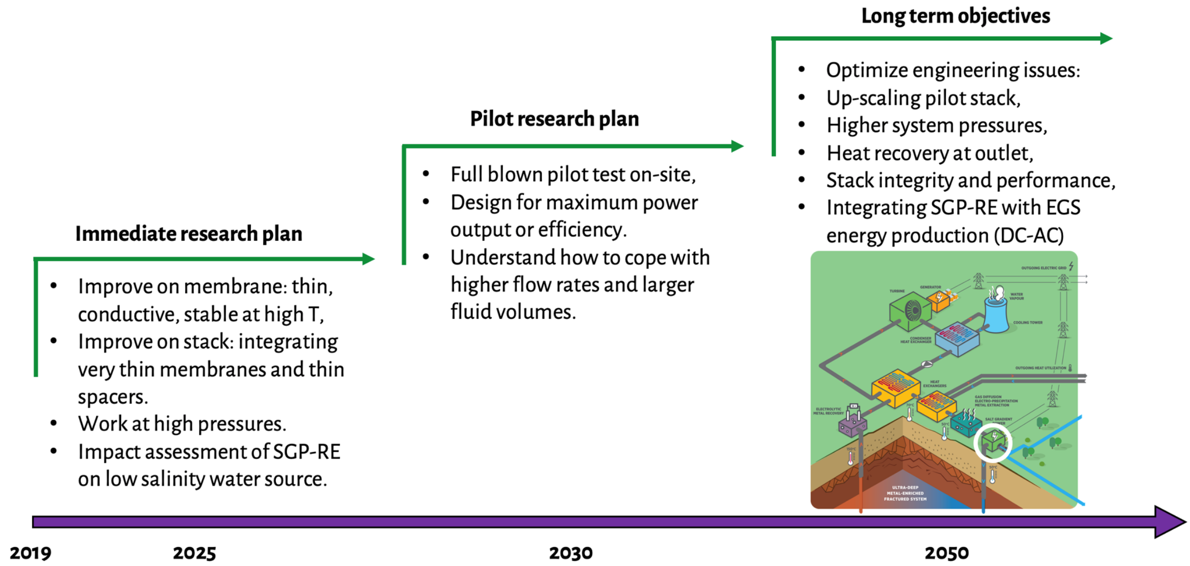

Figure 24: Research plan for CHPM Salinity-gradient power by reverse electrodialysis

System integration

A simplified mathematical models of main component has been delivered, based on expected parameters. Rough description of the physical processes involved has been described and coded. The development shall continue with improving the mathematical description of the components, models for optimisation, to deliver a detailed mathematical model of the integrated CHPM system at large (Figure 25).

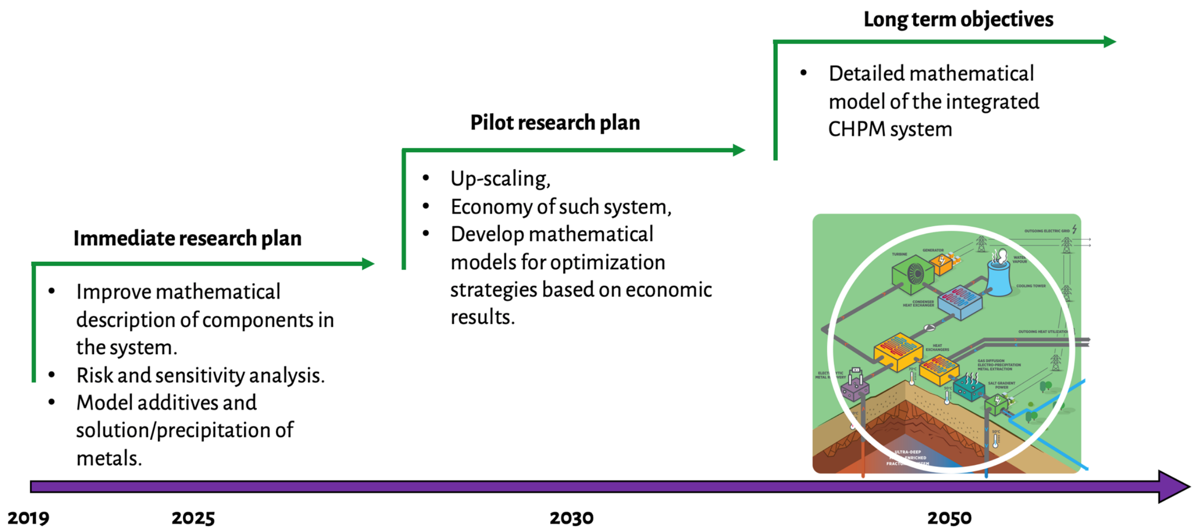

Figure 25: Research plan for CHPM system integration

Pilot area recommendations 2030

Recommendations have been formulated using evaluation templates and study area reports concerning: CHPM geology, geophysics, deep metal enrichment, integrated 3D-4D modeling, EGS geothermal potential, Information on CHPM components, environmental, social, political background, financial aspects. Recommendations include technological components (exploration plan, data), funding opportunities, stakeholder engagement, describing how to arrive to pilot readiness level by 2030.

Cornwall, SW England

SW England, Cornwall is a major magmatic province, characterised high heat production, extensive polymetallic mineralisation (Cornubian Orefield), previous UK HDR project, ongoing

United Downs Deep Geothermal Power project. The Cornwall report[10] on the geological environment, geothermal characteristics, potential for deep metal enrichment, technical, environmental, social and regulatory factors. 3 new models have been developed during the project: Cornubian Batholith (geothermal energy development, fracture mapping), site scale 1 at the HDR project site (fracture data, hydrogeological properties, district fracture network models, potential flow paths) site scale 2 at the NW Carnmenellis granite, UDDGP site. The recommendations cover 1) future exploration plans including 3D seismics, magnetotellurics, deep fluid flow, leaching experiments, mineral filled fractures, etc., 2) funding opportunities, 3) stakeholders' requirements, and 4) overall issues (Figure 26).

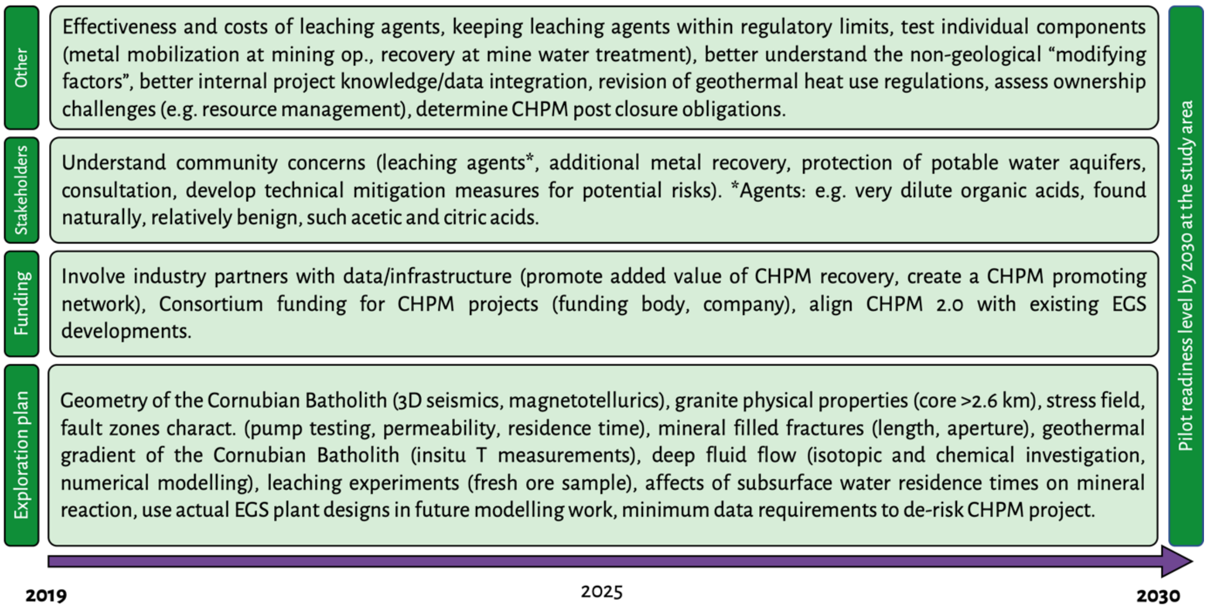

Figure 26: Recommendations for Cornwall study area

Portuguese Iberian Pyrite Belt

The report on the Portuguese Iberian Pyrite belt is part of the Variscan metallogenic province, massive sulphides deposits, prospect for deep mineralization. The study area report[11] provided an update on the geoscientific data and information on SW IPB, 3D modeling, geophysical data. The future research programmes should investigate the deeper ore deposits, with 3D/4D modeling, new deep seismics, 3D electromagnetic forward modeling,

[10] D6.2.1 Report on pilots: evaluation of the CHPM potential of Cornwall, South West England: http://bit.ly/2WNuOcO

[11] D6.2.2 Report on pilots: Portugal Iberian Pyrite Belt http://bit.ly/2WpTw3J

3D inversion. Lombador orebody, is present at 2-3 km, has the potential to extend the lifetime with CHPM technology. Strong cooperation with the mining company and government is recommended (Figure 27).

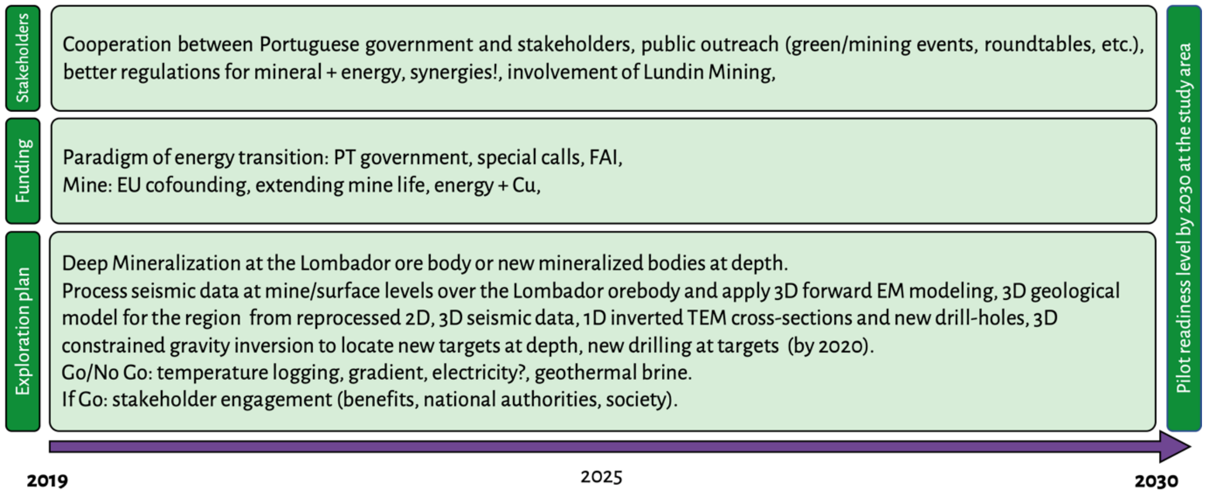

Figure 27: Recommendations for Portuguese Iberian Pyrite Belt study area

<u>Beius Basin and Bihor Mountains</u>

The report from Romania[12] provided information about the CHPM potential of Beius Basin (up and running DHS, Mg skarns, high geothermal potential), and Bihor Mountains (granodiorite-granite plutonic body related, skarn (Fe, Bo, Bi, Mo, W), vein (Cu, Zn, Pb, sulphides). The recommendation related to 1) geothermal modeling, 2) refraction seismic for the plutonic body and mineral indications, 3) fracture network modeling for understanding reservoir characteristics (Figure 28).

[12] D6.2.3 Report on pilots: Evaluation of the CHPM potential of the study site, Romania http://bit.ly/2ETz5RC

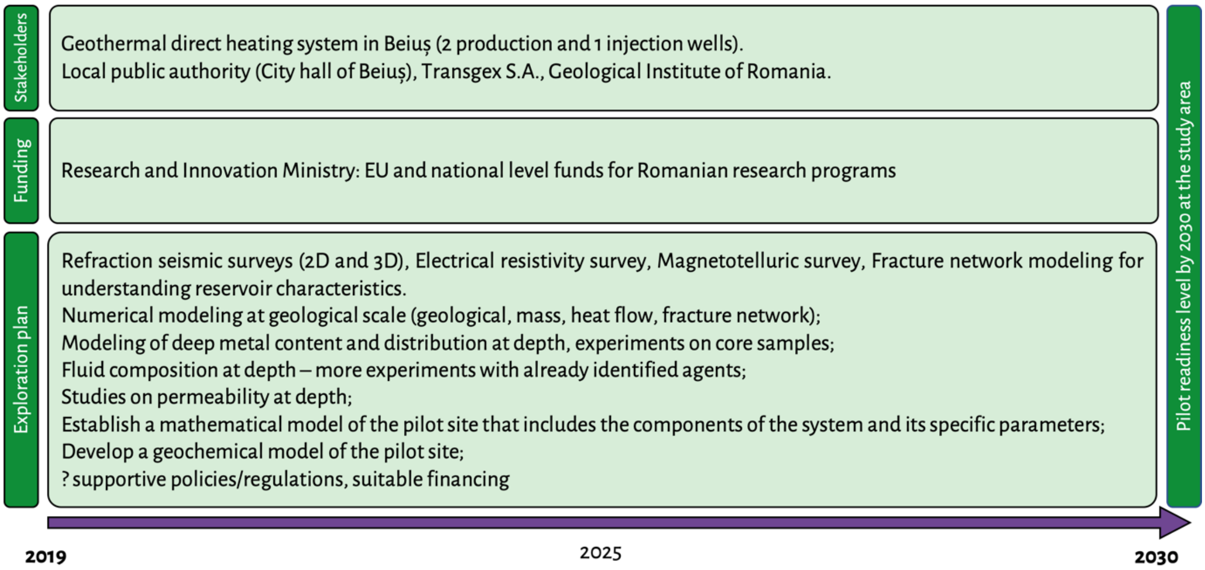

Figure 28: Recommendations for Beius Basin and Bihor Mountains study areas

<u>Kristineberg and Nautanen</u>

The Swedish report[13] described 2 ore provinces: Kristineberg area (Skellefte district, volcanogenic massive sulphide deposits, Zn, Cu, Au), and Nautanen area (Northern Norrbotten district, IOCG, Cu, Fe, Au). The challenges here are the low geothermal gradient, limited information at 5-7 km depth, low permeability and hydraulic conductivity, lack of information about deep-seated fluids. It is recommended that future exploration includes identification of metal bearing formation at crustal depths (seismic velocities, electrical resistivity), 3D/4D modelling, stimulation, involvement of the mining industry and ER regional development funds, achieving public acceptance, etc. (Figure 29).

[13] D6.2.4 Report on pilots: The Kristenberg and Nautanen mining areas in Northern Sweden http://bit.ly/2K18gzq

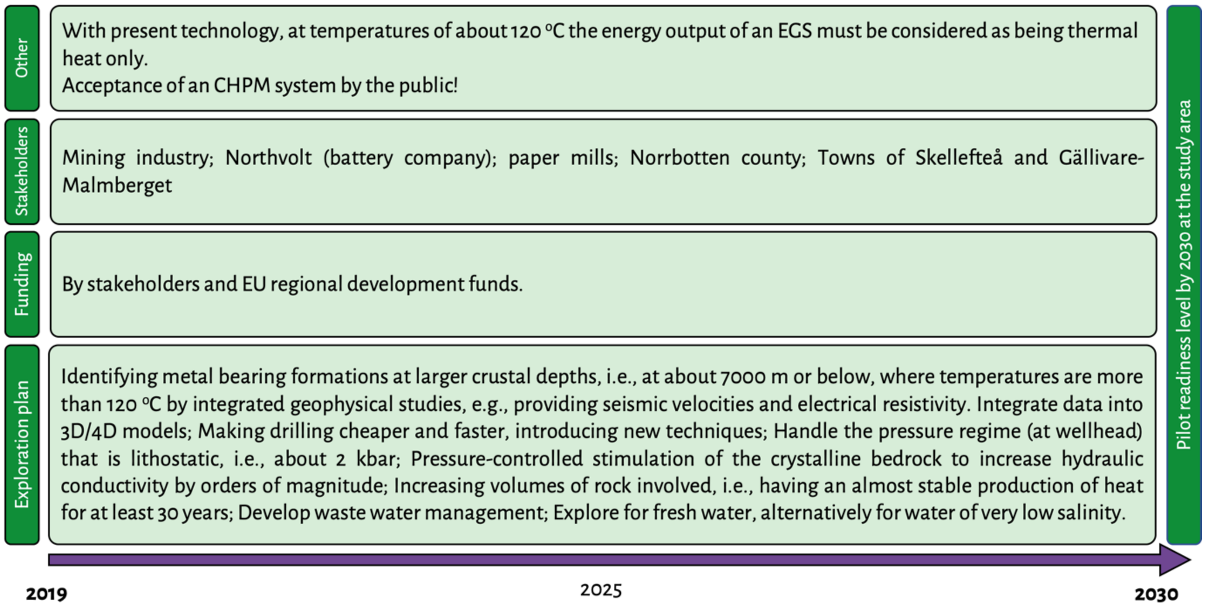

Figure 29: Recommendations for Kristineberg and Nautanen study areas

Overall CHPM concept 2030/2050

When investigating the future for combining geothermal energy and metal extraction, the CHPM roadmap delivered concrete targets, actions, signposts and wild cards linked to exploration, development, operation, and market, all related to the CHPM technology.

Exploration

The Exploration theme investigated emerging issues related to geophysics, data processing (AI, ML) and drilling depths. Identification and use of existing datasets, increased resolution (e.g. magnetotellurics), cost reduction (e.g. drilling), are some of the highlights. Advanced data processing techniques can develop and train machine learning (ML) algorithms for EGS/CHPM datasets. Guidelines for reinterpretation and re-evaluation datasets for CHPM potential and generating classes/models for CHPM exploration targeting are both assets. As a result, it is envisioned to reach a good understanding of mineral provinces with potential deep continuity, reduced data acquisition costs for CHPM, successfully application of AI/machine learning algorithms for (re)interpretation of datasets (Figure 30).

Development

The key topics for discussion related to the development of a CHPM system were reservoir stimulation, information platform, public acceptance. Under reservoir stimulation, the objective is to mobilise metals, improve reservoir performance, and reduce seismic risk, which will require testing soft leaching technology at real geothermal sites. First operators have to involved and individual components can be tested to prove the technology. These case studies can be used to attract major investors. A comprehensive information platform has been envisioned to share geoscientific information and best practises, monitor ongoing projects, and to create a platform for networking and matchmaking for potential CHPM partners. Alternative business cases have been pointed out, such as health, tourism, spa, manufacturing, where CHPM could act as a catalyst to create value for the local community. The key milestones, actions, targets, wildcards and signposts are presented in Figure 31.

<u>Operation</u>

The main topics for discussion related to the development of a CHPM system were metal mobilization, geochemical modelling, metal recovery. It is anticipated that the first CHPM pilots recover already solved metals. The advanced leaching component is added later that is first tested at well-known site, balancing solution and precipitation. Geochemical modelling is envisioned to be used for economic and business forecasts, to attract investors. Alternative recovery business cases are water treatment, non-metallic elements (Si), fluid treatment in flash steam system, abandoned mines. The key milestones, actions, targets, wildcards and signposts are presented in Figure 32.

<u>Market</u>

Market theme investigated market penetration, investors and revenue streams. The key actions outlined here are strategic partnership with geothermal players and operators; modular/flexible approach for the minerals/metals recovery component; CHPM plug-in integration for up-and-running project with high metal content in the geothermal brine; advance framework for classifying geothermal + mineral resources has to be developed, through dialogues with UNFC; government incentives (e.g. tax related) as joint partnerships (PPPs); Branding & Stakeholder engagement. As a result, it is intended to establish a network of stakeholders, by 2025 and to have at least one full business case developed for both energy and mining sector by 2030 (Figure 33).

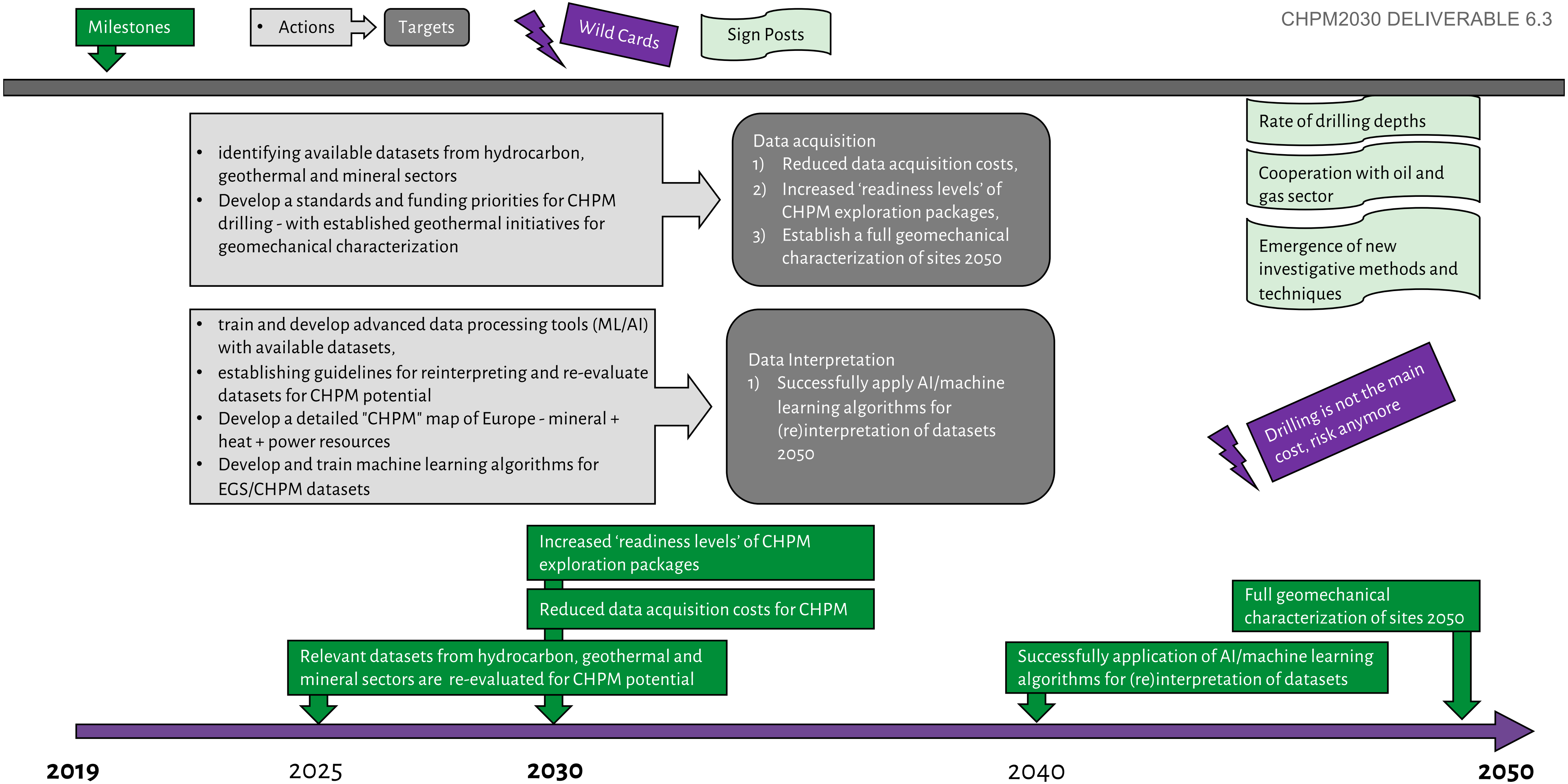

Figure 30: Milestones, Actions, Targets, Wild Cards, and Signposts for CHPM Exploration

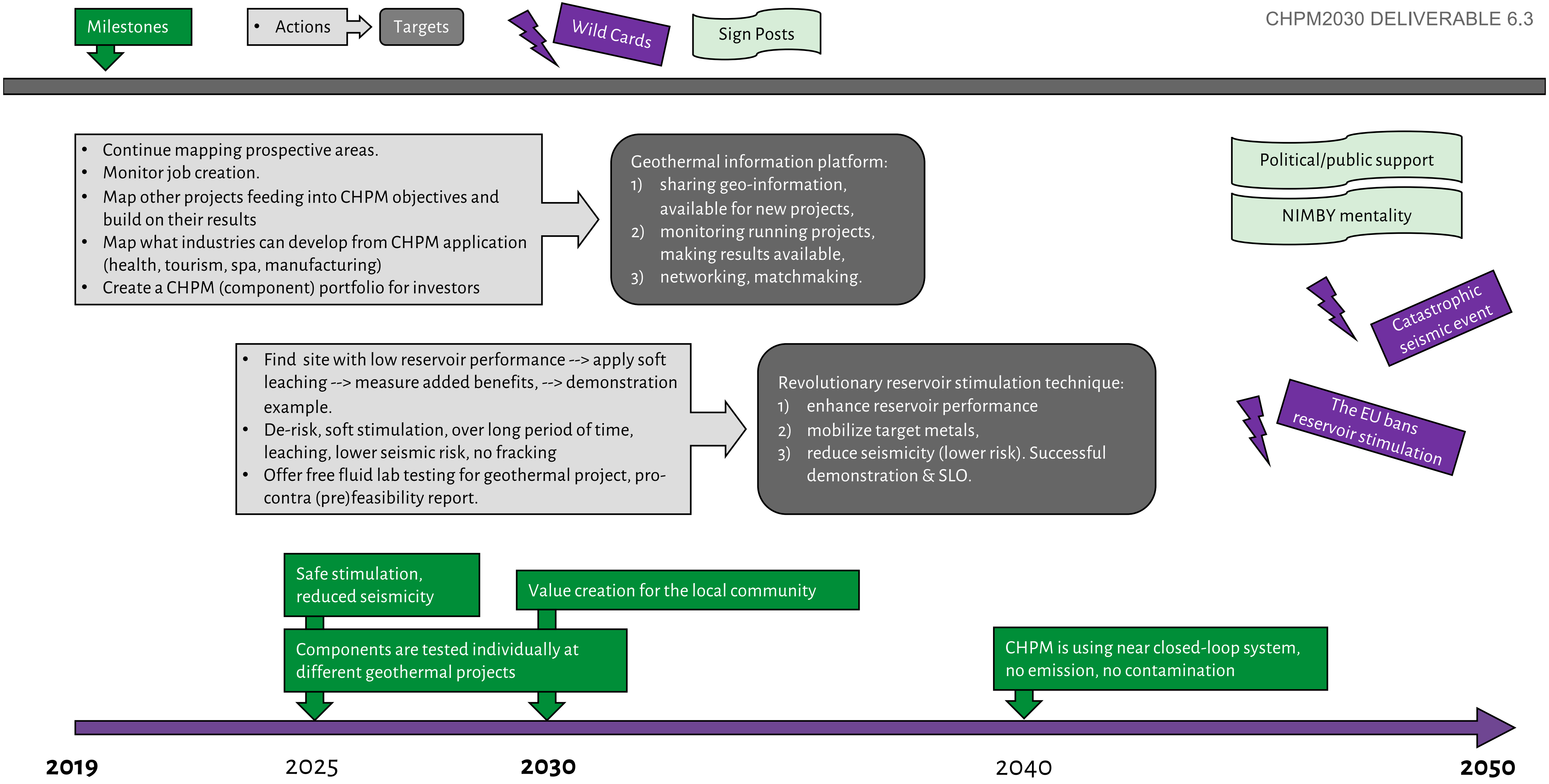

Figure 31: Milestones, Actions, Targets, Wild Cards, and Signposts for CHPM Development

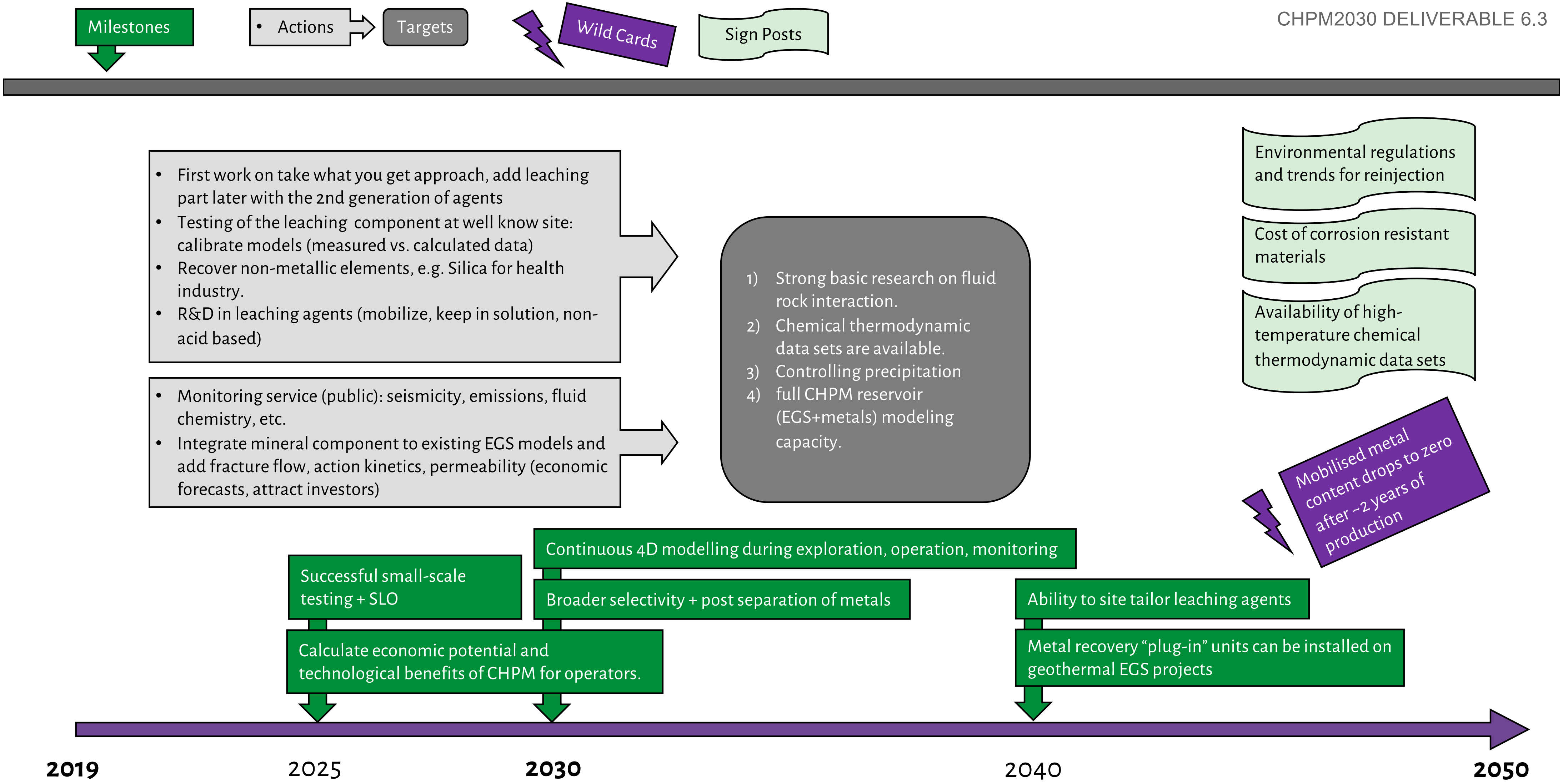

Figure 32: Milestones, Actions, Targets, Wild Cards, and Signposts for CHPM Operation

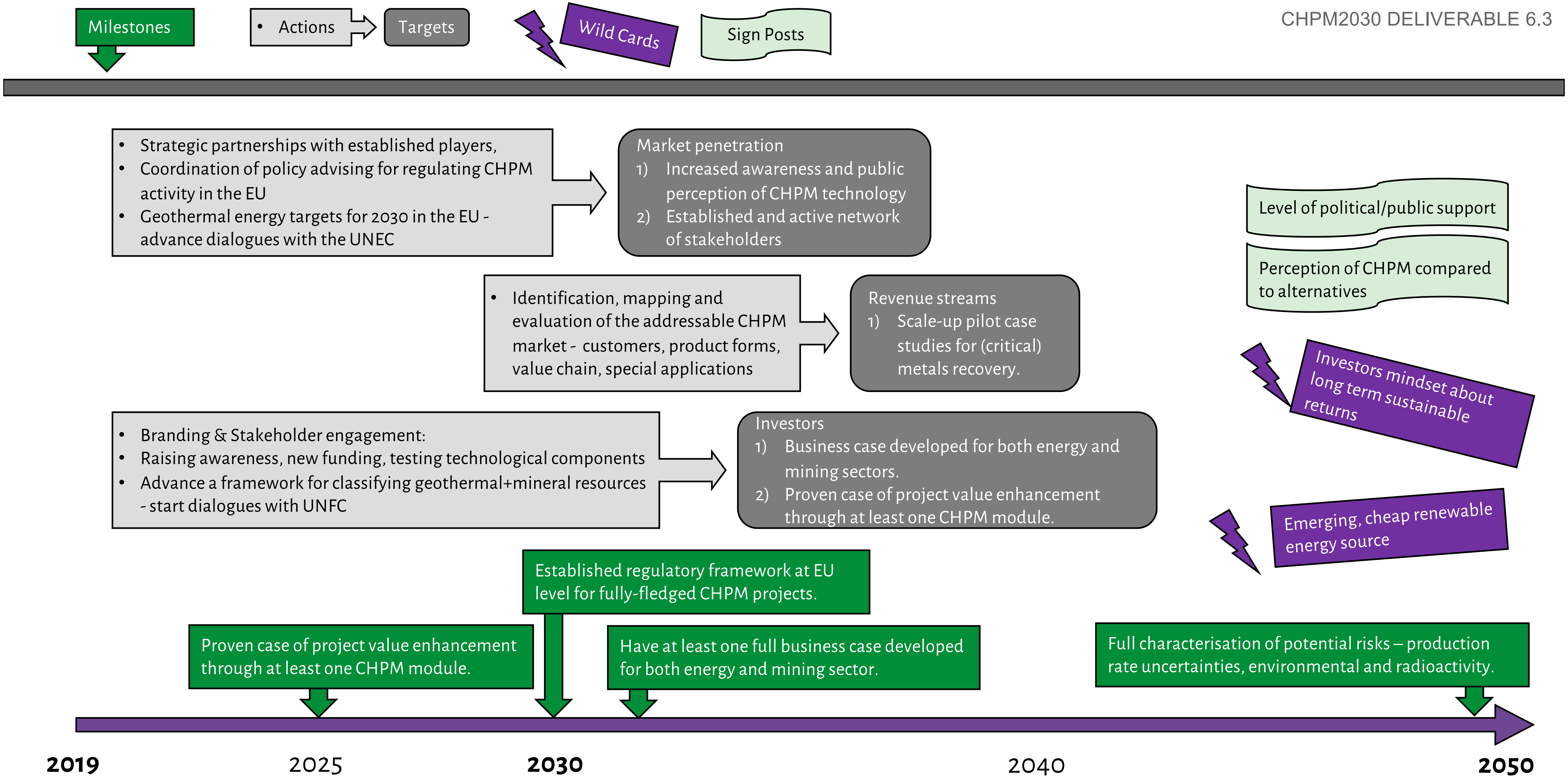

Figure 33: Milestones, Actions, Targets, Wild Cards, and Signposts for CHPM Market

In conclusion the CHPM roadmap, with 2030 and 2050 main timelines, has delivered concrete actions and targets, in the form of recommendations related to the current CHPM technological components (describing the state-of-the-art, immediate research plan (2025), pilot research plan 2030, and long term objectives 2050), potential future pilot areas (detailed description based on a common evaluation framework, and recommendations for future exploration, stakeholder engagement and funding opportunities), and about the overall concept of the combination of geothermal energy and metal extraction (targets, actions, signposts, wildcards linked to exploration, development, operation, and market).

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